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XXXV. *On the Electromagnetic Rotation of the Plane of Polarization of Light by means of Iron, Cobalt, and Nickel.* By A. KUNDT*.

DR. KERR has shown† that the plane of polarization of the light reflected normally from the polished pole of an electromagnet suffers a rotation. The direction of the rotation is opposed to that of the magnetizing current, and consequently to that of the amperian molecular currents of the magnet. Kerr has further examined the reflection of light at the polished side-face of a magnet. He found that here also a rotation of the plane of polarization takes place when the electromagnet is excited or has its magnetism reversed. The phenomena are, however, somewhat complicated.

Plane-polarized light which is reflected at any angle from a metallic surface retains its plane of polarization only in the cases in which that of the incident light is coincident with the plane of incidence, or at right angles to it. In all other positions of the plane of polarization the reflected light is elliptically polarized; Kerr therefore confined his investigations to the first two cases. He finds that if the polarizing and analyzing nicols are at right angles, then when the magnet is excited the field of view becomes bright, which he interprets as a rotation of the plane of polarization produced by the magnetization. The direction and the amount of this rotation are not dependent simply upon the angle of incidence, but are different also according as the plane of polarization of the incident light (the long diagonal of the section of the nicol) is coincident with, or at right angles to, the plane of incidence.

If the light is polarized in the plane of incidence, the direction of rotation is the same for all angles of incidence, and opposed to that of the amperian molecular currents of the reflecting magnet.

If the plane of polarization is at right angles to the plane of incidence, then for angles of incidence from 0° to about 80° the direction of rotation is the same as that of the amperian currents, but opposed to it for incidences between 80° and 90° . The amount of rotation is in both cases a maximum for an angle of incidence of about 65° .

There is also a rotation with oblique incidence of the light upon the polished pole-surface of an electromagnet. The direction of the rotation according to Kerr, so far as I can gather from his data, is the same for all angles of incidence

* Translated from the Berlin *Sitzungsberichte*, July 10, 1884.

† Phil. Mag. [5] 1877, vol. iii. p. 321, and 1878, vol. v. p. 161.

and opposed to the molecular currents, whether the plane of polarization of the incident light is coincident with, or at right angles to, the plane of incidence.

In all the experiments of Dr. Kerr the magnitude of the rotation is very small—in favourable cases it amounts only to a few minutes; and Kerr has consequently made no measurements, but has only estimated the amount of rotation in the different positions and determined its direction. Some two years ago I repeated Kerr's experiments. My experiments completely confirmed all Dr. Kerr's statements; with the one exception that, upon reflection at the surface of a pole, I obtained also a reversal in the direction of rotation at an incidence of about 80° , when the plane of polarization of the incident light and the plane of incidence were at right angles to each other. This reversal seems to have escaped Dr. Kerr. I have thus succeeded in bringing all the phenomena of reflection at the side faces as well as at the poles of the magnets under one point of view, from which possibly an explanation of the same may result.

That a rotation of the plane of polarization takes place at perpendicular incidence upon the pole-surface of an electromagnet has been further confirmed by Gordon*. He obtained a rotation of $26' 45''$ upon reversal of the magnetizing current.

Then Hall† has shown that with cobalt and nickel also, when they form the pole of a magnet, a rotation of the plane of polarization in the direction opposite to that of the magnetizing current takes place. It may be further mentioned that Hall has also examined whether the plane of polarization of the light which traverses a very thin transparent film of nickel is rotated. The transparent film was prepared according to the method given by Wright, by deflagration of a nickel electrode in a Geissler tube. Hall examined two nickel mirrors, but was not able to perceive any rotation, and remarks that "both these experiments on direct transmission have been, we may say, quite negative."

Lastly, we must mention also that Fitzgerald has endeavoured to give a theoretical explanation of the rotation produced by magnets. I shall further on briefly state Fitzgerald's theory, and show that it is not in agreement with the observations.

I have now recently measured the electromagnetic rotation of the plane of polarization upon reflection from iron, cobalt, and nickel, and completely confirmed my previous experiments

* *Physical Treatise on Electricity and Magnetism*, ii. p. 261.

† *Phil. Mag.* 1881, 5th series, xii. p. 171.

and also those of Kerr. I shall further on briefly review the quantitative results obtained.

I have, however, succeeded in rendering Kerr's experiments decidedly more complete by another method; since, having prepared thin transparent films of iron, cobalt, and nickel, I have examined the rotation of the plane of polarization produced upon passage of light through these films. The result is as follows:—

Transparent films of iron, cobalt, and nickel in the magnetic field rotate the plane of polarization of transmitted light very powerfully. The rotation produced by iron for the mean rays of the spectrum is more than 30,000 times as great as that produced by glass of equal thickness. The rotation takes place with all three substances in the direction of the magnetizing current.

After a few brief remarks upon the mirrors and transparent films employed, I give in what follows, first of all, observations upon the electromagnetic rotation upon transmission through metals; then my experiments upon the rotation which is produced by reflection of light from metals; then are included, and added at suitable points, general discussions of the experiments and the conclusions drawn from them.

I. *The Mirrors and Transparent Metallic Films employed.*

In the experiments upon reflection, I at first employed circular steel mirrors of 35 millim. diameter and 6 millim. thickness, of a very high polish. The mirrors were either placed between the poles and suitably fastened there, or attached laterally to the clamps uniting the poles. Any possible distortions were examined by observing in a telescope the images of horizontal and vertical millimetre-scales reflected in the mirrors. Any distortions or changes in the position of the mirrors would be recognized by small irregularities and displacements in the images given by the mirrors. In the series of experiments with mirrors, such as described later on, no irregularities were detected by means of the scale and telescope by which the optical effects observed could have been explained. Then I have employed mirrors consisting of speculum-metal, which had been electroplated with iron or nickel. And, finally, I employed plate-glass mirrors, coated electrolytically with very thin transparent films of iron.

If a glass surface is to be electroplated with a metal, the glass surface must first of all be made conducting. I tried to silver glass in the usual way and then to deposit the iron upon this layer of silver; but so far these attempts have not led to any result. So soon as the current was closed, and iron or

other metal began to deposit itself from the solution upon the silver, the film came off the glass in shreds. With a very good film of silver and exactly adjusted strength of current it might be possible to coat the silver with another metal electrolytically; at least I have at times succeeded in coating small pieces of silvered glass with copper; but I have not pursued the attempt further, since a more convenient method presented itself. M. König, in Paris, for the rotating mirrors employed in his acoustical apparatus uses plate-glass, into one surface of which a very thin transparent reflecting film of platinum has been burnt. The film of platinum is so thin that it is very transparent. Whether it is absolutely continuous is not of any consequence; at least it conducts so well that it may be made an electrode, and covered with a reflecting layer of another metal of any desired thinness.

I have deposited iron according to Varrentrapp's method*; cobalt and nickel from solution of the ammonio-sulphates of cobalt or nickel. The concentration of the solution and strength of current must be adjusted according to the thickness which the film is desired to have. I have further coated some of the iron and nickel films with reflecting surfaces of gold, silver, or copper. These metallic films may easily be obtained so thin that they, together with the platinum, are quite transparent.

The incident white light becomes brown when it traverses the iron film, grey with nickel, and bluish grey with cobalt. The surfaces of the deposited films usually reflect very well; but the physical peculiarities of the different surfaces seem to be somewhat variable. Possibly the metals are in certain cases deposited in a crystalline condition. If we cut a long strip from an iron film, it may easily be converted into a permanent magnet by rubbing with another magnet. It is known that the coercive force of galvanically deposited iron is very large.

We are thus able to prepare permanent *transparent* iron magnets, as also transparent magnets of cobalt or nickel.

When suspended by a silk fibre, these transparent magnets adjust themselves perfectly well in the magnetic meridian under the influence of the earth's magnetism.

I hope to study the behaviour of these very thin transparent magnets later on.

II. *Rotation of the Plane of Polarization of Light by its Passage through Iron, Cobalt, and Nickel.*

A Ruhmkorff's electromagnet of the usual construction was

* Muspratt's *Chemie*, vol. ii. p. 1200.

employed for these experiments. The iron core, wrapped with wire, was provided with conical, rounded, and perforated pole-pieces. The poles were placed about 4 millim. apart. The current, which was furnished by a Gramme machine, had an intensity of about 16 amperes. The glass plate under examination with its metallic covering was placed midway between the poles in a suitable holder, permitting both horizontal and vertical displacement and rotation, as nearly as possible at right angles to the direction of the rays of light which traversed it. Sunlight was always employed.

In order to measure the rotation produced by the film of iron, cobalt, or nickel, a portion of the piece of glass not covered with the electrolytic deposit of metal was compared with a portion covered by the film, by determining first the rotation produced by glass and platinum, and then determining the rotation due to glass, platinum and iron, cobalt, or nickel. Usually the thin platinum layer produced no measurable rotation; so that a portion of the glass covered by the metallic deposit could be compared with a portion from which the metal and platinum had been removed by means of acid. Since the rotation produced by platinum and glass alone, or by the platinum and glass together with the coating of iron, cobalt, or nickel gave rise to a tolerably strong dispersion, the adjustment was made in these experiments for the transition-tint between blue and red; so that the rotation was determined for the mean rays of the spectrum. When not otherwise specified, the rotation given in the following account means the sum of the rotations in both directions produced by reversal of the current. A rotation in the direction of the amperian currents is further specified as positive, and that in the opposite direction as negative.

Iron.

Iron mirror No. 1. Brown, transparent.

Rotation due to glass and platinum upon	0
reversal of current	+1 0
Rotation due to glass, platinum, and iron	+4 30
Rotation produced by iron film	+3 30

Iron mirror No. 2. Very thin, light brown, transparent.

Glass and platinum	+1 30
Glass, platinum, and iron	+2 24
Rotation due to iron	+0 54

Iron mirror No. 3.

Glass and platinum	+1° 42'
Glass, platinum and iron	+3 48
Rotation due to iron	+2 6

Iron mirror No. 4:—

After this mirror had been covered with a tolerably transparent layer of iron, half of it was covered with a further deposit of iron; so that this half was dark brown, though transparent. The platinum and iron were then removed from one portion of the glass.

Rotation by glass alone	+2° 12'
„ glass, platinum, and thin iron film	+3 42
„ glass, platinum, and thick iron film	+5 54
Rotation produced by thin iron film . .	+1 30
„ „ thick „ . .	+3 42

As already remarked, the rotation produced by the film of platinum is not measurable.

Cobalt.

Cobalt mirror No. 1.

Rotation by glass and platinum	+1° 18'
„ glass, platinum, and cobalt . .	+2 36
Rotation by cobalt	+1 18

Cobalt mirror No. 2. Very transparent.

Rotation by glass and platinum	+1 30
„ glass, platinum, and cobalt . .	+2 34
Rotation by cobalt	+1 4

Cobalt mirror No. 3. A portion of the same piece as No. 2.

Rotation by glass and platinum	+1° 30'
„ glass, platinum, and cobalt . .	+2 30
Rotation by cobalt	+1 0

The two mirrors placed one behind the other still transmitted sufficient light. The rotation produced by the two cobalt layers together was found to be the sum of those produced by the two separately, viz.:—

Rotation due to 2 and 3 together . . .	+2° 5'
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Phil. Mag. S. 5. Vol. 18. No. 113. Oct. 1884. Y

Cobalt mirror No. 4.

Rotation due to glass and platinum . .	+ 1	⁰ / ₃
„ „ glass, platinum, and cobalt	+ 3	1
Rotation due to cobalt	+ 1	58

Nickel.

I give observations with two good homogeneous mirrors:—

No. 1.

Rotation due to glass and platinum . .	+ 1	⁰ / ₂₆
„ „ glass, platinum, and nickel	+ 2	5
Rotation due to nickel	+ 0	39

No. 2.

Rotation due to glass and platinum . .	+ 1	35
„ „ glass, platinum, and nickel	+ 2	24
Rotation due to nickel	+ 0	49

The question may now arise whether the rotations obtained for iron, cobalt, and nickel are actually produced by these substances, or whether the observations admit of being explained in any other way. Since in these experiments portions of glass coated with magnetic metal and coated only with platinum are successively brought between the conical magnetic poles, it might be thought that the intensity of the magnetic field between the poles might be different in the two cases, and that the difference in rotation might be thus brought about. I have convinced myself by numerous and varied experiments that even when large masses of iron are brought into the field, neither the rotation of the iron mirror nor that of a piece of glass is perceptibly altered.

It might further be supposed that the thin, strongly magnetic film of iron which clings close to the glass might have some special unknown influence upon the power of rotation possessed by the glass, and the difference observed in rotation between the glass covered with iron and without this covering should be attributed to this effect. In order to decide this point, I placed between the poles a narrow vessel with plane glass sides filled with carbon sulphide, and placed in this a portion of the platinized glass not coated with iron, and determined the rotation produced by the whole system; then a portion of the platinized glass coated with iron was put in the fluid, and the rotation again determined.

In the first case there was a rotation of	+ 11° 25'
„ second „ „	+ 12 27
Difference	+ 1 2

If the platinized glass was placed between the poles without using the sulphide of carbon—

The rotation obtained was	+ 11° 11'
And for the glass with iron	+ 2 13
Difference	+ 1 2

Exactly the same as before.

We see that the rotation of the sulphide of carbon which is in as close contact with the iron as the glass is, is not at all influenced by it. We cannot therefore avoid the conclusion that the difference 1° 2' in both cases is the rotation produced by the iron.

III. Dispersion produced by Rotation, Specific Rotatory Power, and Circular Double Refraction of Iron, Cobalt, and Nickel.

Since lately there has frequently not been sufficient sun for the purpose, I have not been able to make extended experiments on the rotation of the plane of polarization for the different colours produced by iron, cobalt, and nickel. Nevertheless I have been able to recognize with certainty that iron has an anomalous rotatory dispersion. Light which had passed through a tolerably dark red glass was rotated perceptibly more powerfully than blue light obtained by passing the sun's rays through ammoniacal copper-sulphate solution.

Corresponding experiments with cobalt and nickel gave only a feeble rotatory dispersion. Experiments in which the red and blue rays of a somewhat impure spectrum were employed showed also an anomalous rotatory dispersion in the iron.

The specific rotatory power of iron was determined with as good a mirror as possible.

The thickness of the iron film obtained by weighing the mirror before and after coating it with iron with the battery was found to be 0.000055 millim.; the rotation for the mean rays of the spectrum produced by glass and platinum was 1° 37', and that produced by glass, platinum and iron 3° 25': consequently that produced by iron 1° 48'; the thickness of the platinized glass was 1.61 millim. Consequently the iron rotates some 32,000 times more than the glass used.

With another mirror, whose thickness was 0.000069 millim., the rotation of the iron was found to be 35,000 times as great as that of the glass.

Cobalt has a specific rotation nearly the same as that of iron. Nickel, on the other hand, is decidedly weaker. Two nickel mirrors gave a mean rotation of 14,000 times that of the glass.

I, of course, regard these numbers as approximate only, since the determination of thickness by weighing is very inexact. They give occasion, however, for some interesting conclusions.

According to the experiments of Righi*, a circularly-polarized ray in which the motion of the æther-molecules takes place in the same direction as that of the molecular currents, traversing a substance which, in a magnetic field, produces rotation in the same direction as the amperian currents, advances more rapidly than a circularly-polarized ray in which the æther-molecules move in the opposite direction. There is therefore a circular double refraction. If n and n' are the indices of refraction for the two opposite circular rays, and ϕ the amount of the observed rotation, d the thickness of the substance traversed by the ray, and λ the wave-length; then

$$\phi = \frac{\pi \cdot d}{\lambda} (n + n').$$

If we take $\lambda = 0.00058$, for d the thickness of iron film given above, viz. 0.000055, $\phi = 1^\circ 48'$, we have

$$(n - n') = 0.1.$$

This difference in refractive index amounts to more than half of that between the ordinary and extraordinary rays in Iceland spar, and is about ten times as great as the difference of refractive indices in quartz at right angles to the axis.

The difference of the refractive indices for the two circularly-polarized rays in the direction of the axis in quartz, according to Lang, amounts only to 0.0000718.

The film of iron used has therefore, in the magnetic field which I have employed, a rotation 1462 times as great as the natural rotation in quartz of the same thickness as the iron film. It will be necessary to return later on to the circular double refraction of our iron films when we come to speak of Fitzgerald's theory.

* *Nuovo Cimento*, iii. p. 212 (1878).

IV. *Rotation of the Plane of Polarization upon Normal Reflection from Iron, Cobalt, and Nickel.*

For these experiments also Ruhmkorff's electromagnet was employed. The perforated pole furthest from the observer was replaced by a solid pole without perforation. By reflection at a glass plate inclined at an angle of 45° to the axis of the pole, light was sent through the perforated limb of the electromagnet, reflected at the metal plate placed between the poles, and then passed through the glass plate, and so through the analyzing nicol. The reflecting surfaces could be adjusted exactly at right angles to the direction of the incident rays of light, and as nearly as possible at right angles to the axis of the electromagnet, by observations for the purpose.

The plane of polarization of the polarizing nicol was made to coincide as exactly as possible with the plane of incidence, in order to have as much light as possible. If upon reflection from the metallic surface any rotation took place, so that the plane of polarization of the reflected light no longer coincided with the plane of incidence upon the glass plate inclined at 45° , then upon passing through this a further rotation took place corresponding to Fresnel's formula for the refraction of polarized light. The analyzing nicol is therefore used to measure, not simply the electromagnetic rotation at the metallic surface, but the sum of this and the rotation produced by the glass plate. The latter, of course, was placed so far from the magnet that no electromagnetic rotation could be produced in it.

If α denote the angle which the plane of polarization of a ray of light falling upon a glass plate makes with the plane of incidence, then the angle γ between the two planes, after passage through the plate, is given by the formula

$$\tan \gamma = \frac{\tan \alpha}{\cos^2 (i - r)},$$

where i and r denote the angles of incidence and refraction respectively.

Since in the observations i was always nearly 45° and the refractive index of the glass about 1.48, calculation shows that the values of the directly observed rotations must be decreased by about 10 per cent. in order to obtain the actual electromagnetic effect. Dr. Kerr as well as Mr. Gordon seem to have overlooked the effect of the glass plate; at least they do not mention it.

I have retained the same arrangement of the glass plate as these observers, that it might be possible to have the light

actually falling upon the metallic surface exactly at right angles.

Mirrors of iron, cobalt, and nickel were used for these experiments, prepared by electrolytic deposition of the metal upon platinized glass. It has already been remarked that in consequence of the small thickness of these plates, the forces exerted upon them by the magnets are so small that no distortion of the glass plates which support the metal films can occur.

Iron.

Four mirrors were employed.	Rotation.
No. 1. Iron film so thick as to be completely opaque	} $-53^{\circ}6$
No. 2. Transparent	
No. 3. Transparent	$-45^{\circ}4$
No. 4. Transparent	$-1^{\circ}5^{\circ}8$
	$-48^{\circ}8$

The rotation is opposite to the direction of the magnetizing current; consequently the above numbers, like the following ones for cobalt and nickel, are marked with the negative sign. It must be mentioned that a dispersion due to rotation was distinctly observed in reflection also, which, like that produced by the transmission of light, is an anomalous dispersion—*i. e.* the red rays are rotated more powerfully than the blue ones. It is remarkable that mirror No. 3, which was very transparent, shows so large a rotation. I have noticed several times that other mirrors, also of smaller thickness, have shown a comparatively large rotation. I have not yet been able to make more accurate experiments on the connexion of the rotation with the thickness of the reflecting layer.

Cobalt.

Three cobalt mirrors were examined.

No. 1. Transparent, gave a rotation of .	$-1^{\circ}7^{\circ}2$
No. 2. Hardly transparent, „	$-50^{\circ}9$
No. 3. Opaque, „	$-50^{\circ}3$

Here also a feeble dispersion due to rotation could be observed.

Nickel.

Of two mirrors which were examined,

No. 1. Transparent, gave a rotation of .	$-29^{\circ}5$
No. 2. Opaque „	$-23^{\circ}0$

Thus nickel, upon reflection, rotates only about half as powerfully as iron and cobalt. Moreover, as was shown above, the rotation of transmitted light produced by nickel is perceptibly smaller than that due to iron and cobalt.

The molecular condition of the surface must undoubtedly play an important part in reflection; and since this may vary very greatly with the concentration of the solution and the strength of the current, it is hardly to be expected that identical values should be obtained for the rotation of different mirrors. In order to obtain the electromagnetic rotation alone, all the values given above must be diminished by about 10 per cent.

In conclusion, it may further be mentioned that I have also coated platinized glass with iron and then electroplated the iron with silver or copper. These iron mirrors covered with silver or copper showed no perceptible rotation upon reflection. If we adjust matters so that the rays fall accurately vertically upon the metallic surfaces, the glass plate may be dispensed with, replacing it by a perforated mirror of non-magnetic metal, and adjusting it so that the reflected light passes through the hole into the eye of the observer. The rotation observed with this arrangement is produced by reflection at the magnetized mirrors between the poles.

V. *Refutation of Fitzgerald's Theory of Rotation produced by Reflection.*

Mr. Fitzgerald* has endeavoured to give an explanation of the rotation of the plane of polarization produced by reflection. Briefly stated, it is as follows:—Iron, upon magnetization, becomes circularly doubly refractive, just as diamagnetic substances in a magnetic field do. This circular double refraction, as has been shown above, is very considerable in the case of iron. Since the intensity of the light reflected by a body depends upon its index of refraction, right-handed circularly polarized light is reflected by magnetic iron with a different intensity from left-handed. Plane-polarized light may be regarded as consisting of equal quantities of right-handed and left-handed circularly polarized light. Starting from this point, Fitzgerald endeavours to show that plane-polarized light falling at any angle upon a magnetic surface is converted by reflection into elliptically polarized, and that in general the major axis of the ellipse must be rotated towards the direction of oscillation of the incident light. For *normal* incidence upon the pole of a magnet, however, it is easily seen that the angle between the plane of oscillation of the incident light and the major axis of the ellipse is zero. Mr. Fitzgerald therefore himself draws the following conclusion from his theory:—If plane-polarized light falls normally upon the pole of an electromagnet not excited, and if after reflection it be

* Proceedings of Royal Society, xxv. p. 447.

quenched by a nicol, then upon exciting the electromagnet the field should become bright. This brightness should not disappear upon any rotation of the analyzing nicol, but should increase, whether it be rotated to the one side or to the other.

To this my experiments are directly in opposition; inasmuch as, when the electromagnet was excited, the analyzing nicol had always to be rotated through a definite angle in order to obtain good extinction. Whether the extinction itself is *absolute* with homogeneous light, and consequently whether the reflected light remains strictly plane-polarized or whether a certain *small amount* of ellipticity results, cannot of course be decided. In any case Fitzgerald's theory is refuted by the experiments at normal incidence, and it is therefore not necessary to discuss the admissibility of the assumptions upon which it is based. The question how far Voigt's theory on the reflection of light at circularly polarizing media is applicable to our case may remain undecided for the present.

VI.

Rotation of the Plane of Polarization upon Oblique Reflection of Light from the pole-surfaces and side-faces of a Magnet.

For these experiments a large electromagnet with erect legs of iron was employed. These had a height of 47 centim. and a diameter of 11 centim. Each leg was provided with three coils of wire 3 millim. thick: each coil had a resistance of about 0.65 Siemens unit. Two large iron parallelepipeds served as poles. The magnetizing current was furnished by the Gramme machine, and had usually an intensity of 16 amperes. Since the experiments were made in winter, when the sun was little to be relied upon, a Drummond lime-light was employed as source of light. The readings of the analyzing nicol were taken upon a divided circle graduated into quarter-degrees, reading with the vernier to 4 minutes, although the reading could be estimated to 2 minutes with certainty.

The angle of incidence of the rays of light upon the reflecting iron surface was carefully read off upon a divided circle. The plane of polarization of the polarizing nicol was adjusted as exactly as possible in the plane of incidence or at right angles to it, as determined by the good extinction of the light by the analyzer. When the magnet was excited, it was generally not possible to get rid of the light which now passed by rotation of the analyzer; since after reflection the light was no longer plane-polarized, but elliptically polarized. It was always adjusted to the minimum of illumination, so that the plane of oscillation of the analyzing nicol was brought at right angles to the long axis of the rotated elliptical rays.

Since the rotations are very small in amount, it was necessary, in order to obtain results in any measure reliable, to multiply the observations. As a rule, four observations were taken for each angle of incidence, for each of the two positions of the plane of polarization, viz. in the plane of incidence and at right angles to it. In each of the four observations the polarizer was adjusted afresh, and ten readings taken with each direction of the current. In the following a rotation is called positive, as before, when it has the same direction as the projection of the amperian molecular currents upon a plane at right angles to the ray of light.

First Series of Experiments.

A circular iron mirror, of the dimensions given above, was employed. The iron pole-pieces were adjusted at a distance of 29 millim. from each other, and maintained at this distance apart by means of a block of wood inserted between them. The mirror was placed sideways upon the magnet-poles, so as to touch each through a distance of 3 millim. The magnet was thus closed through the steel mirror. The reflecting surface was placed vertical. The angle of incidence J is the angle between the incident rays and the normal to the mirror.

The following Table gives the results obtained. The sign $=$ denotes that the plane of polarization (the long diagonal of the nicol) is parallel, and the sign $\perp$ that it is at right angles to the plane of incidence.

The amount of rotation is given in minutes. Since each number is the result of eighty separate adjustments, the tenths of minutes are given, although the error may amount to several tenths of a minute.

J .	$=$	$\perp$
19°0	-4'8	+2'7
29·9	-4·5	+7·3
39·5	-6·6	+7·7
50·1	-7·7	+6·9
61·3	-8·0	+7·5
65·0	-9·4	+8·7
70·0	-7·1	+8·1
75·0	-6·0	+6·8
80·3	-	+2·6
82·0	-4·3	-2·3
85·2	-3·9	-1·9

These experiments completely confirm Kerr's results—that

for the position of parallelism the direction of rotation is the same for all incidences and opposed to the molecular currents, while when the planes are at right angles the rotation changes sign for an angle of about 82° .

Our experiments also show a maximum rotation at 65° , as Kerr gives.

Second Series of Experiments.

An exactly similar series of experiments was made with a steel mirror of the same size, whose surface had been electroplated with nickel. The following values were obtained:—

J.	=	$\perp$
$20\cdot0$	$0\cdot0$	$+0\cdot0$
$30\cdot1$	$-1\cdot7$	$+1\cdot8$
$40\cdot0$	$-2\cdot7$	$+1\cdot4$
$50\cdot0$	$-4\cdot7$	$+0\cdot3$
$61\cdot5$	$-4\cdot2$	$-0\cdot7$
$65\cdot3$	$-3\cdot8$	$-2\cdot2$
$75\cdot0$	$-1\cdot1$	$-1\cdot9$

With nickel also the direction of rotation remains the same for all incidences =, but for the position $\perp$ changes its sign between 50° and 60° .

The amount of rotation is, on the whole, perceptibly smaller than with iron. This is in agreement with what was said above as to the ratio of the rotatory power of nickel to that of iron.

In order to test whether any perceptible distortion or bending took place when the magnet was excited, the images of a vertical and horizontal millimetre-scale were observed by means of a telescope in the manner already described. When the current was established, there occurred always a very slight displacement, and also a small bending of the mirror. The latter was inferred from the fact that the divisions and numbers of the scale between became somewhat indistinct. These displacements and distortions were, however, extremely slight; and the same whether the current was sent in the one direction or in the opposite. They could not therefore have exerted any perceptible effect upon the observed rotations. Besides the complete series of observations described, a large number of separate observations were made with the various mirrors under various conditions. They were all in complete agreement with the numbers of the above tables. The following may be quoted:—

Another steel mirror, similar to the one used for the series of experiments, gave at an angle of incidence of $65^{\circ}3$,

$$\begin{array}{cc} = & \perp \\ -8'6 & +9'0 \end{array}$$

This mirror was then electroplated with silver. Upon establishing or reversing the current there was no perceptible brightening of the field.

The pole-pieces of the magnet were then put into contact, and the mirror which was to be examined was placed at the side of the magnet, but without touching it. For this purpose mirrors of non-magnetic metal and platinized glass were employed which had been electrolytically coated with a thin film of iron. An accurate examination of the same by means of the scale and telescope showed not the smallest displacement or distortion when the magnet was excited. A rotation was observed in every case, as was to be expected from the results given in the above tables. Thus, for example, a glass mirror coated with iron gave for an angle of incidence of 65° , when the iron-coated side was about 2 millim. from the side of the magnet, the following rotations:—

$$\begin{array}{cc} = & \perp \\ -8'1 & +13'0 \end{array}$$

A rotation could still be observed when the mirror was at a distance of 45 millim. from the side surface of the magnet.

I have made also a number of experiments on the rotation produced upon oblique incidence on the end faces of a magnet. The arrangement was the same as that employed by Kerr. Platinized glass coated with iron, cobalt, or nickel was used in every case. The mirror was fastened in front of the plane-pole of an electromagnet without touching it, and a pointed pole (submagnet of Kerr) brought near to the mirror. If the plane of polarization coincided with the plane of incidences, then for all incidences the direction of rotation is opposed to that of the magnetizing current if we imagine the reflected ray of light rotated in the line joining the poles.

If the plane of polarization is at right angles to the plane of incidence, then at an incidence of about 80° the rotation is also oppositely, but from 80° to 90° similarly, directed with the magnetizing current. This reversal in the direction of rotation, as already remarked, escaped Kerr's notice. Since I have not yet been able to make a complete series of observations with one and the same mirror on the variation of rotation with the angle of incidence, I defer giving numbers for the present.

VII.

Rotation of the Plane of Polarization of Light which has twice traversed a glass plate and been reflected at the back surface of the plate.

The phenomena of reflection of light from metals have led to the view that the light upon reflection penetrates into the metal to a certain depth. This easily suggests the suspicion that the rotation of the plane of polarization of light which has suffered reflection from magnetic metallic surfaces arises in the very thin layer which the rays traverse upon reflection. A theory of rotation upon the assumption of the penetration of the light would be difficult to establish.

We may, however, easily state matters so that, in general at least, a process takes place analogous to that of reflection at metallic surfaces, upon the assumption of the penetration of light. Suppose that we have a glass plate in a magnetic field: let rays of light fall upon it at any angle of incidence. The rays are refracted into the glass, traverse the plate, are reflected at the back surface, and after traversing the plate a second time are refracted out of the glass.

If we have the amount of the electromagnetic rotation of the rays by glass given, then, by help of Fresnel's formula for reflection and refraction in isotropic bodies, the total rotation which the plane of polarization has suffered in the plate can be calculated. We will consider the following special case, which is analogous to our previous experiments on rotation at the side-faces of a magnet.

Let the lines of force of the magnetic field in which the glass plate is placed be parallel to the plane of the plate. Let the thickness of the plate be d , and the electromagnetic rotation per unit length in the direction of the lines of force be ϕ . Let the plane of polarization of the incident light coincide with the plane of incidence, and be parallel to the lines of force. Then, if Fresnel's formula for refraction at the first surface and reflection at the second surface be employed, the angle γ through which the plane of polarization is rotated upon emergence from the plate—if i and r represent the angles of incidence and refraction, and if the electromagnetic rotation in the plate is so small that the angle, its tangent, and its sine may be considered identical—is given by the formula

$$\tan \gamma = 2\phi d \tan \gamma \frac{\sin i \sin r}{\cos^2(i-r)}.$$

Since all the factors of ϕ are positive, γ has the same sign as ϕ for any value of i . For $i=0$, $\gamma=0$. The rotation of the

plane of polarization which the glass plate shows upon excitation of the magnetic field thus varies, no doubt, in magnitude with the angle of incidence, but always takes place in the same direction as the electromagnetic rotation which the rays suffer in the plate.

If, on the other hand, the plane of polarization of the light before its entry into the plate is at right angles to the plane of incidence, if we adopt the same symbols, and if the electromagnetic rotation is again small, then the rotation x , suffered by the plane of polarization upon emergence from the plate, is given by the formula

$$\tan x = -2\phi d \tan \gamma \frac{\sin i \sin r \cos (i-r)}{\cos (i+r)}.$$

If $i+r < 90$, x is negative; but if $i+r > 90$, x is positive.

For $i+r=90$, that is, for the polarizing angle, $x=90$; but in this case the amplitude of the light is zero.

The case considered above was examined experimentally in the following manner:—The poles of the large electromagnet were adjusted at a distance of about 3 centim. apart. A glass plate, the walls of which were not accurately parallel, so that the rays reflected from the back surface were well separated from those reflected at the front surface, was placed against the vertical side-faces of the poles so that it connected them. The plane of incidence of the light was horizontal. The angles of incidence were read off upon a large divided circle.

The following double rotations were obtained upon exciting the electromagnet at different angles of incidence for the rays reflected at the back surface.

The signs = and $\perp$ denote, as before, that the plane of polarization of the incident light is parallel or at right angles to the plane of incidence. The rotations are given in degrees.

Angle of incidence.		Rotation.
	=	
50°5	.....	+ 0°8
61°3	.....	+ 1°6
70°0	.....	+ 2°5
80°4	.....	+ 3°4
	$\perp$	
30°7	.....	— 0°7
39°5	.....	— 1°8
50°5	.....	— 4°8
53°8	.....	— 27°4
60°4	.....	+ 24°1
61°3	.....	+ 12°0
70°0	.....	+ 6°2
80°4	.....	+ 4°2

The polarizing angle of the glass ($i + r = 90^\circ$) was found to be $56^\circ.4$.

A similar series of experiments was made, with the two poles of the electromagnet pushed close together and the glass plate placed against the side surface of the closed magnet.

The rotations were similar to those given above. There is consequently a complete analogy between the phenomena obtained with the glass plate and the previously given observations of reflections at the side-faces of a magnet.

In that case, as in this, when the plane of incidence and the plane of polarization coincide all rotations have the same sign. If, however, the plane of polarization is at right angles to the plane of incidence, then, with metals as with glass, the sign of the rotation changes—for glass at the polarizing angle ($56^\circ.4$), for iron at about 80° , for nickel at about 60° .

Nevertheless we have the difference that, with the magnetic metals the direction of rotation is the opposite to that in the case of glass. If it is not allowable to assume that it is proved by this analogy that, upon reflection at metallic surfaces, the light penetrates to a small depth into the metal, and that the rotation takes place in the thin layer which the reflected rays traverse, yet the phenomena of rotation observed upon reflection at the side of a magnet admit of being brought under a simple and uniform expression. The fact that the light rotated upon oblique incidence on metals does not preserve its condition of plane polarization, but becomes elliptical, has been shown above.

Instead of bringing our glass plate up to the side-face of a magnet, we may bring it in front of the pole-surfaces so that the lines of force are at right angles to it. The amount of the rotation of the plane of polarization when the magnet is excited may be calculated as a function of the angle of incidence and position of the plane of polarization by means of Fresnel's formula, as explained above. The result is that, when the plane of polarization of the incident light lies in the plane of incidence, the rotation always has the same sign, viz. positive; but when the plane of polarization is at right angles to the plane of incidence, then from 0° up to the polarizing angle the rotation is positive, and thence on to 90° it is negative.

These phenomena are therefore exactly analogous to those of rotation at the pole-surfaces of a magnet, with the difference that we must ascribe a negative power of rotation to the magnet.

VIII.

In the preceding I have given a general view of the electromagnetic rotation of iron, cobalt, and nickel upon transmitted and upon reflected light. A more exact investigation of the dispersion due to rotation, of the dependence of rotation upon the thickness of the layers in reflection, &c., must be reserved for a subsequent occasion. Other questions suggest themselves: as, for example, whether the rotation attains its maximum with the induced magnetic moment, whether it is possible to recognize a rotation produced by a thin metallic film, which is permanently magnetized instead of being temporarily magnetized, &c.

I will here, in conclusion, only collect together the facts now known of the electromagnetic rotation of the plane of polarization. We will, as usual, designate a rotation in the direction of the hypothetical amperian molecular currents, which represent at the place in question the magnetic field actually present as *positive*, and an opposite rotation as *negative*.

1. Most isotropic solid bodies, fluids, and those gases which have been examined rotate the plane of polarization in the positive direction.

2. A concentrated solution of ferric chloride produces a negative rotation. The negative rotation of other magnetic salts is recognized by the diminution in the positive rotation of the solvent.

3. Oxygen, which is comparatively powerfully magnetic, produces positive rotation, as shown by Herr Röntgen and myself.

4. The plane of polarization of light which traverses iron, cobalt, and nickel is rotated in the positive direction.

5. According to Kerr, negative rotation is produced upon normal reflection from a magnetic pole. The same has been shown above to hold good for cobalt and nickel.

6. Upon passing through, as well as upon reflection from, iron, the rotational dispersion of the light is anomalous—that is, red rays are rotated more powerfully than blue ones.

7. The complicated phenomena which take place upon oblique reflection from the pole-surfaces, or side-faces of a magnet, may, as shown above, be brought together by the assumption that, in reflection, the light traverses a very thin film of the metal, and that negative rotation is produced by this layer.