



## XXVII. On Kerr's magneto-optic phenomenon

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obviated by the use of the wire-gauze tray suspended just below the surface of the water.

When dealing with liquids, where dissolution takes place almost instantaneously, the "uncertain interval" when the temperature is between the initial and final points is practically *nil*, and may be overlooked. The process in making the determination therefore consists in ascertaining the rate of cooling at the "initial temperature," and correcting the last reading of this so as to give its value at the moment of the addition of the solution (15 seconds generally after this last reading), and dating the commencement of the rate of cooling at the "final temperature" from this moment. Three or four readings at intervals of one minute generally suffice to determine this latter rate satisfactorily.

I now invariably read the thermometers without stopping the stirrers and tapping-apparatus, and I believe that greater accuracy in the results is thereby obtained.

## XXVII. On Kerr's Magneto-optic Phenomenon.

By H. E. J. G. DU BOIS, of the Hague\*.

§ 1. **INTRODUCTORY.**—Dr. Kerr has shown, in 1877, that the mode of vibration of light is in general affected by reflexion from a magnet. Hitherto this phenomenon has been almost exclusively studied from an optical point of view †; in particular, the complicated behaviour of light, obliquely reflected from magnets, has been much discussed. A magnetic curve was, however, given by Prof. Kundt, from which I drew the following conclusion ‡: for light normally reflected, the rotation is probably proportional to the magnetization, as it is for light transmitted through magnets. Starting from this, I have now further investigated the phenomenon

\* Translated by the Author from Wied. *Ann.* xxxix. p. 25 (1890); a synopsis of results had been communicated to the British Association, Newcastle. See Proceed. of Sect. A, Sept. 17, 1889 Report.

† Literature:—Kerr, *Phil. Mag.* [5] iii. p. 321 (1877), and v. p. 161 (1878); Kaz, *Dissert.*, Amsterdam (1884); Kundt, Wied. *Ann.* xxiii. p. 228 (1884), and xxvii. p. 198 (1886); Righi, *Ann. de Chim. et Phys.* [6] iv. p. 433 (1885), ix. p. 65 (1886), and x. p. 200 (1887).

Theoretical papers:—Fitzgerald, *Proc. Roy. Soc.* xxv. p. 447 (1876); *Phil. Mag.* [5] iii. p. 529 (1877); *Phil. Trans.* clxxi. p. 691 (1880); Wied. *Ann.* xxv. p. 136 (1885). Rowland, *Phil. Mag.* [5] ix. p. 432 (1880), and xi. p. 254 (1881). H. A. Lorentz, *Versl. en Mededeel. Amsterdam*, xix. p. 217 (1883), and *Arch. Néerl.* xix. p. 123 (1884). van Loghem, *Dissert.*, Leiden, 1883, and Wied. *Beibl.* viii. p. 869 (1884). Voigt, Wied. *Ann.* xxiii. p. 493 (1884). Ketteler, *Theor. Optics*, Brunswick, 1885.

‡ du Bois, Wied. *Ann.* xxxi. pp. 965, 974 (1887).

in its intimate connexion with magnetization. Optical complications were purposely avoided by working at almost normal incidence. I have also determined the effect of temperature, the rotational dispersion, and the characteristic absolute constants.

§ 2. *Method*.—Light from a Linnemann's burner (incandescent zirconia disk) was made to pass horizontally in succession through red glass, a lens, a Lippich's penumbral polarizer; it then reached the vertical mirror of the magnet, by which it was reflected into the analyser and telescope. By special constructive devices the parts of the apparatus, passed through by the light before and after reflexion respectively, could be fixed on a common base so near to each other as to have their optical axes inclined at but  $2^\circ$ ; this angle is halved by what I shall call the apparatus's medial line. The observer's eye was, of course, carefully screened from the burner. The medial line was adjusted normal to the mirror. By this arrangement practically normal incidence (at  $1^\circ$ ) was ensured; in fact, Righi\* noticed hardly any change in the phenomenon up to  $15^\circ$  of incidence.

The same physicist has found that with plane-polarized light, normally incident, the reflected vibrations are exceedingly oblong ellipses, the azimuth of whose major axis naturally differs from that of incidence. I saw no reason for making measurements of ellipticity; working with a penumbral polarizer, the azimuth of the major axis is what is actually observed. When using good mirrors and avoiding all diffused light, the alternative extinction of each half of the field of vision proved satisfactory, thus showing the ellipticity to be very small. The analyser's azimuth was measured by a modification of Poggendorff's mirror-and-(vertical)-scale method†. The arrangement and dimensions of lenses, diaphragms, the telescope, &c., had been calculated beforehand with a view to obtain the field of vision as bright and uniform as possible.

§ 3. The metallic cores principally used were ovoids (prolate ellipsoids of revolution) of different material, on to which small reflecting-planes had been ground in various positions.

\* Righi, *Ann. Chim. et Phys.* [6 sér.] ix. pp. 120 and 132 (1886).

† [This was separately described (*Wied. Ann.* xxxviii. p. 494, 1889) in order not to encumber the present paper with details, and does not pretend to anything beyond a mere laboratory expedient. It has since come to my notice that other experimenters have used similar devices.]

I desire to thank Messrs. Hartmann and Braun, of Bockenheim and Frankfort, and their foreman, Mr. G. Troll, who executed this difficult job for me with perfect success. The ovoids were magnetized in a coil of 1080 turns, 30 centim. long. In order to let light pass, small looking-tubes (.7 centim. diam.) had been fixed between the wire during winding. These lay in meridian planes through the coil's axis, and inclined at various angles to it.

§ 4. Notwithstanding the resulting slight irregularity of winding, the field was sufficiently uniform over the space to be covered by the ovoids. This was tested by the magnetic rotation in bisulphide of carbon, measured at different points on the coil's axis. At the same time the field could thereby be determined in absolute measure; and a numerical factor deduced, by means of which the readings of an ampere-meter in the coil's circuit were afterwards reduced to fields. The ovoids' moment was magnetometrically determined in the ordinary manner, the coil's action on the magnetometer being compensated by that of a second coil. Apart from ovoids, I have also worked with small reflecting disks, fixed between the poles of a Ruhmkorff electromagnet. Certain other arrangements will be described in due time.

§ 5. *Notations*, often recurring :— $\mathfrak{H}$ , intensity of coil's field;  $\mathfrak{I}$ , magnetization, and  $\mathfrak{J}$ , mean magnetization of ovoids;  $2a$ ,  $2b$ , their major and minor axes;  $n=b/a$ , axial ratio;  $\mathfrak{N}$ , outward normal to mirror;  $\alpha$ , angle  $\angle(\mathfrak{I}, \mathfrak{N})$ .  $K$ , Kerr's constant (see § 24);  $\theta$ , temperature;  $\lambda$ , wave-length;  $\epsilon_0$ , rotation on "polar" reflexion;  $\epsilon$ , rotation (according to § 2 this is to be understood as meaning the angle between the incident rectilinear vibration and the major axis of the reflected ellipse). Of course,  $2\epsilon$  was in the first place determined experimentally by reversing the current, generally as a mean of from 10 to 30 observations of azimuth. In every case below, however, the values of  $\epsilon$  are given in minutes, radian measure being still too little usual in such work. Otherwise, wherever the contrary is not expressly stated, all quantities and scales of diagrams are given in C.G.S. units. Wherever the sense of rotations has to be expressed with reference to vectors, I shall use the system of the vine and European "right-handed screw"\*. Accordingly, the sign of Kerr's effect, *e. g.* for iron, is *negative*, the sense of rotation having to be referred to the direction of magnetization.

\* Maxwell, *Treatise*, 2nd ed. i. p. 24.

## FIRST PART.

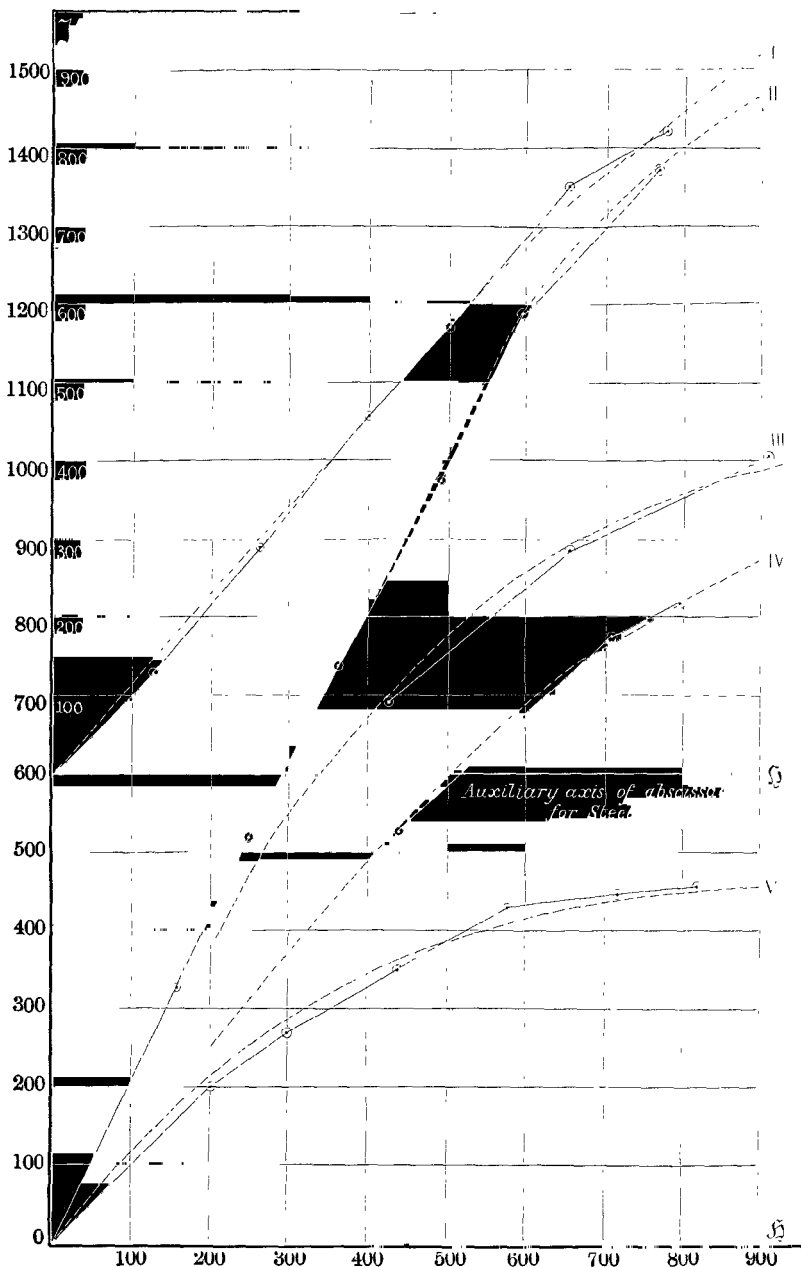
§ 6. I begin by describing the experiments with the ovoids. The polarizer consisted of a nicol and a Hartnack-Prazmowski's semi-prism (see § 16). The zirconia disk stood in the focus of the first lens, which thus projected parallel rays on to the mirror. Distance of vertical scale about 175 centim.

§ 7. *Normal temporary magnetization*.—The 5 ovoids used in this case were provided at one end with circular mirrors perpendicular to the axis of revolution, and were magnetized parallel to the latter. In this case, therefore, the reflexion, according to Dr. Kerr's nomenclature, is "polar," *i. e.* the metal is magnetized normally to the mirror ( $\alpha=0$ ). An ellipsoid (particular cases : sphere, spheroid, ovoid) is known to be the only finite figure in which iron is uniformly magnetized when subjected to a uniform field. In particular, no figure bounded by planes exists, for which this might be the case otherwise than approximately. Instead of such of vanishing size I had to use mirrors whose dimensions were only so far reduced as was consistent with sufficient intensity of the reflected beam. The ovoidal shape was necessarily disfigured by the missing segments ; and the magnetization, uniform on the whole, must be differently distributed in the neighbourhood of the small planes ; it is easy to see that it must be less than with an infinitely small mirror.

§ 8. Some preliminary trials were made to show that this is the correct view of the case. On turning down the mirror of one ovoid successively from .7 to .5 and then to .3 centim. diam., the rotation increased each time, *ceteris paribus*. Another ovoid, provided with mirrors at both ends, showed the lesser rotation at the larger mirror. Lastly, an ovoid was fitted as one pole-piece into an electromagnet, with the result that the rotation, for about the same estimated mean degree of magnetic saturation, proved considerably larger than when the ovoid was magnetized in the coil. The second bored pole-piece acts in the same manner as Kerr's "sub-magnet," *i. e.* it prevents the self-demagnetizing action of the plane end. In the final experiments the observed rotation may be estimated at 60 to 75 per cent. of that which would occur were the mirror of vanishing size (by data of § 19).

§ 9. The rotation, evidently a local action of magnetization, was now directly compared with the magnetometer-deflexion, apparently an action at a distance. The quotient (moment/volume) gives the mean magnetization  $\mathfrak{J}'$  of the ovoid, plotted in the broken curves of fig. 1 as a function of

Fig. 1.



- I. Glass-hard English Cast Steel (tempered at  $100^{\circ}$ ),  
 $2a=10$ ;  $2b=2$ ;  $n=\frac{1}{2}$ .  
 II. Soft Swedish Iron (annealed):  
 $2a=12.6$ ;  $2b=1.8$ ;  $n=\frac{1}{2}$ .

- III. Cast Iron:  
 $2a=12.6$ ;  $2b=1.8$ ;  $n=\frac{1}{2}$ .  
 IV. Cast Cobalt:  
 $2a=10$ ;  $2b=2$ ;  $n=\frac{1}{2}$ .  
 V. Hard-drawn pure Nickel:  
 $2a=10$ ;  $2b=2$ ;  $n=\frac{1}{2}$ .

the magnetizing field. The rotation  $\epsilon_0$  proved very nearly proportional to  $\mathfrak{J}'$ ; for each ovoid the mean  $m$  of the ratios  $\epsilon_0/\mathfrak{J}'$  was therefore calculated. By marking the values of  $\epsilon_0/m$  in the figure, and joining these points  $\odot$ , lines are obtained consisting of straight parts nearly coinciding with the broken curves, so as even partly to overlap in the small diagram. Proportionality is now seen to exist between  $\epsilon_0$  and  $\mathfrak{J}'$  at the first glance. The optical phenomenon, however, can evidently only depend upon the magnetic condition immediately behind the mirror; the following conclusion therefore appears justified: Within the comparatively narrow range of fields applied ( $\mathfrak{H}$  between 100 and 900 C.G.S.), the distribution remains unchanged; accordingly,  $\mathfrak{J}$ , the magnetization at the mirror, is proportional to  $\mathfrak{J}'$ , the mean magnetization throughout the ovoid.

I. *This gives the Law of Proportionality:*

$$\epsilon_0 = K\mathfrak{J},$$

where  $K$  is a constant.

In order to give this result a solid experimental foundation I have worked with 5 ovoids of different metals and various axial ratios. Accordingly each curve is seen to exhibit its peculiar character between the extremes of steel and nickel, though in each case verifying the proportionality to be proved.

§ 10. *Inclined temporary magnetization.*—All researches hitherto published refer either to "polar" ( $\alpha = 0$ ) or to "equatorial" ( $\alpha = 90^\circ$ ) reflexion. The case of magnetization inclined to the mirror's normal remains to be investigated. On to a large ovoid ( $2a=15$ ;  $2b=3$ ;  $n=1/5$ ) of soft Swedish iron small elliptical mirrors (minor axes .25 centim.) were ground under different angles to the axis of revolution. These were so small in comparison with the ovoid that the latter's longitudinal magnetization might be considered uniform. Accordingly the rotation observed may be estimated (by data of § 19) at 90 to 95 per cent. of that with an infinitely small mirror. The inclinations of the mirrors to the axis of revolution were measured in the lathe; the angles  $\alpha$  are their complements.

§ 11. The rotation was now measured for 4 mirrors with the same current flowing in the coil, and the beam of light passing forwards and backwards through the looking-tubes mentioned in § 3. The value zero for equatorial reflexion at normal incidence is taken from previous observers.

The numbers in the last line were calculated by analogy to Verdet's cosine law. The apparatus for these last experi-

	Polar, $\epsilon_0$ .	Inclined.			Equat.
$\alpha$ .....	$0^\circ$	$39^\circ.4$	$50^\circ.5$	$77^\circ.2$	$90^\circ$
Rotat. observ. $\epsilon$ .....	$-16'.5$	$-12'.6$	$-9'.7$	$-4'.6$	0
Rotat. calcul. $\epsilon_0 \cos \alpha$	$-16'.5$	$-12'.8$	$-10'.5$	$-3'.7$	0

ments having been difficult to construct, many sources of error occurred; considering these, the observed and calculated values of  $\epsilon$  sufficiently agree.

II. *This leads to the Cosine Law*

$$\epsilon = \epsilon_0 \cos (\mathfrak{I}, \mathfrak{N}).$$

It must still be remarked that the plane parallel to the mirror's normal and to the direction of magnetization may be called a "magnetic principal plane." In the above experiments this principal plane and the plane of polarization of the incident light were both horizontal. Experiments with a cobalt mirror, obliquely magnetized, proved that the same rotation is obtained whether one plane is perpendicular or parallel to the other. The effect is therefore independent of the azimuth of incidence. Equally good extinction was observed with inclined magnetization as on polar reflexion.

§ 12. *Normal residual magnetization.*—In order to obtain this an elongated ovoid ( $2a=18$ ;  $2b=1.2$ ;  $n=1/15$ ) of glass-hard English cast steel, tempered at  $100^\circ$ , had to be used. This, on the other hand, offered the disadvantage that the end was considerably disfigured by grinding on a mirror. The magnetic distribution must therefore differ considerably from a uniform one. I succeeded in obtaining a residual rotation in the shape of a change of the analyser's zero on impressing reversed residual magnetizations; it could be measured as a mean of 30 observations. The influence of magnetic history was each time eliminated after the manner of Gaugain, Auerbach, Maxim, Ewing, and others, by gradually diminishing reversals. Results follow:—

	$\mathfrak{I}$ .	$\mathfrak{I}'$ .	$\epsilon_0$ .	$\epsilon_0/\mathfrak{I}'$ .
Residual .....	0	180	$-0'.6$	$-.0033$
Residual .....	0	250	$-0'.8$	$-.0032$
Temporary .....	200	570	$-2'.8$	$-.0049$



§ 13. On account of the slight rotation no very sharp conclusions can be drawn from these numbers. The ratios of the last column are certainly all of the same order of magnitude; the first two, corresponding to residual rotations, appear to be equal and less than the third. This is easily explained by the plausible assumption of a residual distribution differing from the temporary one in giving comparatively less magnetization near the mirror. The result appears to me to lead to the following interpretation :—

For the law of proportionality it matters not whether the magnetization be residual or kept up by external induction.

This would tend to prove that the rotation is an immediate effect of magnetization and depends upon it alone\*.

§ 14. *Effect of temperature.*—The ovoids could be fixed in a brass tube closed at one end, and fitted at the other with a number of diaphragms, through the central apertures of which the mirror remained visible. This tube was heated by a horizontal perforated burner; the necessary draught being obtained by two waterjet-exhausters, which thus acted like chimneys. This arrangement could be introduced inside the coil, separated from it by an asbestos jacket. With a current of 30 amperes the coil and its contents could be electrically heated up to  $170^{\circ}$ ; by means of the burner the ovoid could be raised to higher temperatures still. Magnetic and optical observations were then made simultaneously during cooling. The rate of cooling could be modified at will by regulating the enclosing coil's temperature by the current. The temperature was given with sufficient approximation by a thermometer having its bulb near the mirror and stem projecting from the apparatus. Of course the metals were heated only for a short time and never beyond the temperature at which they begin to show surface-colours; as the least film of oxide on the mirror completely modifies the phenomena †.

§ 15. The results are given in Table I. The numbers for cobalt, iron, and steel on the whole lead to the conclusion that the value of  $\epsilon_0/\mathfrak{Z}'$  is but little variable with temperature. At the same time  $\mathfrak{Z}'$  varies so little ‡ with  $\theta$  that the distribution may be safely considered constant. Consequently  $\epsilon_0/\mathfrak{Z}$  ( $=K$ ) is proportional to  $\epsilon_0/\mathfrak{Z}'$ , i. e., by the above, practically constant.

For nickel, however,  $\mathfrak{Z}'$  diminishes considerably while  $\theta$

\* du Bois, Wied. *Ann.* xxxi. p. 973 (1887).

† Kundt, Wied. *Ann.* xxvii. p. 199 (1886).

‡ See footnote † next page.

TABLE I.

$\theta$ .	$\epsilon_0$ .	$\mathfrak{Z}'$ .	$\epsilon_0/\mathfrak{Z}'$ .	$\theta$ .	$\epsilon_0$ .	$\mathfrak{Z}'$ .	$\epsilon_0/\mathfrak{Z}'$ .
Cobalt. $\mathfrak{S}=930$ .				Steel. $\mathfrak{S}=930$ .			
29°	-10·9	894	-.0121	31°	-10·7	983	-.0109
98	-11·0	894	-.0123	101	-10·8	979	-.0111
167	-11·2	894	-.0126	147	-10·7	964	-.0111
220	-11·2	897	-.0125				
Iron. $\mathfrak{S}=930$ .				Nickel. $\mathfrak{S}=820$ .			
27°	-13·0	1528	-.0085	27°	-4·9	472	-.0103
78	-12·3	1524	-.0080	99	-5·4	452	-.0118
120	-12·1	1523	-.0080	162	-5·2	426	-.0123
164	-13·6	1517	-.0090 *	245	-4·8	330	-.0146
				282	-3·2	198	-.0163

increases†: the self-demagnetizing action thereby decreases at higher temperatures, so that the distribution approaches to uniformity, and the values of  $\mathfrak{Z}$  and  $\mathfrak{Z}'$  tend to become equal. It follows that even if  $\epsilon_0/\mathfrak{Z}$  be constant,  $\epsilon_0/\mathfrak{Z}'$  will none the less increase with  $\theta$ , and this is what the numbers for nickel actually do. Experiment therefore does not contradict the highly probable assumption that  $K$  is practically constant for nickel as well as for the other metals. At temperatures above 280° no more data could be obtained with sufficient accuracy. But on further heating I observed a rapid decrease of both rotation and magnetization until both vanished for temperatures above 335°, only to reappear simultaneously on cooling. This qualitative experiment affords a convincing instance of the close relation between both quantities. The result of this paragraph may be thus expressed:—

III. *The variation of the constant  $K$  with temperature is practically zero*; it is certainly less than a few per cent. per 100°, and therefore much below that of the electric resistance

\* It is quite possible that a thin colourless film of oxide begins to cover iron about 164°, which would explain the larger rotation here given; the temperature corresponding to a pale yellow is stated to be about 220° on heating for a short time. See Loewenherz, *Zeitschr. f. Instrum. Kunde*, ix. p. 316 (1889). For cobalt, and especially for nickel, these temperatures happen to lie much higher.

† It may not be superfluous to remark that from the values of  $\mathfrak{Z}'$  given, nothing more than a qualitative conclusion may be drawn as to the thermomagnetic behaviour of the metals; for the self-demagnetizing action of the rather short ovoids tends to diminish any temperature-variations of their magnetization. For quantitative determinations in thermomagnetism the metals have to be used in forms fulfilling the condition of perfect or approximate endlessness.

and index of refraction\*. It may also be remarked that Dr. Sissingh† has not been able to observe any change in the two ordinary constants of reflexion for iron between 20° and 120°.

## SECOND PART.

§ 16. The experiments in which the electromagnet was used remain to be described. Polarizer and analyser now consisted of genuine Lippich prisms‡. Working with a parallel beam of light was now given up, and an image of the zirconia disk thrown on the analyser's diaphragm instead; by this artifice of Lippich's the disturbing effect of any flickering of the source of light on the accuracy of observation is counteracted. Distance of vertical scale is 400 centim. nearly. These improved arrangements, together with the mounting of the optical apparatus on a pillar, separate from the electromagnet, considerably increase the accuracy of the results stated below above that hitherto attained.

§ 17. *Other active substances.*—Besides the three metals, exhibiting negative rotation on reflexion, I have detected Kerr's effect on common magnetic iron-ore. A piece of loadstone, ground and polished, showed a slight rotation between the poles of an electromagnet. Its numerical value varies over the mirror, but it is always *positive*. For quantitative measurement this material is of no use on account of its heterogeneous structure.

I therefore got a mirror ground parallel to the octaheder (111) of a small crystal of magnetite ( $\text{Fe}_3\text{O}_4$ , holohedr. tesseral). With a strong current in the electromagnet this gave a rotation  $\epsilon_0 = +5'$  for red light; the extinction was perfect, proving the ellipticity to be quite negligible. The rotation proved independent of the azimuth of incidence relatively to the crystal's principal directions; I therefore abstained from having other mirrors ground on in different positions, magnetite evidently behaving like an isotropic body. It would be interesting to observe the effect on transmitted light. However, hitherto I have not been able to find any method of procuring transparent films of this highly opaque substance.

§ 18. I have further tried the following much less magneti-

\* Kundt, *Berl. Berichte*, Dec. 1888, p. 1393.

† Sissingh, *Dissert.*, Leiden, 1885, p. 136; *Arch. Néerl.* xx. p. 216 (1886).

‡ Lippich, *Wien. Ber.* xci. 2, p. 1081 (1885). These prisms, as made by Dr. Steeg and Reuter, of Homburg, give a perfectly uniform field of vision with a well-defined line of demarcation; unfortunately, the linseed-oil used in their construction requires months for drying, so that I could not use them from the beginning.

zable, though powerfully absorbent, substances, but without any positive result—sulphide of iron ( $\text{FeS}$ , amorphous), and oxide of iron ( $\text{Fe}_2\text{O}_3$ , rhombohedr. hemihedr. hexagonal; mirror normal to principal axis). The fact that a measurable Kerr's effect has hitherto been detected only on the strongly magnetizable opaque substances Co, Ni, Fe,  $\text{Fe}_3\text{O}_4$ , points once more to the important part which magnetization plays in the phenomenon. I am much obliged to Prof. Bücking for kindly supplying me with these minerals.

§ 19. *Absolute constants.*—After having considerably improved the accuracy of the optical observations, as pointed out in § 16, I could venture to apply them in their turn to magnetic measuring purposes. This application of the law of proportionality I shall describe\* in detail; at present I will only mention that by means of it I was able to find the magnetizations corresponding to the rotations  $\epsilon_0$  given below. By division the absolute values of the constant K are obtained for “red” light in minutes per unit magnetization.

	Cobalt.	Nickel.	Iron.	Magnetite.
$\epsilon_0$ .....	−20'97	−7'25	−22'99	
$\mathfrak{J}$ .....	1060	453	1669	
K .....	−0198	−0160	−0138	+012

The value for magnetite is approximate; the others refer to the massive metals free from oxide; I could not detect any effect due to the polishing material. Thick electrolytic films gave about the same rotation under the same circumstances, but in general this depends on their thickness and surface condition†; such films are, therefore, hardly suited for absolute measurement.

§ 20. *The rotational dispersion* of Kerr's phenomenon is anomalous, but only for iron is it sufficiently developed to interfere with working in white light. For quantitative measurement I applied spectral analysis in connexion with Lippich's‡ penumbral method. By means of a prism “à vision directe” a solar spectrum was thrown on a small screen.

\* In the April number of this Magazine.

† See Kundt, Wied. *Ann.* xxvii. p. 199 (1886).

‡ Lippich, *loc. cit.* p. 1070; and Wied. *Ann.* xxxvi. p. 767 (1889).

All parts of this combination were rigidly put together, and its optical axis adjusted perpendicular to the medial line (§ 2) of the optical apparatus. Instead of Lippich's slitted screen a "slitted mirror" of adjustable breadth was set up vertically at  $45^\circ$  to the spectral screen in about the same place where the zirconia disk previously stood. This mirror, therefore, projected a sufficiently homogeneous beam of light into the polarizer.

§ 21. The positions of the lines Li  $\alpha$ , D,  $b$ , F, G were marked on the spectral screen and checked by means of spectra of Li, Na, and H. The slitted mirror was afterwards set to these. The "red" light used in the preceding experiments was not quite homogeneous, but owing to the slight dispersion sufficiently exact measurements could be made with it. Strictly speaking a definite wave-length cannot be assigned to the "red" light. But in order to allow a reduction of the spectral measurements to absolute values the question arises: which part of the spectrum is rotated through the same angle as was found for the "red" light? To this a definite answer may be given; by trial and interpolation I found for the wave-length  $\lambda = 62 \times 10^{-6}$  centim.

§ 22. The rotation was determined with each metal for six colours, each angle being obtained from thirty observations. The values of K (in minutes per unit magnetization) are given in Table II.; the numbers marked with an asterisk are

TABLE II.

Colour.	Line.	$\lambda \times 10^6$ cm.	Cobalt.	Nickel.	Iron.	Magnetite.
Red.	Li $\alpha$	67.1	-.0208	-.0173*	-.0154	+.0096
"Red."	.....	62	-.0198*	-.0160*	-.0138*	+.0120*
Yellow.	D	58.9	-.0193	-.0154*	-.0130	+.0133*
Green.	$b$	51.7	-.0179	-.0159	-.0111	+.0072*
Blue.	F	48.6	-.0181	-.0163*	-.0101	+.0026*
Violet.	G	43.1	-.0182*	-.0175*	-.0089	

the means of two separate series of observations. In plotting  $K = \text{func.}(\lambda)$  perfectly continuous curves of dispersion are obtained, showing the following characters:—

IV. *Cobalt has a faintly pronounced minimum for bluish green. Nickel a minimum for yellow. The iron curve runs almost straight down from red to violet. Lastly, for magnetite a maximum occurs in the yellow.*

Unfortunately quantitative observations with the poorly reflecting magnetite could not be pursued beyond blue. Further measurements might have proved the more interesting, as the rotation appeared almost to vanish for violet. I do not deem it impossible that the rotation passes through zero and changes sign in the ultra-violet, though this point appears difficult to decide.

### THIRD PART.

§ 23. *The combined expression of both experimental laws,  $\epsilon_0 = K\mathfrak{J}$  and  $\epsilon = \epsilon_0 \cos(\mathfrak{J}, \mathfrak{N})$ , leads to the general law:—*

$$\epsilon = K\mathfrak{J}_n \cos(\mathfrak{J}, \mathfrak{N}) = K\mathfrak{J}_n,$$

where  $\mathfrak{J}_n$  stands for the component magnetization normal to the mirror. This relation was found for red light, but may evidently be extended to radiations of all wave-lengths; it may be thus expressed:—

V. *The rotation of the major axis of vibration of radiations normally reflected from a magnet is algebraically equal to the normal component magnetization, multiplied into a constant K.*

Poisson, as is well known, has shown how any arbitrary magnetic distribution may be replaced, without prejudice to its internal or external action, by fictitious magnetic fluids, distributed in a definite manner throughout the magnet and on its surface\*. The surface-density  $\mathfrak{s}$  of the latter portion is given by the equation  $\mathfrak{s} = \mathfrak{J}_n$ . By the above we now have the rotation proportional to the surface-density, and it would thus appear theoretically possible to determine the latter by purely optical means. It would, however, be of no practical use to introduce the fictitious quantity  $\mathfrak{s}$  into the physical equation; it has no meaning beyond that of a purely mathematical symbol.

§ 24. The constant K is a quantity of dimension  $[L^{\frac{1}{2}} M^{-\frac{1}{2}} T]$  in electromagnetic measure. For four substances it is given in Table II. as a function of the wave-length; it hardly varies with temperature. I venture to propose calling it “Kerr’s constant;” for another quantity, which I have previously defined and denoted  $\Psi^\dagger$ , the name “Kundt’s constant”

\* Not to be confounded with Gauss’s surface distribution, the action of which may be substituted for that of the magnet only for points external to it. Both distributions do not coincide except in the particular case of solenoidal magnetization.

† The constant  $\Psi$  for radiations of definite wave-length is algebraically equal to the rotation which the plane of polarization of such radiations would experience on normal transmission through a plate of unit thickness and unit normal magnetization; du Bois, Wied. *Ann.* xxxi. p. 968 (1887).

appears suited. These names are formed analogously to that of another magneto-optic quantity, viz. "Verdet's constant," which is quite generally accepted; they recall the names of the discoverers of the corresponding phenomena, and are not limited to any particular language. I therefore believe that no objection can be made against their introduction, which appears desirable in order to avoid confusion among three essentially different constants of nature.

§ 25. *Conclusion.*—To my mind the experiments discussed leave no doubt but that the peculiar phenomena connected with reflexion from magnets solely depend upon the magnetization existing immediately behind the mirror; and I believe that no theory ought to ignore this fact. They also supply an experimental proof, which, however, is hardly required, for the assumption that at least part of the incident radiation penetrates below the surface and is there acted upon by magnetism, to be reflected out again afterwards. For, supposing the ray's path to lie entirely outside the metal, the action could only depend upon the magnetic condition of the air, which, however, is not the case.

I have been able to show, on a former occasion, that magnetization also is the quantity upon which the effect on transmission of radiations through magnets depends; this of course is intimately related to Kerr's phenomenon. The latter is doubtless the more complicated of the two phenomena, and differs from the former in sign and in the character of its dispersion\*. I believe the following simple kinematical explanation may be given for this difference; in doing so the dynamics of both phenomena are left aside as a remoter question.

§ 26. On normal transmission through a magnetic film the resulting difference of phase between the two opposite circularly polarized rays depends on their different velocity of propagation only; for the geometrical path is the same for both, viz. the film's thickness. On normal reflexion, however, the "optical path"† in the metal (=retardation of phase) is proportional for each ray to the quotient of the geometrical path by the velocity of propagation. Now the latter as well as the geometrical path (in consequence of the different depth

\* The rotation is known to be positive on transmission through Co, Ni, and Fe; its dispersion is anomalous, but according to Dr. Lobach (*Dissert.*, Berlin, 1890) it shows neither maxima nor minima.

† "Optical path" = geometrical path  $\times$  index of refraction; a convenient expression used by some authors.

of penetration \*) is different for the two circular rays. Accordingly it is easily seen that the difference of optical path, and therefore the difference of phase, may have the opposite sign for reflexion or transmission respectively. In fact it is only necessary that the swifter circular ray penetrate so much deeper than the slower one, that the acceleration of phase, which it would otherwise acquire, be thereby changed into a retardation behind the phase of the slower ray.

Generally speaking it is therefore possible that the rotations on reflexion or transmission respectively have the same or opposite signs. The former might even have different signs according to wave-length, and vanish for particular values of  $\lambda$ . Experiment seems to point to a case of this kind with magnetite (§ 22). The curves of dispersion for reflexion and transmission of course need not show any analogy; in any particular case this depends upon the properties of the substance. The above considerations were hinted at by Voigt †, though in a different form; but they are not limited to any particular optical theory, whether electric or elastic. They are of a purely kinematical nature; the hypothesis of circular birefraction and "biabsorption," on which they are based, must, however, be retained.

The contents of this paragraph have therefore to be considered apart from all that precedes; with this sole exception I have striven to cling to experiment and its immediate consequences, free from any additional assumption. In conclusion, I beg to tender my best thanks to Prof. F. Kohlrausch, in whose laboratory these experiments were carried out.

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\* The most general assumption is that part of each circular ray is reflected in the surface itself. The rest then penetrates into the metal, and every elementary sheet of its substance again reflects a "circular element," with amplitude the less, the greater the depth at which reflexion ensues. The reflected pencil now consists of one circular vibration and an infinity of circular elements vibrating in the same sense. Kinematic integration gives a single circular vibration in this sense. This consideration, therefore, leads to the same result as the assumption, made above, of direct penetration of the pencil as a whole, and subsequent reflexion at a definite depth. The two resulting opposite circular vibrations now possess difference of phase, thence rotation, and slight difference of amplitude, thence slight ellipticity in the reflected ray. (Compare the geometrical method of circular elements by Dr. Wiener, Wied. *Ann.* xxxv. pp. 3-5, 1888.)

† Voigt, Wied. *Ann.* xxiii. p. 508 (1884).