ON THE ELECTRICAL AFTERCURRENTS OF TRANSVERSELY MAGNETIZED IRON RODS. BY PROF. H. STREINTZ.

The experiments referred to in this paper were carried out by the author in conjunction with Dr. F. Streintz.

The phenomenon was discovered by Villari, that in a rod of iron or steel through which a galvanic current has passed, when agitated after the interruption of this current, a galvanic current is again generated the same in direction as that originally conducted through the rod. He subsequently investigated some properties of these aftercurrents, and gave an explanation of the phenomenon:—namely, that the rod is transversely magnetized by the current; and if we employ the notion of molecular magnets, these arrange themselves in concentric circles around the axis of the rod. Now, if the rod be agitated after the interruption of the current, the molecular magnets obey the direction-force which tends to mingle them again irregularly. We can here avail ourselves of the representation of the molecular magnets returning to the positions which they had before the action of the current. Now, in this return they generate in the rod an induction-current, to which Villari gives the name of "agitation-current," but which may with equal suitableness be designated as an aftercurrent.

Afterwards H. Herwig studied the properties of transverse magnetism on iron tubes.

The author now shows that in a very simple manner the quantity of the magnetizing force can be calculated which is exerted upon the molecular magnets by the current originally conducted through the rod. Starting from Biot and Savart's theorem, that a rectilineal current of infinite length acts upon a pole of a magnet with a force inversely proportional to the perpendicular distance of the pole from the conductor, the problem is reduced to one of the plane; so that we have to calculate the action of a circular surface with uniform mass (the rods investigated had a circular cross section) upon a mass-point situated in the surface.

In accordance with the laws of force previously stated, however, a circular line with uniform mass exerts no action on a point situated in the enclosed surface, while it acts on an external point in the same plane as if the mass of the circle were collected in the centre.

Now by this the calculation becomes very simple, and we obtain, as the force which is exerted upon a magnetic pole situated at the distance r from the axis, $p=\frac{kr}{a^2}$, in which k is a constant, and a the semidiameter of the rod. The total moment upon all the molecular magnets contained in the rod is then $R=Kla$, where K, again, is a constant, and l denotes the length of the rod.

The author has also investigated by experiment the properties of the aftercurrents; and in so doing he found some confirmed which could be foreseen from the theoretical developments, and also discovered various other properties, some of them indeed very striking, which could not have been determined *à priori*.—*Kaiserliche Akademie der Wissenschaften in Wien, math.-naturw. Classe*, Dec. 13, 1877.

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XXIV. *On Reflection of Polarized Light from the Equatorial Surface of a Magnet.* By JOHN KERR, *LL.D., Mathematical Lecturer of the Free-Church Training College, Glasgow.**

IN trying to carry forward the magneto-optic inquiry which formed the subject of my last communication to this Magazine†, I proceeded to examine a lateral face of an intensely magnetized iron bar as a reflector, and had the pleasure of obtaining good effects in the first trial. I have lately performed a series of careful experiments on the subject; and I propose to give an account of these and of their very interesting results in the present paper. I mean to describe the experiments at sufficient length, for the guidance of any one who would like to repeat them. Most of them are, I think, rather easier and more satisfactory than those described in my former paper.

1. *Apparatus.*—The electromagnet is the same upright horseshoe that was used in my former experiments, a small but effective instrument constructed by Mr. Ladd. Each coil contains about 200 turns of thick double wire. The coils are put into circuit, through a good Ruhmkorff's commutator, with a series of six Grove's elements, the connexions being made in the usual way as for magnetization of the horseshoe.

The reflecting bar is a rectangular prism of soft iron, 7 inches long, 2 wide, $\frac{3}{8}$ thick. The iron was selected and specially forged; and its structure is homogeneous and very

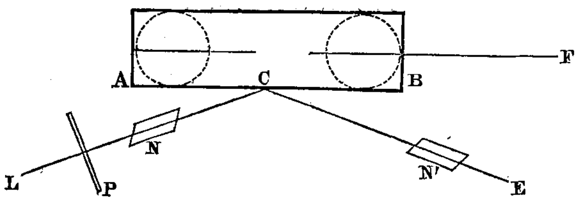
* Communicated by the Author.

† "On Rotation of the Plane of Polarization by Reflection from the Pole of a Magnet," May, 1877.

fine. One lateral face of the bar (7 by $\frac{3}{8}$) was planed and carefully polished by a skilled workman.

It may be worth mentioning that three such bars were forged at the same time, were cemented together, planed and polished in block, and then separated. The middle one was kept as the best reflector; but most of my results were verified upon each of the three.

2. *Arrangements.*—The electromagnet stands upright upon a solid table; the reflecting bar lies flat and stably on the poles of the horseshoe, in the position of an armature, its length horizontal, and its polished face vertical; the two Nicols and the lamp stand upon the same table as the magnet, and at the same height as the mirror. The diagram shows all the pieces, in horizontal section through the lamp L and the



observer's eye E. N is the first Nicol, C the point of incidence on the reflector AB, and N′ the second Nicol. The poles of the horse-shoe, below the bar, are indicated by the dotted circles. The piece P between the lamp and the first Nicol was often found useful in the more delicate observations: it is a metallic screen, containing a long horizontal slit about $\frac{1}{8}$ of an inch wide. Sometimes the flat flame L has its edge presented to C; and then, the piece P being in position, the object seen at C through N′ is a small segment of the flame, sensibly square. But generally, except when the angle of incidence is near 90°, the width of the flame is presented; and then the object seen in the mirror is a long horizontal rectangle, uniformly illuminated, strongly outlined above and below, and bringing out small changes of small intensity very delicately.

In the diagram, the axis of the bar A B is produced through the end B next the observer; the extremity F of the axis thus produced is used afterwards as a point of reference.

In all my later observations, the values of the angle of incidence $\frac{1}{2}$ L C E were assigned beforehand as carefully as possible, but by a method which cannot pretend to great accuracy. A broad sheet of drawing-paper, which had been cut away at the proper angle through one of its corners, was laid flat on the table, and aligned against the fixed stand of

the magnet and the movable stand of the lamp, each of the stands presenting suitably a long straight edge in contact with the table.

It will be observed that, according to these arrangements, the lines of magnetic force at the point of incidence remain sensibly parallel to the trace of the plane of incidence on the reflecting surface, through all changes of incidence from near grazing to near normal.

3. *Specification of Rotations of the Nicols.*—I shall have occasion repeatedly to speak of right-handed and left-handed rotations of the two Nicols. In the employment of these terms, I shall always view the second Nicol from the point E, and the first Nicol from the point C. By a right-handed rotation of the second Nicol, I mean, therefore, a rotation of the analyzer which is with watch-hands when viewed from E; and by a left-handed rotation of the first Nicol, I mean a rotation of the polarizer which is against watch-hands when viewed from the point of incidence C.

4. *Specification of Magnetizations of the Reflector.*—In the statement of results, I shall always specify the two magnetizations of the reflector by giving the direction of the magnetizing current, the current being supposed to circulate spirally round the bar A B, out of one coil into the other. These directions of magnetizing currents may of course be conceived and remembered more simply, as the directions of Amperean currents in the magnetized bar. By a right-handed current I shall always understand here, a magnetizing current whose effective direction, round the reflecting bar A B, is with watch-hands when viewed from the point F.

The three points of reference now fixed will be carefully adhered to:—E for movements of the second Nicol or analyzer; C for movements of the first Nicol or polarizer; and F for directions of the magnetizing current, or for directions of Amperean currents in the magnetized reflector.

5. *Optical Observations with the Mirror and the two Nicols.*—These belong properly to Optics, and present nothing new; some of them, also, were described in my former paper; but they are given here for their bearing on subsequent methods and results, and for the useful practice which they afford in the management of the apparatus. Suppose the pieces placed as in the diagram (2).

Whatever be the angle of incidence, there are only two arrangements of the Nicols which give pure extinction of the reflected image. In one of these arrangements the principal section of the first Nicol is parallel to the plane of incidence, and in the other it is perpendicular.

When the incidence is between grazing and principal, 90° to 85°, and the two Nicols are initially at pure extinction, any very small rotation of the first Nicol may be neutralized perfectly, or very nearly, in the polariscope, by a small rotation of the second Nicol, provided the two rotations are both right-handed or both left-handed, and properly related to each other in magnitude; but if the two rotations are one right-handed and the other left-handed, the effect of one in the polariscope is strengthened by the other *ab initio*.

When the incidence is between principal and normal, 65° to 30°, and the two Nicols are initially at pure extinction, any very small rotation of the first Nicol may be similarly neutralized by a small rotation of the second Nicol, provided the rotations are one right-handed and the other left-handed; but if the rotations are both right-handed or both left-handed, the effect of one is strengthened by the other *ab initio*.

When the incidence is about 75°, and the two Nicols are initially at pure extinction, no small rotation of the first Nicol can be neutralized, or its effect in the polariscope sensibly weakened, by a rotation of the second Nicol either way.

It appears from these observations, that the arrangement of the two Nicols for extinction is very sharply defined at or very near the principal incidence only. At other incidences there is a sensible though small range of angular magnitude, increasing as the angle of incidence approaches either $\frac{\pi}{2}$ or 0, through which we can turn the first Nicol either way from pure extinction, without losing the power to recover a pretty good extinction by a proper displacement of the second Nicol.

The next observation requires a compensating slip of glass. That which I generally employ is a piece of good plate, $\frac{1}{8}$ of an inch thick, 1 wide, and 7 or 8 long. It is held between the mirror and the second Nicol, its plate-faces perpendicular to the reflected ray, and its length at 45° to the plane of reflection. If the slip has been properly chosen, and is in good condition, it is quite inactive in the polariscope, except when purposely strained by the observer's hands. The only strains applied are compression along the length and tension along the length.

When the angle of incidence is about 75°, and the two Nicols are initially at pure extinction, any very small rotation of the first Nicol is neutralized perfectly or very nearly by the compensating slip feebly strained: the right-handed rotation is neutralized by compression right hand down, and, therefore, also by tension left hand down; and the left-handed rotation is neutralized by tension right hand down, and, therefore, also

by compression left hand down. By a contrary strain with the same hand down in each of these cases, or by a similar strain with the other hand down, the effect of rotation of the first Nicol in the polariscope is very clearly strengthened *ab initio*. These observations with the slip of strained glass were described and explained in my former paper. It may be remembered that a right-handed rotation of the first Nicol was there compensated by tension right hand down, and not, as here, by compression right hand down. The reason of this difference is obvious, the plane of reflection being there vertical, but here horizontal. I proceed now to the observations with the magnetized mirror and the two Nicols, placed always as in the diagram (2).

6. *First Experiment*.—The plane of polarization of the light incident upon the mirror is constantly parallel to the plane of incidence; and the initial extinction is made as pure as possible.

(1) The second Nicol is turned righthandedly through an extremely small angle from the position of extinction; and the light thus restored faintly in the polariscope is watched for changes of intensity when the reflecting bar is magnetized successively by contrary currents.

(2) The second Nicol is turned lefthandedly through an extremely small angle past the position of extinction; and the optical effects of contrary magnetizing currents are observed as in the former case. The following is an accurate statement of the results:—

(1) The light restored from extinction by a very small right-handed displacement of the second Nicol is always strengthened by a right-handed magnetizing current, and always weakened by a left-handed current.

(2) The light restored from extinction by a very small left-handed displacement of the second Nicol is always weakened by a right-handed current, and always strengthened by a left-handed current.

The intensity of these optical effects of magnetization varies very noticeably with the angle of incidence. About incidence 85° the effects are very faint, but perfectly regular and much better than merely sensible; about incidence 75° they are more distinct, and very sensibly stronger; about incidences 65° and 60° they are comparatively clear and strong, a good deal stronger than at 75°; about incidence 45° they are still pretty strong, but very sensibly fainter than at 60°; about incidence 30° they are again very faint, much the same as at 85°.

Between 30° and the normal I have made very few observations, and these not satisfactory; between 85° and 90° I have obtained no sure effect, nothing that could be recovered with certainty; but within the preceding range of incidence, 85° to 30°, I have always recovered the effects easily, and always in the forms now stated.

The right-handed current conspires with (or strengthens the effect of) a right-handed rotation of the second Nicol, and so forward consistently, the optical effect of the current being reversed by reversal of the current, and also by reversal of rotation of the second Nicol.

7. Returning for a moment to the method of observation, suppose the second Nicol turned righthandedly through a small angle from extinction.

(1) Only right-handed currents are applied, the circuit being closed and broken at intervals. When the circuit is closed, the light is strengthened in the polariscope; when the circuit is broken, the light is weakened.

(2) Only left-handed currents are applied. When the circuit is closed, the light is weakened; when the circuit is broken, the light is strengthened.

(3) Contrary currents are transmitted in succession, the reversal being made by a rapid half-turn of the commutator. In this case, the passage from left-handed current to right-handed strengthens the light in the polariscope, and the contrary passage from right-handed current to left-handed weakens the light.

The magnetic changes of the bar in (3) are more than twice as great as those in (1) or (2), because of the imperfect demagnetization of the bar at the instant of *break*. It is observed accordingly in the experiment, that the optical changes in (3) are far superior to those in (1) and (2), generally much more than twice as strong. Sometimes, indeed, about the extreme incidence 85° or 30°, and when circumstances are unfavourable, I find the effects in (3) still quite distinct, while those in (1) and (2) are almost or altogether imperceptible. Another fact of the same kind which I have noticed in (1) and (2) is, that the effect of *make*, whether it be an increase or a diminution of intensity in the polariscope, is generally more distinct, strikes the eye more sharply, than the effect of *break*. I may state here finally that, when the effects are very weak, the observer may often bring them out better and better by making the rotation of the second Nicol smaller and smaller till the restoration in the polariscope is merely an imperfect extinction.

8. *Second Experiment.*—The plane of polarization of the light incident on the mirror is constantly perpendicular to the plane of incidence. All the other arrangements, and the observations, are precisely as in the first experiment. The second Nicol is turned through an extremely small angle from the position of extinction, first righthandedly, then lefthandedly; and in each case the effects of the two magnetizing currents are observed in the polariscope.

About incidence 85°, the light restored by a right-handed rotation of the second Nicol is strengthened by a right-handed current, and so forward, the effects being undistinguishable in any way from those obtained in the first experiment at the same incidence, except that (under equally favourable conditions) they are certainly and considerably fainter. About incidence 80° the effects are still of the same kind, but a good deal fainter—so faint, indeed, that they cannot be brought out very distinctly except under the most favourable conditions (the battery fresh, the initial extinction very pure, and the displacement of the second Nicol extremely small). About incidence 75° the regular effects disappear. About incidence 70° they reappear very faintly, as faintly as at 80°, but quite distinctly contrary to those obtained at 80° and 85°: the light restored by a right-handed rotation of the second Nicol is now weakened by a right-handed current, and strengthened by a left-handed current, and so forward. At incidences 65°, 60°, 45°, 30°, the effects are of the same kind as at 70°, still contrary, therefore, to those obtained at 85°; about incidence 60° they are comparatively clear and strong, though sensibly fainter than those obtained in the first experiment at the same incidence; about 30° they are faint but still distinct, and clearly stronger than the contrary effects obtained at 85°. It appears thus that, in the second experiment, the optical effects of magnetization fall under two distinct cases:—

(1) Between grazing and principal incidences, the law is the same as in the first experiment: the right-handed current conspires with a right-handed rotation of the second Nicol, and so forward.

(2) Between principal and normal incidences, this law is simply reversed: the left-handed current conspires with a right-handed rotation of the second Nicol, and so forward.

9. Any details that could be given as to the methods of observation in the second experiment would be a virtual repetition of article (7); but some remarks are due to the case of principal incidence. In my earlier observations at and about incidence 75° in this experiment, I was much perplexed with the results. The effects of magnetization were sometimes imperceptible, while in other cases they were quite sensible though faint. Sometimes they were similar to the effects at 85°, and sometimes similar to the contrary effects at 60°; but they were more frequently of another kind: either the right-

handed current or the left-handed, sometimes one and sometimes the other, conspired feebly with each rotation of the second Nicol, the right-handed and the left-handed in succession. The latter effects were certainly due to slight misplacements of the first Nicol, which impaired the purity of the initial extinction. All these irregularities disappeared in the most carefully conducted of my later observations, where due attention was given to two principal conditions—the assignment of a proper value (75° exactly or nearly) to the angle of incidence, and the purification of the initial extinction by exact adjustment of the first Nicol. Upon the whole, the result of my observations is that, in the second experiment, at and about incidence 75°, neither magnetization has any regular effect in the polariscope. I have little doubt that, with higher powers, magnetization would have a distinct optical effect, and that effect an increase of intensity in every case; but I merely describe things at present as I have seen them.

10. *Third Experiment.*—The two Nicols are placed initially at pure extinction, the plane of polarization of the light incident on the mirror being parallel to the plane of incidence. The second Nicol remains fixed.

The first Nicol is turned through an extremely small angle from the position of extinction, first righthandedly and then lefthandedly; and in each case the effects of the two magnetizing currents are observed in the polariscope.

About incidence 85° the light restored by a right-handed rotation of the first Nicol is weakened by a right-handed current, and strengthened by a left-handed current; while the light restored by a left-handed rotation of the first Nicol is strengthened by a right-handed current, and weakened by a left-handed current. The effects are fainter than those obtained at the same incidence in the first experiment, but they are distinct and perfectly regular. About incidence 80° the effects are still regular and of the same kind, but very faint, and requiring extremely small displacements of the first Nicol to bring them out clearly. About incidence 75° the regular effects disappear; and some irregular effects, which make their appearance here as in the second experiment, are eliminated by the assignment of a proper value to the angle of incidence, and by exact adjustment of the second Nicol.

At incidences 65°, 60°, 45°, 30°, the effects are contrary to those obtained at 85°: the light restored by a right-handed rotation of the first Nicol from extinction is strengthened by a right-handed current, and so forward. At incidence 60°, and even at 45°, the effects are very distinct and comparatively strong, but always fainter than those obtained at the same incidences in the first experiment. It appears thus that in the third experiment, as in the second, the optical effects of magnetization fall under two cases:—

(1) Between grazing and principal incidences the right-handed current conspires with a left-handed rotation of the first Nicol, and so forward consistently.

(2) Between principal and normal incidences, the preceding law is simply reversed; the right-handed current conspires with a right-handed rotation of the first Nicol, and so forward.

11. *Fourth Experiment.*—The two Nicols are placed initially at pure extinction, the plane of polarization of the light incident on the mirror being perpendicular to the plane of incidence. All the other arrangements and the procedure are as in the third experiment: the second Nicol remains fixed; and the first Nicol is displaced through a very small angle from the position of extinction, first righthandedly and then lefthandedly. The results are very similar to those obtained in the first experiment.

(1) The light restored by a right-handed rotation of the first Nicol is always weakened by a right-handed current, and always strengthened by a left-handed current.

(2) The light restored by a left-handed rotation of the first Nicol is always strengthened by a right-handed current, and always weakened by a left-handed current.

Very near grazing incidence, between 90° and 85°, the effects are insensible; about incidence 85° they are very faint, but regular and quite distinct; they increase in strength quite evidently through the incidences 80°, 75°, 70°, to somewhere between 65° and 60°, where they are, I think, as clear and as strong as those obtained in the first experiment; they then diminish gradually to incidence 30°, where they are very faint, but still somewhat stronger than at 85°.

It appears thus that, in the fourth experiment, the right-handed current conspires always with a left-handed rotation of the first Nicol.

12. The four experiments which have been described were repeated at several incidences with mirrors of steel. Some finely polished knife-blades were tried, and several masses of other forms. The best was a small bar-magnet of hard steel, which had one of its narrow faces polished on a cutler's wheel (one of those large wheels used for sword-blades). The curvature of this mirror was inconsiderable; and its polish was extremely fine. The arrangements were as in the diagram (2), the bar being laid stably from pole to pole of the horseshoe.

All the old effects were recovered regularly. Only one thing new attracted my notice, which was, the greater superiority of *reversal* to *break*, and even of *make* to *break*, in the case of steel, than in the case of soft iron (7); but I do not know how far my judgment in this matter may have been influenced by expectation.

13. *Synopsis of the preceding Results—two Laws with two Exceptions.*

First Law. The right-handed current conspires with a small right-handed rotation of the analyzer from extinction; and so forward.

Second Law. The right-handed current conspires with a small left-handed rotation of the polarizer from extinction; and so forward.

First Exception. When the plane of polarization of the light incident on the mirror is perpendicular to the plane of incidence, the First Law is reversed for all incidences between principal and normal.

Second Exception. When the plane of polarization of the light incident on the mirror is parallel to the plane of incidence, the Second Law is reversed for all incidences between principal and normal.

14. I may say here, with reference to the various statements of fact which I have made in the preceding articles, that they are founded on a large number of perfectly concordant observations. The angles of incidence quoted are of course only rough approximations (2); and some of the other details may be modified by future observation; but the broad facts are as certain to my mind as any thing in Physics.

The next two experiments afford interesting verifications of former results, as they show that when two actions already known as conspiring actions are applied separately, their optical effects are similar, or rather similarly directed. To prepare the way, I must mention some delicate optical phenomena, which present themselves in connexion with very small movements of either Nicol through the position of extinction. Each Nicol is supposed to be near the mirror; the piece P is in position (2); and the incidence is between principal and normal. When the extinction is perfect, and the observer's attention has been once directed, he can generally detect an obscure cloud, which is pretty definitely formed, and sometimes finely formed as a dark horizontal band, covering the old place of the reflected image, and extending well across the field. In these circumstances, any almost immeasurably small rotation of either Nicol, in one direction or the contrary, produces a regular and very sensible change in the field of vision—a continuous displacement of the band, upwards in one case and downwards in the other, the form and direction of

the band being fairly preserved through large displacements. In the next two experiments, I make use of this movement of the band as a mere initiation of restoration from pure extinction in the polariscope. I call it a mere initiation of restoration, because the band has already undergone a large displacement over the surface of the mirror, by rotation of the second Nicol or otherwise, before there is any sensible restoration of the reflected image from pure extinction.

15. *Fifth Experiment.*—The plane of polarization of the light incident on the mirror is parallel to the plane of incidence; and the extinction in the polariscope is made as pure as possible, the old place of the reflected image being covered by an obscure cloud or band (art. 14). The observations now to be described in this article and in art. 16 have been made repeatedly at the four incidences 70°, 65°, 60°, 45°, with consistent and uniformly distinct results.

(1) The two Nicols are untouched, and remain in their initial positions of pure extinction. A left-handed current sends the band up through a small distance very clearly; a right-handed current sends the band down; contrary currents in rapid succession act accordingly, and give larger displacements of the band (art. 7).

(2) With open circuit, a right-handed rotation of the second Nicol through the position of extinction sends the band down very clearly. Compared with observation (1), this verifies the First Law stated in art. 13, that the right-handed current conspires with a right-handed rotation of the second Nicol.

(3) With open circuit, a right-handed rotation of the first Nicol through the position of extinction sends the band down certainly, though the effect is not generally so good as that in (2). The results in (1) and (3) verify the exception to the second Law stated in art. 13, as the present incidences lie between principal and normal.

16. *Sixth Experiment.*—The plane of polarization of the light incident on the mirror is perpendicular to the plane of incidence; other things as in art. 15.

(1) The effects of magnetization obtained in art. 15 are simply reversed. A right-handed current sends the band up very clearly; a left-handed current sends the band down; contrary currents in rapid succession act accordingly.

(2) With open circuit, a right-handed rotation of the second Nicol sends the band down (exactly as in art. 15). This agrees with the exception to the First Law stated in art. 13.

(3) With open circuit, a right-handed rotation of the first Nicol sends the band down (exactly as in art. 15). This agrees with the Second Law (art. 13).

The reader would have a false view of these two experiments, if he thought there was any thing uncertain about the phenomena, any mere guess-work in the observations. On the contrary, the effects are perfectly regular, almost invariably very sensible, and sometimes beautifully distinct. In one or two trials which I conducted in favourable circumstances along with several friends, I found that the movements of the band, whether produced by currents or by displacements of the second Nicol, were sufficient to make a strong, correct, and immediate impression upon an eye quite uneducated, and which had been merely directed to the right point.

I think that any discussion of the optical phenomena here utilized would be quite irrelevant.

17. In the next two experiments, I apply the compensating slip of glass already described (art. 5). It is introduced into the path of the reflected light, between the mirror and the second Nicol, its length at 45° to the plane of reflection, and its plate-faces perpendicular to the ray. Of the four methods of straining the glass, I generally choose *compression right hand down*. To apply the action, I hold the slip at the lower end, between finger and thumb of the right hand, taking care to have the piece properly directed, and exert a small pressure downwards by the fore-finger of the left hand laid along the upper end of the slip. A very feeble pressure is sufficient to give a perceptible restoration of the reflected image from pure extinction.

18. *Seventh Experiment.*—The plane of polarization of the light incident on the mirror is parallel to the plane of incidence; and the two Nicols are kept at pure extinction.

When the light is restored very faintly by the compressed glass, it is not sensibly strengthened or weakened by either magnetization of the mirror; and this holds true for all incidences between 85° and 30°. Sometimes, indeed, when working in this way, I obtained sure though very faint changes of intensity in the polariscope—an increase by one current, and a decrease by the other; but in several cases where these effects were closely examined, they were found to be caused by imperfection of initial extinction, and particularly by slight misplacements of the second Nicol. Upon the whole, if there was any regular effect here, it was too faint to be certainly characterized.

19. *Eighth Experiment.*—The plane of polarization of the light incident on the mirror is perpendicular to the plane of incidence; and the initial extinction is made as pure as possible, particular attention being given to the placing of the first Nicol. Other things are as in the seventh experiment.

About incidence 75°, the light restored by compression right hand down is strengthened by the right-handed current, and weakened by the left-handed current, the actions of the currents from reversal being regular and very clear though faint.

About incidence 60° the effects are of the same kind, but a great deal stronger. Each of the currents acts clearly now from its own break (art. 7), the right-handed current conspiring always with compression right hand down, therefore also with tension left hand down; and the left-handed current conspiring always with tension right hand down, therefore also with compression left hand down. These four cases of conspiring actions, as well as the four corresponding cases of contrary or mutually compensating actions (right-handed current with tension right hand down, &c), are all brought out regularly and strongly about incidence 60°.

At incidence 45° the effects are still of the same kind, regular and very distinct though not strong, not nearly so strong as at 60°. Between principal incidence and grazing, about 85°, the effects are still of the same kind, the right-handed current clearly conspiring here as elsewhere, though here very faintly, with compression right hand down.

20. It is worth noticing that we might have anticipated some of the results brought out in the last two experiments, those of them, namely, that are obtained at incidences near 75°. It has been mentioned already as a result easily obtained with the present apparatus, that a small right-handed rotation of the first Nicol from extinction, at or near incidence 75°, is neutralized by compression right hand down (art. 5). From this we infer that compression right hand down is optically equivalent, at least in an approximate manner, to a left-handed rotation of the first Nicol. We have, then, two cases, according to the fourth and third experiments:—

(1) When the plane of polarization of the light incident on the mirror is perpendicular to the plane of incidence, the right-handed current conspires with a left-handed rotation of the first Nicol, and should conspire therefore with the optical equivalent of that rotation, compression right hand down, as it does actually in the eighth experiment.

(2) When the plane of polarization is parallel to the plane of incidence, and the angle of incidence is about 75°, neither current conspires with any small rotation of the first Nicol; so that neither current should conspire with compression right hand down, which is actually the case in the seventh experiment.

21. I have now given all my positive results; but there are

two other lines of experiment which I have tried without effect, and which ought to be briefly noticed.

(1) The mirror, as formerly, an equatorial face of a magnetized bar, the plane of incidence perpendicular to the lines of magnetic force, and the incidence varying from near normal to near grazing. The arrangements were of course somewhat different from those already described; but they were not more difficult, and were made with equal care; and I think that the experiments were altogether as delicate as any of the preceding. Working in this way at different times, I saw no appearance of optical effect of magnetization.

(2) The mirror an equatorial face of a magnet, the incidence normal, and the inclination of the plane of incidence to the lines of magnetic force varying from 0° to 90°. As the normal incidence was obtained by the employment of a mirror of unsilvered glass, the light was a good deal weaker than formerly; but otherwise the experiment was as delicate as any of the preceding. Nothing like an optical effect of magnetization was observed in any instance.

From these experiments, and from all that I have seen upon the subject, I think it probable, in the highest degree, that magnetization of a reflector even to saturation would be absolutely without optical effect in the cases now exemplified (that is, in the case of normal incidence upon an equatorial face), and in any case where the fronts of the incident and reflected waves are parallel to the lines of magnetic force.

I return now to the consideration of our first arrangement, where the lines of magnetic force are parallel to the intersection of the reflecting surface and the plane of incidence.

22. Law of the optical action of magnetism at incidences near grazing.

Whatever be the angle of incidence between grazing and principal, the effect of magnetization of the mirror, when sensible, is to turn the plane of polarization of the reflected light through a very small angle, in a direction always contrary to that of the Amperean currents; for, whatever be the angle of incidence between grazing and principal, the two laws stated in art. 13 hold true throughout the first four experiments without exception.

(1) The right-handed current conspires with a right-handed rotation of the second Nicol. But the effect of a right-handed rotation of the second Nicol (before magnetization of the mirror) is virtually to turn the reflected ray lefthandedly, or to displace its plane of polarization lefthandedly, with reference to the principal section of the analyzer. And since the right-handed current conspires with the right-handed rotation of the

analyzer, it adds actually to the virtual left-handed rotation of the reflected ray, or turns the plane of polarization left-handedly.

(2) The right-handed current conspires with a left-handed rotation of the first Nicol. But we have seen in art. 5, that a left-handed rotation of the first Nicol is neutralized (near grazing incidence) by a left-handed rotation of the second Nicol; and from this we infer that a left-handed rotation of the first Nicol turns the plane of polarization of the reflected ray lefthandedly. And since the right-handed current conspires with a left-handed rotation of the first Nicol, it adds to the consequent left-handed rotation of the reflected ray, or turns the plane of polarization lefthandedly.

Of course this proof assumes, and the conclusion implies, that the reflected light may be considered as approximately plane-polarized in all the preceding instances of conspiring actions, as well as in the corresponding instances of mutually compensating actions, both in the optical observations (art. 5), and throughout the first four experiments.

23. It is proved thus beyond question, at least as a very approximate expression of facts, that, near grazing incidence, the effect of magnetization of the mirror upon a reflected ray is to turn the plane of polarization through an extremely small angle, in a direction contrary to that of the Amperean currents. Under what conditions, on what assumptions, may this be accepted as the law of the action at all incidences? To prepare for a definite answer to this question, I shall first subject the statement of the law to a simple transformation.

When the vibration reflected from the unmagnetized mirror is either parallel or perpendicular to the plane of reflection, the effect of magnetization is to introduce a new and very small component vibration in a direction perpendicular to the primitive vibration, the sense of the new component being that assumed by the primitive vibration when turned through a right angle in a direction contrary to the Amperean currents. And for incidences between grazing and principal, the difference of phases of the two components (the primitive and the new) is much nearer to 0 than to $\frac{\pi}{2}$.

It is important to observe here, that the results obtained in the fifth and sixth experiments necessitate the assumption of some such law as this, even for incidences between principal and normal. For the direction of the primitive vibration is in those experiments exactly parallel or perpendicular to the plane of reflection, and the Nicols remain constantly in their initial position of pure extinction; so that the observed effects of magnetization, effects which are of the same kind as those produced by rotation of the second Nicol, cannot be explained by any mere changes of the primitive vibration in amplitude or phase, or by any thing except the introduction of a new and very small component in a direction perpendicular to the primitive vibration.

24. *General Law of the Action of Magnetism upon the Reflected Ray.*

The three following assumptions appear to me to afford a perfect explanation of all the principal phenomena. They were suggested as above, and were tested by a careful mathematical discussion of the results of all the experiments in succession. The discussion presents little difficulty, but is too tedious to be offered here.

(1) When the original vibration is parallel or perpendicular to the plane of reflection, the effect of magnetization of the mirror is to turn the vibration through a very small angle in a direction contrary to the Amperean currents.

The resolved parts of the vibration so turned, one in the direction of the primitive vibration and the other perpendicular to it, may be called the primitive component and the new component respectively, as in art. 23.

(2) The primitive component is always reflected according to the same laws of retardation of phase, after magnetization of the reflector as before.

(3) Whether the new component be parallel or perpendicular to the plane of reflection, and whatever be the angle of incidence, the phase-retardation of the new component (with reference to a standard reflected ray, polarized in the plane of incidence, and incident in the same phase as the actual primitive), is always an angle in the first quadrant, and much nearer to zero than to $\frac{\pi}{2}$.

It will be admitted that the assumption (3) is a very remarkable one, and very important if true. I hope to see this geometric theory of the phenomena verified by the mathematicians, or something better put in its place.

25. It would be superfluous now to offer any explanation of the absence of all optical effect of magnetization in the case of normal incidence (art. 21). It is not so easy to understand the absence of effect at incidences very near grazing, 85° to 90°, in the first four experiments. We might expect indeed, on the contrary, that as the ray approaches parallelism to the lines of force, or as the front of the wave approaches perpendicularity, the magnetic force would act at a greater advantage, and the optical effect would therefore become stronger.

But against this we have what appears to be fairly established by observation as a general truth in optics, that the specific differences of reflectors become less and less marked as incidence approaches grazing, until at grazing they almost entirely disappear.

26. I shall not make any lengthened comparison between the effects now observed in connexion with the equatorial surface and those formerly obtained in the case of the polar surface. The two sets of results are not inconsistent, nor do they differ materially in any way, except that the present set contains a larger amount of detail as to the variations of optical effect, variations extending even to reversal. I have no doubt that this enlargement of results is due to better means and improved arrangements in the present series of experiments. It will be remembered that a submagnet, separated from the mirror by a very narrow chink, was found indispensable in the case of the polar surface. In the present experiments there is no place for such an adjunct, and the reflector is fully exposed to view at all incidences, which is a great improvement. The new arrangements are also simpler and more manageable upon the whole, and much better adapted for delicate and exact optical observation.

In one respect I have certainly found the polar surface superior to the equatorial. In the case of the polar surface, and with the power that I have applied, it is easy to obtain, by magnetic force alone, a very distinct restoration of the reflected light from pure extinction, though the restoration is never very strong; but in the case of the equatorial surface, and with equal or greater powers, I have never seen any stronger effect of unassisted magnetic force than those fine movements of the band in the fifth and sixth experiments.

27. The first facts of magneto-optics discovered long ago by Faraday, their more immediate consequences discovered afterwards by Verdet and others—these and the additional facts now published by myself must be all included ultimately under one physical theory. It is very probable that the remarkable theory of magnetism which has been advanced by Sir William Thomson in a discussion of the former class of facts, will apply as well to the latter. Probably also the theory itself may receive additional confirmation in the process. I think it equally probable that the new facts will find important applications in the mechanical parts of the Wave Theory. But in any event there is a new physical action secured thoroughly to science, a specific action of magnetized iron upon light incident at any point of its surface.

Glasgow, January 21, 1878.