XI. *Further Researches on the Polarity of the Diamagnetic Force.* *By* John Tyndall, *F.R.S., Membre de la Société Hollandaise des Sciences; Foreign Member of the Physical Society of Berlin, and Professor of Natural Philosophy in the Royal Institution.*

Received November 27,—Read December 20, 1855.

INTRODUCTION.

A YEAR ago I placed before the Royal Society the results of an investigation "On the Nature of the Force by which Bodies are repelled from the Poles of a Magnet*." The simultaneous exhibition of attraction and repulsion in the case of magnetized iron is the fact on which the idea of the polarity of this substance is founded; and it resulted from the investigation referred to, that a corresponding duality of action was manifested by bismuth. In those experiments the bismuth was the moveable object upon which fixed magnets were caused to act, and from the deflection of the bismuth its polarity was inferred. But, inasmuch as the action is reciprocal, we ought also to obtain evidence of diamagnetic polarity by reversing the conditions of experiment; by making the magnet the moveable object, and inferring from its deflection the polarity of the mass which produces the deflection. This experiment would be complementary to those described in the communication referred to, and existing circumstances invested the experiment with a great degree of interest and importance.

In fact an experiment similar to that here indicated was made by Professor W. Weber, previous to my investigation, and the result was such as to satisfy its author of the reverse polarity of diamagnetic bodies. I will not here enter into a minute description of the instrument and mode of experiment by which this result was obtained; for the instrument made use of in the present inquiry being simply a refinement of that made use of by M. Weber, its explanation will embrace the explanation of his apparatus. For the general comprehension of the criticisms to which M. Weber's results have been subjected, it is necessary, however, to remark, that in his experiments a bismuth bar, within a vertical spiral of copper wire, through which an electric current was transmitted, was caused to act upon a steel magnet freely suspended without the spiral. When the two ends of the bar of bismuth were permitted to act successively upon the suspended magnet, a motion of the latter was observed, which indicated that the bismuth bar was polar, and that its polarity was the reverse of that of iron.

Notwithstanding the acknowledged eminence of M. Weber as an experimenter,

* Philosophical Transactions, 1854.

this result failed to produce general conviction. Mr. Faraday, in his paper "On the polar or other condition of diamagnetic bodies*," had shown that results quite similar to those obtained by M. Weber, in his first investigation with bismuth, were obtained in a greatly exalted degree, with gold, silver and copper; the effect being one of induction, and not one due to diamagnetic polarity. He by no means asserted that his results had the same origin as those obtained by M. Weber; but as the latter philosopher had made no mention of the source of error which Mr. Faraday's experiments rendered manifest, it was natural to suppose that it had been overlooked, and the observed action attributed to a wrong cause. In an article published in his 'Massbestimmungen' in 1852, M. Weber, however, with reference to this point, writes as follows:—"I will remark that the article transferred from the Reports of the Society of Sciences of Saxony to Poggendorff's 'Annalen' was only a preliminary notice of my investigation, the special discussion of which was reserved for a subsequent communication. It will be sufficient to state here, that in the experiments referred to I sought to eliminate the inductive action by suitable combinations; but it is certainly far better to set aside this action altogether, as has been done in the experiments described in the present memoir."

One conviction grew and strengthened throughout these discussions—this, namely, that in experiments on diamagnetic polarity great caution is required to separate the pure effects of diamagnetism from those of ordinary induction. With reference to even the most recent experiments of M. Weber—those to which he has referred at the conclusion of the above citation—it is strongly urged that there is no assurance that the separation referred to has been effected. In those experiments, as already stated, a cylinder of bismuth was suspended within a vertical helix of covered copper wire, and the action of the cylinder upon a magnet suspended opposite to the centre or neutral point of the helix was observed. To increase the action, the position of the cylinder was changed at each termination of the minute swing of the magnet, the amplitude of the oscillations being thus increased, and the effect rendered more sensible to the eye. Now, it is urged, there is every reason to believe that in these motions of a metallic mass within an excited helix induced currents will be developed, which, acting upon the magnet, will produce the motions observed. The failure indeed to demonstrate the existence of diamagnetic polarity by other means has, in the case of some investigators, converted this belief into a certainty.

Among the number whom M. Weber's experiments have failed to convince, M. Matteucci occupies a prominent place. With reference to the question before us this philosopher writes as follows†:—"In reading the description of the experiments of M. Weber, we are struck on beholding the effects produced by moving the bismuth when there is no current in the spiral. Although the direction of oscillation in this latter case is opposed to that observed when the spiral is active, still

* Experimental Researches, 2640, Philosophical Transactions, 1850, p. 171.

† Cours Spécial sur l'Induction, p. 206.

the fact excites doubts as to the truth of the conclusions which have been drawn from these experiments*. *To deduce rigorously the demonstration of diamagnetic polarity, it would be necessary to substitute for the bismuth, masses formed of insulated fragments of the metal*†, *to vary the dimensions of the cylinder, and above all, to compare the effects thus obtained with those which would probably be obtained with cylinders of copper and silver in a state of purity.*

"We are obliged to make the same remarks on another series of experiments which this physicist has made to obtain anew, by the effects of induction, the proof of diamagnetic polarity. It is astonishing that after having sought to neutralize the development of induced currents in the moving cylinders of bismuth, by means of a very ingenious disposition of the spiral—it is astonishing, I repeat, that no attempt was made to prove by preliminary essays with metals possessing a higher conductibility than bismuth, that the same end could be obtained. I cannot leave you ignorant that the doubts which I have ventured to advance against the experiments of M. Weber are supported by the negative result which I have obtained in endeavouring to excite diamagnetic polarity in bismuth by the discharge of the Leyden jar."

It will be seen in the following pages that the conditions laid down by M. Matteucci for the rigorous demonstration of diamagnetic polarity are more than fulfilled.

The conclusions of M. Weber find a still more strenuous opponent in his countryman Professor v. Feilitzsch, who has repeated Weber's experiments, obtained his results, but who denies the validity of his inferences. M. v. Feilitzsch argues that in the experiments referred to it is impossible to shut out ordinary induction, and for the rigorous proof of diamagnetic polarity proposes the following conditions‡. "To render the experiment free from the action of induced currents two ways are open. The currents can be so guided that they shall mutually neutralize each other's action upon the magnet, or the induced currents can be *completely got rid of* by using, instead of a diamagnetic *conductor*, a diamagnetic *insulator*." To test the question, M. v. Feilitzsch resorted to the latter method: instead of cylinders of bismuth he made use of cylinders of wax, and also of a prism of heavy glass, but in neither case was he able to detect the slightest action upon the magnet. "However the motions of the prism might be varied, it was not possible either to cause the motionless magnet to oscillate, or to bring the magnet from a state of oscillation to one of rest."

* It is not my place to account for the effect here referred to. I may however remark, that there appears to be no difficulty in referring it to the ordinary action of a diamagnetic body upon a magnet. It is the result which Brugmann published upwards of half a century ago; the peculiar form of this result in one of the series of experiments quoted by M. Weber must, I think, be regarded as purely accidental.—J. T.

† Also in page 204:—"Il fallait donc, pour prouver si l'influence d'un corps diamagnétique produit sur un aimant une variation de sens contraire à celle développée dans le fer doux, opérer avec ce corps *privé de conductibilité.*"

‡ Poggendorff's Annalen, xcii. 377.

M. v. Feilitzsch pushes his experiments further, and finds that when the bismuth is *motionless* within its spiral, the position of the magnet is just the same as when the bismuth is entirely withdrawn; hence his final conclusion, that the deflection of the magnet in Weber's experiments is due to induced currents, which are excited in the bismuth by its mechanical motion up and down within the spiral.

These divergent opinions upon a question of such vital bearing upon the general theory of magnetic phenomena, naturally excited in me the desire to make myself acquainted with the exact value of M. Weber's experiments. The most direct way of accomplishing this I considered to be, to operate with an instrument similar to that made use of by Weber himself; I therefore resolved to write to the constructor of his apparatus, but previous to doing so the thought occurred to me of writing to M. Weber, to inquire whether his further reflections on the subject had suggested to him any desirable modification of his first instrument. In reply to my question he undertook to devise for me an apparatus, surpassing in delicacy any hitherto made use of. The design of M. Weber was ably carried out by M. Leyser of Leipzig, and with the instrument thus placed in my possession I have been able, not only to verify the experiments of M. Weber, but to satisfy the severest conditions proposed by those who saw in the results of these experiments the effects of ordinary induction.

DESCRIPTION OF APPARATUS.

A sketch of the instrument made use of in the present investigation is given in fig. 2. BO, B′O′ is the outline of a rectangular box, the front of which is removed so as to show the apparatus within. The back of the box is prolonged, and terminates in two semicircular projections, which have apertures at H and H′. Stout bolts of brass, which have been made fast in solid masonry, pass through these apertures, and the instrument, being secured to the bolts by screws and washers, is supported in a vertical position, being free from all disturbance save such as affects the foundations of the Royal Institution. All the arrangements presented to the eye in fig. 2 are made fast to the back of the box, but are unconnected with the front, so as to permit of the removal of the latter. WW′ are two boxwood wheels with grooved peripheries, which permit of motion being transferred from one wheel to the other by means of a string *ss′*. Attached to this string are two cylinders, *mn*, *op*, of the body to be examined: in some cases the cylinders are perforated longitudinally, the string passes through the perforation, and the cylinders are supported by knots on the string. HE, H′E′ are two helices of copper wire overspun with silk, and wound round two brass reels, the upper ends of which protrude from H to G, and from H′ to G′. The internal diameter of each helix is 0·8 of an inch, and its external diameter about 1·3 inch; the length from H to E is 19 inches, and the centres of the helices are 4 inches apart; the diameters of the wheels WW′ being also 4 inches. The cross bar GG′ is of brass, and through its centre passes the screw R, from which depends a number of silk fibres which support an astatic arrangement of two magnets, the front one of which, SN, is shown in the figure. An enlarged section of the instrument through the system of magnets is shown in fig. 4. The magnets are connected by a brass cross-piece, in which is the point of suspension P; and the position of the helices is shown

Fig. 1.

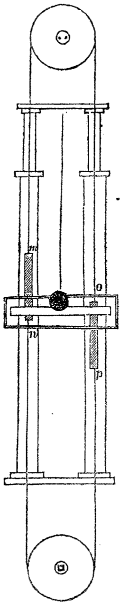


Fig. 2.

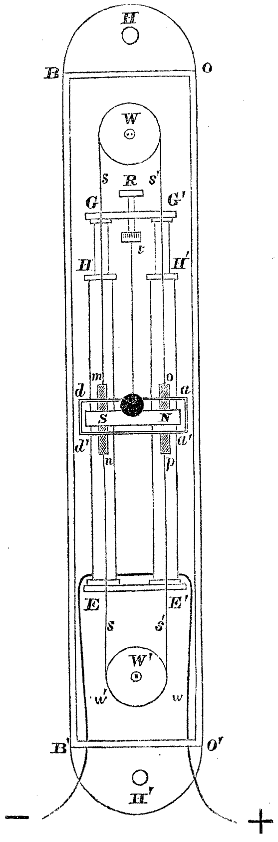


Fig. 3.

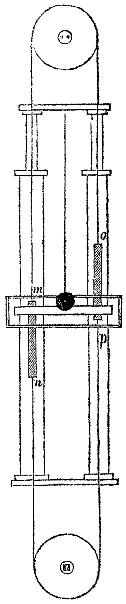
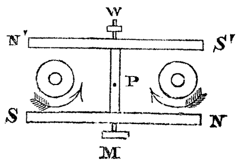


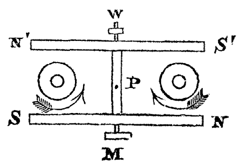
Fig. 4.



to be between the magnets. It will be seen that the astatic system is a horizontal one, and not vertical, as in the ordinary galvanometer. The black circle in front of the magnet SN, fig. 2, is a mirror, which is shown in section at M, fig. 4; to balance the weight of this mirror, and adjust the magnets in a horizontal position, a brass washer, W, is caused to move along a screw, until a point is attained at which its weight has brought both the magnets into the same horizontal plane. There is also another adjustment, which permits of the magnets being brought closer together or separated more widely asunder. The motions of the compound magnet are observed by means of a distant scale and telescope, according to the method applied to the magnetometer of Gauss. The rectangle *da*, *d'a'*, fig. 2, is the outline of a copper damper, which, owing to the currents induced in it by the motion of the magnet, soon brings the latter to rest, and thus expedites experiment.

It is well known that one end of a magnet attracts, while the other end repels the same pole of a magnetic needle; and that between both there is a neutral point which neither attracts nor repels. The same is the case with the helices HE, H′E′; so that when a current is sent through them, if the astatic magnet be exactly opposite the neutral point, it is unaffected by the helices. This is scarcely attainable in practice; a slight residual action remains which draws the magnets against the helices; but this is very easily neutralized by disposing an external portion of the circuit so as to act upon the magnets in a direction opposed to that of the residual action. Here then we have a pair of spirals which, when excited, do not act upon the magnets, and which therefore permit us to examine the pure action of any body capable of magnetic excitement placed within them. In the experiments to be described, it was always arranged that the current flowed in opposite directions through the two spirals; so that if the bodies within them were polar, the two upper ends of these bodies should be poles of opposite names, and consequently the two lower ends opposed also. Supposing now our two cylinders to occupy the central position indicated in fig. 2: even if the cylinders became polar through the action of the surrounding current, the magnets, being opposite to the neutral points of the cylinders, would experience no action from the latter. But suppose the wheel W′ to be so turned that the two cylinders are brought into the position shown in fig. 1, the upper end *o* of *op* and the lower end *n* of *mn* will act simultaneously upon the suspended magnets. For the sake of illustration, let us suppose the ends *o* and *n* to be both north poles, and that the section, fig. 4, is taken when the bars are in the position shown in fig. 1. The right-hand pole *o* will attract S′ and repel N, which attraction and repulsion sum themselves together to produce a deflection of the system of magnets. On the other hand, the left-hand pole *n*, being also north, will attract S and repel N′, which two effects also sum themselves to produce a deflection in the same direction as the former two. Hence, not only is the action of terrestrial magnetism annulled by this arrangement, but the moving force due to the reciprocal action of the magnets and the bodies within the helices is increased fourfold. By turning the wheel in the other direction we bring the cylinders into the position shown in fig. 3, and thus may study the action of the ends *m* and *p* upon the magnets.

Fig. 4.



By means of the screw R the magnets can be raised or lowered; and at the end, *t*, of the screw is a small torsion circle which can be turned independently of the screw; by means of the latter the suspending fibre can be twisted or untwisted without altering the level of the magnets.

The front of the box is attached by means of brass hasps, and opposite to the mirror M a small plate of glass is introduced, through which the mirror is observed; the magnets within the box being thus effectually protected from the disturbances of the external air. A small handle to turn the wheel W′ accompanied the instrument from its maker; but in the experiments, I used, instead of it, a key attached to the end of a rod 10 feet long; with this rod in my right hand, and the telescope and scale before me, the experiments were completely under my own control. Finally, the course of the current through the helices was as follows:—Proceeding from the platinum pole of the battery it entered the box along the wire *w*, fig. 2, which passed through the bottom of the latter; thence through the helix to H′, returning to E′; thence to the second helix, returning to E, from which it passed along the wire *w*′ to the zinc pole of the battery. A commutator was introduced in the circuit, so that the direction of the current thus indicated could be reversed at pleasure.

EXPERIMENTS.—DEPORTMENT OF DIAMAGNETIC BODIES.

A pair of cylinders of chemically pure bismuth, 3 inches long and 0·7 of an inch in diameter, accompanied the instrument from Germany. These were first tested, commencing with a battery of one cell of GROVE. Matters being as sketched in fig. 2, when the current circulated in the helices and the magnet had come to rest, the cross wire of the telescope cut the number 482 on the scale. Turning the wheel W′ so as to bring the cylinders into the position fig. 1, the magnet moved promptly, and after some oscillations took up a new position of equilibrium; the cross wire of the telescope then cut the figure 468 on the scale. Reversing the motion so as to place the cylinders again central, the former position 482 was assumed; and on turning further in the same direction, so as to place the cylinders as in fig. 3, the position of equilibrium of the magnet was at the number 493. Hence by bringing the two ends *n* and *o* to bear upon the astatic magnet, the motion was from greater to smaller numbers, the position of rest being then fourteen divisions less than when the bars were central. By bringing the ends *m* and *p* to bear upon the magnet, the motion was from smaller to greater numbers, the position of rest being eleven divisions more than when the bars were central.

As the positions here referred to will be the subject of frequent reference, for the sake of convenience I will call the position of the cylinders sketched in fig. 1, Position 1; that sketched in fig. 2, Position 2; and that sketched in fig. 3, Position 3. The results which we have just described, tabulated with reference to these terms, would then stand thus:—

I.

Bismuth cylinders.

length 3 inches.
diameter 0·7.

Position 1.	468
Position 2.	482
Position 3.	493

In changing therefore from position 1 to position 3, a deflection corresponding to twenty-five divisions of the scale was produced.

Wishing to place myself beyond the possibility of illusion as regards the fact of deflection, I repeated the experiment with successive batteries of two, three and four cells. The following are the results:—

II.

	2 cells.	3 cells.	4 cells.
Position 1.	450	439	425
Position 2.	462	450	437
Position 3.	473	462	448

In all the cases cited we observe the same result. From position 2 to position 1 the motion is from larger to smaller numbers; while from position 2 to position 3 the motion is from smaller to larger numbers.

It may at first sight appear strange that the amount of the deflection did not increase with the battery power; the reason, in part, is that the magnet, when the current circulated, was held in a position free from the spirals, by forces emanating partly from the latter and partly from a portion of the external circuit. When the current increased, the magnetization of the bismuth increased also, but so did the force which held the magnets in their position of equilibrium. To remove them from this position, a greater amount of force was necessary than when only the residual action of a feeble current held them there. This fact, coupled with the circumstance that less heat was developed, and less disturbance caused by air currents, when a feeble battery was used, induced me for some time to experiment with a battery of two cells. Subsequent experience however enabled me to change this for five cells with advantage.

Notwithstanding the improbability of the argument, still it may be urged that these experiments do not prove beyond a doubt that the bismuth cylinders produce the motion of the magnets in virtue of their excitement by the voltaic current; for it is not certain that these cylinders would not produce the same motion wholly independent of the current. Something of this kind has occurred to M. Leyser* in his experiments, and why not here?

In answer to this I reply, that if the case be as here suggested, the motion of the magnet will not be changed when the current surrounding the bismuth cylinders flows in the opposite direction. Here is the experiment.

III.

Position 1.	764
Position 2.	742
Position 3.	704

We observe here that in passing from position 2 to position 1 the motion is from smaller to larger numbers; while in passing from position 2 to position 3 the motion

* Scientific Memoirs, New Series, vol. i. page 184.

is from larger to smaller numbers. This is the opposite result to that obtained when the current flowed in the opposite direction; and it proves that the polarity of the bismuth cylinders depends upon the direction of the current, changing as the latter changes. It was pleasant to observe the prompt and steady march of the magnet as the cylinders were shifted in the helices. When the magnets, operated on by the bars of bismuth, were moving in any direction, by bringing the two opposite ends of the bismuth bars into action, the motion could be promptly checked; the magnets could be brought to rest, or their movement converted into one in the opposite direction.

I may add to the above a series of results obtained some days subsequently in the presence of Professors FARADAY, DE LA RIVE and MARCET.

IV.

Bismuth cylinders.

Position 1.	670
Position 2.	650
Position 3.	630

The difference between positions 1 and 3 amounts here to forty divisions of the scale; subsequent experience enabled me to make it still greater.

It was found by experiment, that when the motion was from lower to higher numbers it denoted that the poles NN′, fig. 4, were repelled from the spirals, and the poles SS′ attracted towards them. When, on the contrary, the motion was from larger to smaller numbers, it indicated that the poles NN′ were attracted and the poles SS′ repelled. In the position fig. 1, therefore, of Tables III. and IV. the poles NN′ were repelled by the ends *no* of the bismuth cylinders, and the poles SS′ attracted, while in the position fig. 3, the poles NN′ were attracted by the ends *mp*, and the poles SS′ repelled; the ends *n* and *o*, therefore, acted as two north poles, while the ends *m* and *p* acted as two south poles. Now the direction of the current in the experiments recorded in the two tables referred to was that shown by the arrows in fig. 4. Standing in front of the instrument, the direction in the adjacent face of the spiral H′E′ was from right to left, while it was from left to right in HE. From this we may infer that the polarity of the bismuth cylinders was the reverse of that which would be excited in cylinders of iron under the same circumstances. The assertion however shall be transferred from the domain of deduction to that of fact before we conclude.

Let us now urge against these experiments all that ever has been urged by the opponents of diamagnetic polarity. The bismuth cylinders are metallic conductors, and in moving them through the spirals induced currents more or less powerful may be excited in these conductors. The motion observed may not, after all, be due to diamagnetic polarity, but to the currents thus excited. I reply, that in all cases the number set down marks the *permanent* position of rest of the magnets. Were the action due to induced currents, these currents, being momentary, could only impart a *shock* to the magnets, which, on the disappearance of the currents, would return to their original position. But the deflection is permanent, and is therefore due to an enduring cause. In his paper on "Supposed Diamagnetic Polarity," Mr. FARADAY rightly observes,—"If the polarity exists, it must be in the particles, and for the time permanent, and therefore distinguishable from the momentary polarity of the mass due to induced temporary currents, and it must also be distinguishable from ordinary magnetic polarity by its contrary direction." These are the precise characteristics of the force made manifest by the experiments now under consideration.

Further, the strength of induced currents depends on the conducting power of the mass in which they are formed. Expressing the conducting power of bismuth by the number 1·8, that of copper would be expressed by 73·6*, the conductivity of the latter being therefore forty times that of the former. Hence the demand made by the opponents of diamagnetic polarity, to have the experiments repeated with cylinders of copper; for if the effect be due to induced currents, they will show themselves in copper in a greatly increased degree. The following is the result of a series of experiments made with two copper cylinders, of the same dimensions as the bismuth ones already described.

V.

Cylinders of Copper.

Position 1.	754
Position 2.	754
Position 3.	755

Now if the effects obtained with bismuth were due to induced currents, we should have the same effects forty times multiplied in the case of copper, in place of which we have scarcely any sensible effect at all.

Bismuth is the only substance which has hitherto produced an action in experiments of this nature; another illustration, however, is furnished by the metal antimony, which possesses a greater conductive power, but a less diamagnetic power than bismuth. The following results were obtained with this substance:—

VI.

Cylinders of Antimony.

length 3 inches.
diameter 0·7.

	Current direct†.	Current reversed‡.
Position 1.	693	244
Position 2.	688	252
Position 3.	683	261

* Philosophical Magazine, Series 4, vol. vii. p. 37.

† As in III. and IV.

‡ As in I. and II.

On comparing these numbers with those already obtained with bismuth, we observe that for like positions the actions of both metals are alike in direction. We further observe that the results are determined, not by the relative conductive powers of the two metals, but by their relative diamagnetic powers. If the former were the determining cause, we should have greater deflections than with the bismuth, which is not the case; if the latter, we should have less deflections, which is the case.

The third and severest condition proposed by those who object to the experiments of M. Weber is to substitute insulators for conductors. I call this condition severe for the following reasons:—according to the experiments of Faraday*, when bismuth and sulphur are submitted to the same magnetic force, the repulsion of the former being expressed by the number 1968, that of the latter will be expressed by 118. Hence an action which, with the means hitherto used, was difficult of detection in the case of bismuth, must wholly escape observation in the case of sulphur, the intensity of whose excitement is nearly twenty times less. The same remarks apply, in a great measure, to all other insulators.

But the admirable apparatus made use of in this investigation has enabled me to satisfy this condition also. To Mr. Faraday I am indebted for the loan of two prisms of the self-same heavy glass with which he made the discovery of diamagnetism. The bismuth cylinders were withdrawn from the helices and the prisms of glass put in their places. It was now necessary to have a perfectly steady magnet, the expected result being so small as to be readily masked by, or confounded with, a motion arising from some extraneous disturbance. The feeble warmth developed in the helices by a current from two cells I found able to create air currents of sufficient power to defeat all attempts to obtain the pure action of the prisms. To break up these currents I stuffed all unfilled spaces of the box with old newspapers, and found the expedient to answer perfectly. With a fresh battery, which delivered a constant stream throughout the duration of an experiment, the magnet was admirably steady†, and under these favourable conditions the following results were obtained:—

VII.

Prisms of Heavy Glass.

length 3 inches.
width 0·6.
depth 0·5.

	Current direct.
Position 1.	664
Position 2.	662
Position 3.	660

* Proceedings of the Royal Institution, 1853, p. 5.

† It was necessary however to select a portion of the day when Albemarle Street was free from cabs and carriages, as the shaking of the entire building, by the rolling of these vehicles, rendered the magnets unsteady.

Thus in passing from position 1 to 3, or *vice versâ*, a permanent deflection corresponding to four divisions of the scale was produced. By raising or lowering the respective prisms at the proper moments the amplitude of the oscillations could be considerably augmented, and, when at a maximum, could be speedily extinguished by reversing the motions of the prisms. In six different series of experiments made with this substance the same invariable result was obtained. It will be observed that the deflections are in all cases in the same direction as those produced by bismuth under the same circumstances.

The following results were afterwards obtained with the same prisms in the presence of M. De la Rive; the current was "direct."

VIII.

Position 1.	652
Position 2.	650
Position 3.	648

On the negative result arrived at with this substance, it will be remembered that M. v. Feilitzsch bases one of his arguments against the conclusions of M. Weber.

Calcareous spar was next submitted to experiment. Two cylinders of the transparent crystal were prepared and examined in the manner already described. The results are as follows:—

IX.

Cylinders of Calcareous Spar.

length 3 inches.
diameter 0·7.

	Current direct.
Position 1.	699·5.
Position 2.	698·5.
Position 3.	697·5.

Here, as in the other cases, the deflection was permanent, and could be augmented by the suitable raising or lowering of the respective cylinders. The action is small, but perfectly certain. The magnet was steady and moved promptly and invariably in the directions indicated by the numbers. It will be observed that the deflections are the same in kind as those produced by bismuth.

The intrusion of other employments compelled me to postpone the continuation of these experiments for several weeks. On taking up the subject again, my first care was to assure myself that the instrument retained its sensibility. Since the experiments last recorded it had been transported over several hundred miles of railway, and hence the possibility of a disturbance of its power. The following experiments, while they corroborate the former ones, show that the instrument retained its power and delicacy unimpaired:—

X.

Bismuth cylinders.

	Current direct.	Current reversed.
Position 1.	612	264
Position 2.	572	230
Position 3.	526	200

The deflections, it will be observed, are the same in kind as before; but by improved manipulation the effect is augmented. In passing from position 1 to 3 we have here a deflection amounting in one case to 64, and in the other to 86 divisions of the scale.

To Mr. Noble I am indebted for two cylinders of pure statuary marble; the examination of these gave the following results:—

XI.

Cylinders of Statuary Marble.

length 4 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	601	215
Position 2.	598	218
Position 3.	596	220

Here, in passing from position 1 to 3, we have a permanent deflection corresponding to five divisions of the scale. As in all other cases, the impulsion of the magnet might be augmented by changing the position of the cylinders at the limit of each swing. The deflections are the same in kind as those produced by bismuth, which ought to be the case, as marble is diamagnetic.

An upright iron stove influenced by the earth's magnetism becomes a magnet with its bottom a north and its top a south pole. Doubtless, though in an immensely feebler degree, every erect marble statue is a true diamagnet, with its head a north pole and its feet a south pole. The same is certainly true of man as he stands upon the earth's surface, for all the tissues of the human body are diamagnetic.

A pair of cylinders of phosphorus enclosed in thin glass tubes were next examined.

XII.

Cylinders of Phosphorus.

length 3·5 inches.
diameter 0·63.

	Current direct.		Current reversed.
	Series I.	Series II.	
Position 1.	620	670	224
Position 2.	618	668	226
Position 3.	616	666	228

The change of the bars from position 1 to 3 is in this case accompanied by permanent deflection corresponding to four divisions of the scale. The deflection indicates the polarity of diamagnetic bodies. The magnet was remarkably steady during these experiments, and the consequent clearness and sharpness of the result pleasant to observe.

XIII.

Cylinders of Sulphur.

length 6 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	658·5	222
Position 2.	657	223·5
Position 3.	655·5	225·5

XIV.

Cylinders of Nitre.

length 3·5 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	648·5	263
Position 3.	647	265

Finally, as regards solid diamagnetics, a series of experiments was made with wax; this also being one of the substances whose negative deportment is urged by M. v. Feilitzsch against M. Weber.

XV.

Cylinders of Wax.

length 4 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	624·5	240
Position 3.	623	241

The action is very small, but it is nevertheless perfectly certain. The argument founded on the negative deportment of this substance must therefore give way.

When we consider the feebleness of the action with so delicate a means of examination, the failure of M. v. Feilitzsch to obtain the effect, with an instrument constructed by himself, will not excite surprise.

Thus in the case of seven insulating bodies the existence of diamagnetic polarity has been proved; the list might be augmented without difficulty, but sufficient, I trust, has been done to remove the scruples of those who saw in M. Weber's results an action produced by induced currents.

A portion of the subject hitherto untouched, but one of great interest, has reference to the polar condition of liquid bodies while under magnetic influence. The first liquid examined was distilled water; it was enclosed in thin glass tubes, corked at the ends, and by means of a loop passing round the cork the tubes were attached to the string passing round the wheels WW′. Previous to using, the corks were carefully cleansed, so that any impurity contracted in cutting, or by contact with ferruginous matters, was completely removed. The following are the results obtained with this liquid:—

XVI.

Cylinders of Distilled Water.

length 4 inches.
diameter 0·65.

	Current direct.	Current reversed.
Position 1.	605	246
Position 2.	603	248
Position 3.	601	250

The experiment was many times repeated, but always with the same result; indeed the polarity of the liquid mass is as safely established as that of iron. Pure water is diamagnetic, and the deflections produced by it are the same as those of all the other diamagnetic bodies submitted to examination.

From the position which it occupies in Mr. Faraday's list*, I had also some hopes of proving the polarity of sulphide of carbon. The following results were obtained:—

XVII.

Cylinders of Bisulphide of Carbon.

length 4 inches.
diameter 0·65.

	Current direct.	Current reversed.
Position 1.	631	210
Position 2.	629	213
Position 3.	626	216

* Proceedings of the Royal Institution, 1853, p. 5.

As in the case of distilled water, we observe a deflection in one direction when the current is "direct" and in the other when it is "reversed," the action in the first case, in passing from position 1 to 3, amounting to five and in the latter case to six divisions of the scale. The polarity exhibited is that of diamagnetic bodies.

DEPORTMENT OF MAGNETIC BODIES.

Thus far we have confined our examination to diamagnetic substances; turn we now to the deportment of magnetic bodies when submitted to the same conditions of experiment. Here we must select the substances suitable for examination, for all are not so. Cylinders of iron, for example, of the same size as our diamagnetic cylinders, would, through the intensity of their action, quite derange the apparatus; so that we are obliged to have recourse to bodies of smaller size or of feebler magnetic capacity. Besides, the remarks of writers on this subject render it of importance to examine whether bodies through which the magnetic constituents are very sparingly distributed present a veritable polarity the same as that exhibited by iron itself.

Slate rock usually contains from eight to ten per cent. of oxide of iron, and a fragment of the substance presented to the single pole of an electro-magnet is attracted by the pole. A cylinder of slate from the Penrhyn quarries near Bangor was first examined. It was not found necessary to increase the effect by using two cylinders, and the single one used was suspended in the right-hand helix H′E′. The deportment of the substance was as follows:—

XVIII.

Cylinder of Penrhyn Slate.

length 4 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	620	280
Position 2.	647	240
Position 3.	667	198

Comparing these deflections with those obtained with diamagnetic bodies, we see that they are in the opposite direction. With the direct current a change from position 1 to 3 is followed, in the case of diamagnetic bodies, by a motion from higher to lower numbers; while in the present instance the motion is from lower numbers to higher. In the former case the north poles of the astatic magnet are attracted, in the latter they are repelled. We also see that a *direct* current acting on diamagnetic bodies produces the same deflection as a *reverse* current on magnetic ones. Thus, as we promised at a former page, the opposite polarities of diamagnetic and magnetic bodies are transferred from the region of deduction to that of fact.

XIX.

Cylinder of Caermarthen Slate.
length 4 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	664	300
Position 2.	690	235
Position 3.	720	185

The deflections in this case are also indicative of magnetic polarity.

These two cylinders were so taken from the rock that the axis of each lay in the plane of cleavage. The following experiments, made with a cylinder of the same size, show the capability of a rock of this structure to be magnetized across the planes of cleavage.

XX.

Cylinder of Slate: axis of cylinder perpendicular to cleavage.

	Current direct.	Current reversed.
Position 1.	655	240
Position 2.	678	205
Position 3.	695	192

Chloride of iron was next examined: the substance, in powder, was enclosed in a single glass tube, which was attached to the string passing round the wheels WW′ of the instrument.

XXI.

Cylinder of Chloride of Iron.
length 3·8 inches.
diameter 0·5.

	Current direct.	Current reversed.
Position 1.	185	990
Position 2.	——	230
Position 3.	990	185

The deflection here indicates ordinary magnetic polarity. The action was very powerful. When swiftly moving in any direction, a change in the position of the cylinder instantly checked the magnet in its course, brought it to rest, or drove it forcibly in the opposite direction. The numbers 185 and 990 mark indeed the utmost limit between which it was possible for the magnet to move; here it rested against the helices.

Two glass tubes were filled with red oxide of iron and examined. The action of the poles of these cylinders upon the magnets was so strong, as to efface, by the velocity imparted to the magnets, all distinct impression of the numbers on the scale.

By changing the position of the tubes within the helices, the magnets could be driven violently through the field of view, or could be held rigidly against the respective helices. As in all other cases, the centre of the cylinders were neutral points, and the two ends of each were poles of opposite qualities. The polarity was of course the same as that of iron.

A small quantity of iron filings were kneaded thoroughly in wax, and a cylinder formed from the mass. Its deportment was also very violent, and its polarity was of course just as clear and pronounced as that of a solid cylinder of iron could possibly be.

Sulphate of iron was next examined: the crystallized substance was enclosed in two glass tubes and tested in the usual manner.

XXII.

Cylinders of Sulphate of Iron.

length 4·5 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	510	510
Position 2.	600	370
Position 3.	700	220

The red ferroprussiate of potassa is a magnetic salt; with this substance the following results were obtained:—

XXIII.

Cylinders of red Ferroprussiate of Potassa.

length 4·5 inches.
diameter 0·65.

	Current direct.	Current reversed.
Position 1.	610	250
Position 2.	630	220
Position 3.	655	197

In this case also the crystallized salt was enclosed in glass tubes.

Two glass tubes were next filled with carbonate of iron in the state of powder: the following are the results:—

XXIV.

Cylinders of Carbonate of Iron.

length 4 inches.
diameter 0·5.

	Current direct.
Position 1.	185
Position 2.	620
Position 3.	740

In all these cases the deflections show that the bodies are polar after the manner of iron.

As the complement of the experiments made with diamagnetic liquids, we now pass on to the examination of the polarity of magnetic liquids. A concentrated solution of sulphate of iron was enclosed in two glass tubes and submitted to examination.

XXV.

Sulphate of Iron solution in tubes.

length 4 inches.
diameter 0·65.

	Current direct.
Position 1.	548
Position 2.	600
Position 3.	648.

A solution of muriate of nickel, examined in the same manner, gave the following results:—

XXVI.

Muriate of Nickel solution in tubes.

length 3·6 inches.
diameter 0·65.

	Current direct.	Current reversed.
Position 1.	605	224
Position 2.	632	200
Position 3.	650	185

A solution of muriate of cobalt yielded as follows:—

XXVII.

Muriate of Cobalt solution in tubes.

length 3·6 inches.
diameter 0·65.

	Current direct.	Current reversed.
Position 1.	630	262
Position 2.	645	235
Position 3.	660	202

In all these cases we have ample evidence of a polar action the reverse of that exhibited by diamagnetic liquids. These, I believe, are the first experiments on which the action of either liquid magnets or liquid diamagnets upon a suspended steel magnet has been exhibited.

Thus far then the following substances have been submitted to examination :—

Diamagnetic bodies.	Magnetic bodies.
Bismuth.	Penrhyn slate.
Antimony.	Caermarthen slate.
Heavy glass.	Slate perpendicular to cleavage.
Calcareous spar.	Chloride of iron.
Statuary marble.	Sulphate of iron.
Phosphorus.	Carbonate of iron.
Sulphur.	Ferrocyanide of potassium.
Nitre.	Oxide of iron.
Wax.	Iron filings.
Liquids.	Liquids.
Distilled water.	Sulphate of iron.
Bisulphide of carbon.	Muriate of nickel.
	Muriate of cobalt.

Every substance in each of these lists has been proved to be polar under magnetic influence, the polarity of the diamagnetic bodies being invariably opposed to that of the magnetic ones.

In his investigation on the supposed polarity of diamagnetic bodies, Mr. FARADAY made use of a core of sixpenny pieces, and obtained with it the results he sought. Wishing to add the testimony of silver as a good conductor to that of copper, two cylinders were formed of sixpenny pieces, covered with paper and submitted to experiment. The following are the results obtained :—

XXVIII.

Silver cylinders (sixpenny pieces).

	Current direct.
Position 1.	724
Position 2.	774
Position 3.	804

The action here was prompt and energetic, strongly contrasted with the neutrality of copper; but the deflection was permanent, and could not therefore be the result of induced currents. Further, it was a deflection which shows magnetic polarity, whereas pure silver is feebly diamagnetic. The cylinders were removed and examined between the poles of an electro-magnet; they proved to be magnetic.

On observing this deportment of the silver, I tried the copper cylinders once more. The results with a direct current were,—

XXIX.

Position 1.	766
Position 2.	767
Position 3.	768

Here almost the same neutrality as before is evidenced.

Deeming that the magnetism of the cores of silver was due to magnetic impurity attaching itself to the paper which covered them, a number of fourpenny pieces were procured, washed in ammonia and water, and enclosed in thin glass tubes. The following were the results :—

XXX.

Silver cylinders (fourpenny pieces).

	Current direct.
Position 1.	490
Position 2.	565
Position 3.	660

Here also we have a very considerable action indicative of magnetic polarity. On examining the cylinders between the poles of an electro-magnet, they were found decidedly magnetic. This, therefore, appears to be the common character of our silver coins. The tubes which contained the pieces were sensibly neutral.

Knowing the difficulty of demonstrating the existence of diamagnetic polarity in ordinary insulators, M. MATTEUCCI suggested that insulated fragments of bismuth ought to be employed, the insulation being effected by a coat of lac or resin. I constructed a pair of cylinders in accordance with the suggestion of M. MATTEUCCI. The following are the results they yielded with a direct current :—

XXXI.

Position 1.	730
Position 2.	750
Position 3.	768

Here we have a very marked action, but the polarity indicated is magnetic polarity. On subsequent examination, the cylinders proved to be magnetic. This was due to impurities attaching themselves to the resin.

But the resin may be done away with and the powdered metal still rendered an insulator. This thought was suggested to me by an experiment of Mr. FARADAY, which I will here describe. Referring to certain effects obtained in his investigations on supposed diamagnetic polarity, he writes thus :—" If the effect were produced by induced currents in the mass, division of the mass would stop these currents, and so alter the effect; whereas, if produced by *a true diamagnetic polarity,* division of the mass would not affect the polarity seriously or in its essential nature. Some copper filings were therefore digested for a few days in dilute sulphuric acid to remove any adhering iron, then well washed and dried, and afterwards warmed and stirred in the air, until it was seen by the orange colour that a very thin film of oxide had formed upon them; they were finally introduced into a glass tube and employed as a core. It produced no effect whatever, but was as inactive as bismuth." (Exper. Resear. 2658.)

Now when bismuth is powdered and exposed to the action of the air, it very soon becomes tarnished, even without heating. A quantity of such powder was prepared, and its conducting power for electricity tested. The clean ends of two copper wires proceeding from a battery of GROVE were immersed in the powder; but though the wires were brought as near as possible to each other, short of contact, not the slightest action was observed upon a galvanometer placed in the circuit. When the wires touched, the needle of the galvanometer flew violently aside, thus proving that the current was there, but that the powder was unable to conduct it. Two glass tubes were filled with the powder and submitted to experiment. The following results were obtained:—

XXXII.

Cylinders of Bismuth Powder.

length 3 inches.
diameter 0·7.

	Current direct.	Current reversed.
Position 1.	640	230
Position 2.	625	245
Position 3.	596	260

These deflections are the same in kind as those obtained with the cylinders of massive bismuth. This experiment responds perfectly to the conditions proposed by Mr. FARADAY. We have here no cessation of action. The division of the mass does not affect the result seriously or in its essential nature, and hence the deportment exhibits the characteristics of "a true diamagnetic polarity."

In summing up the results of his inquiry on this subject, Mr. FARADAY writes thus:—"Finally, I am obliged to say that I can find no experimental evidence to support the hypothetical view of diamagnetic polarity, either in my own experiments, or in the repetition of those of WEBER, REICH and others. .... It appears to me also, that, as magnetic polarity conferred by iron or nickel in small quantity, and in unfavourable states, is far more easily indicated by its effects upon an astatic needle, or by pointing between the poles of a strong horseshoe magnet, than by any such arrangement as mine or WEBER'S or REICH'S, so *diamagnetic polarity would be much more easily distinguished in the same way*." I was struck, on reading this passage, to find how accurately the surmise has been fulfilled by the instrument with which the foregoing experiments were made. In illustration of the powers of this instrument, as compared with that made use of by Mr. FARADAY, I may be permitted to quote the following result from his paper on supposed diamagnetic polarity, so often referred to:—"A thin glass tube, 5½ inches by three-quarters of an inch, was filled with a saturated solution of protosulphate of iron, and employed as an experimental core; the velocity given to the machine at this and all average times was such as to cause five or six approaches and withdrawals of the core in one second;

yet the solution produced no sensible indication on the galvanometer." Referring to Table XXV., it will be seen that the instrument made use of in the present inquiry has given with a solution of protosulphate of iron a deflection amounting to no less than one hundred divisions of the scale. Mr. Faraday proceeds:—"A tube filled with small crystals of protosulphate of iron caused the needle to move about 2°. . . . Red oxide of iron produced the least possible effect." In the experiments recorded in the foregoing pages, the crystallized sulphate of iron gave a deflection of nearly two hundred divisions of the scale, while the red oxide gave a deflection as wide as the helices would permit, which corresponds to about eight hundred divisions of the scale. The correctness of Mr. Faraday's statement regarding the inferiority of the means first devised to investigate this subject, is thus strikingly illustrated. It might be added, that red ferroprussiate of potash and other substances, which have given us powerful effects, produced no sensible impression in experiments made with the other instrument.

Thus have we seen the objections raised against diamagnetic polarity fall away one by one, and a body of evidence accumulated in its favour, which places it among the most firmly established truths of science. This I cannot help thinking is mainly to be attributed to the bold and sincere questioning of the principle when it seemed questionable. The cause of science is more truly served, even by the denial of what may be a truth, than by the indolent acceptance of it on insufficient grounds. Such denials drive us to a deeper communion with Nature, and, as in the present instance, compel us through severe and laborious inquiry to strive after certainty, instead of resting satisfied, as we are prone to do, with mere probable conjecture.

Royal Institution,
November 1855.