



## XLIX. The magneto-optics of sodium vapour and the rotatory dispersion formula

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XLIX. *The Magneto-Optics of Sodium Vapour and the Rotatory Dispersion Formula.* By R. W. WOOD, *Professor of Experimental Physics, Johns Hopkins University* \*.

[Plate V.]

IT has been shown in a previous paper † that the vapour of metallic sodium is an ideal substance for investigating the effect of a strong absorption-band on the magnetic rotation of the plane of polarization. The preliminary work was not very satisfactory, however, as the method employed did not admit of very accurate determinations of the wave-lengths, and the verification of the rotatory dispersion formula could only be considered as approximate. Improvements in the methods of observation and design of the apparatus have been accompanied by an increase in accuracy, which could scarcely have been hoped for, as will be seen by the following comparisons.

In the preliminary work no readings of the rotation for wave-lengths between the sodium lines could be obtained, while in the present case accurate readings have been made for as many as *nine* different values of  $\lambda$  between  $D_1$  and  $D_2$ . Rotations as great as  $1440^\circ$  (four complete revolutions) have actually been observed, and this with a 10 cm. column of not very dense vapour, in a field of only 2000 C.G.S. units. This was for a wave-length midway between  $D_1$  and  $D_2$ . In the earlier work it was only with the greatest difficulty that the bright lines which appeared in the region of the red and green channelled absorption spectrum could be seen. They have now been photographed to the number of about 160 with the 14-foot concave grating. Comparatively few of the absorption-lines show any trace of magnetic rotation, scarcely one per cent.; and the fact seems to have been established that these lines coincide with the bright lines of the fluorescent spectrum of the vapour, which has been found to be by no means the exact complement of the absorption spectrum as was at first supposed.

In the present paper the magneto-optics of the vapour for light travelling along the lines of force will be discussed. The double-refraction of the vapour, which occurs when the rays are perpendicular to the field, has also been studied, and will be reported in a subsequent paper. An exhaustive study of the fluorescence of the vapour has been made, and the lines of the spectrum to the number of several hundred

\* Communicated by the Physical Society: read June 30, 1905.

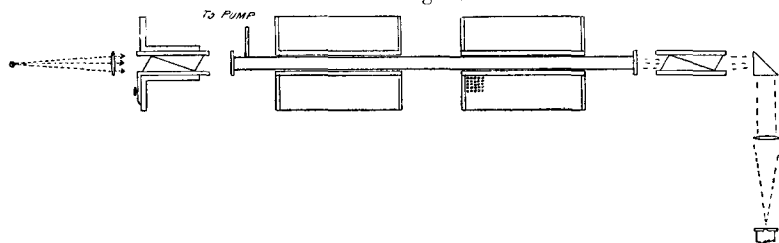
† Wood and Springsteen, "The Magnetic Rotation of Sodium Vapour," *Phys. Review*, July 1905.

accurately measured. Very remarkable effects have been observed when the vapour is illuminated with a *very* narrow band of approximately homogeneous light, the lines in the fluorescent spectrum changing their position and appearing to dance about in the liveliest manner with the slightest change in the wave-length of the exciting light. The motion is of course only an illusion, lines disappearing and others reappearing, like the sparks of a spinthariscopes. Stokes's law is violated in a most flagrant manner, bright lines coming out on both sides of the excited region. The behaviour of the spectrum indicates that we are dealing with a number of groups of electrons, each group containing a large number of vibrators. The excitation of one of the vibrators sets the whole group agoing, but does not start disturbances in the other groups. These and other remarkable phenomena will be fully discussed in the following Number of this Journal; they are mentioned here only on account of the apparent relation between magnetic rotation and the fluorescence.

In the earlier experiments referred to above, the sodium was heated in a tube of hard glass, the ends of which were closed with thin plate glass. The tubes lasted but a short time, owing to the chemical action of the metal, and in fact usually cracked on a second heating. In the present work a tube of thin steel has been used, the ends of which projected from the helices of the magnet. It was found that the field-strength within the steel tube did not differ greatly from that obtained when glass tubes were used.

The arrangement of the apparatus is shown in fig. 1. A piece of thin seamless steel tubing of such a diameter as to

Fig. 1.



slip easily through the hollow cores of the electromagnet, from which the conical pole-pieces have been removed, is procured. A short piece of small brass tubing is brazed into one end, through which the tube is exhausted. It has been found that a good vacuum is essential, all trace of the rotation disappearing in hydrogen or nitrogen at atmospheric pressure. In the earlier work this fact was not known, and the tubes

were exhausted and then sealed off from the pump. The hydrogen liberated from the sodium must have raised the pressure to at least 15 cms. in all of these experiments. In the light of what is now known, it is surprising that any results at all were obtained under these conditions.

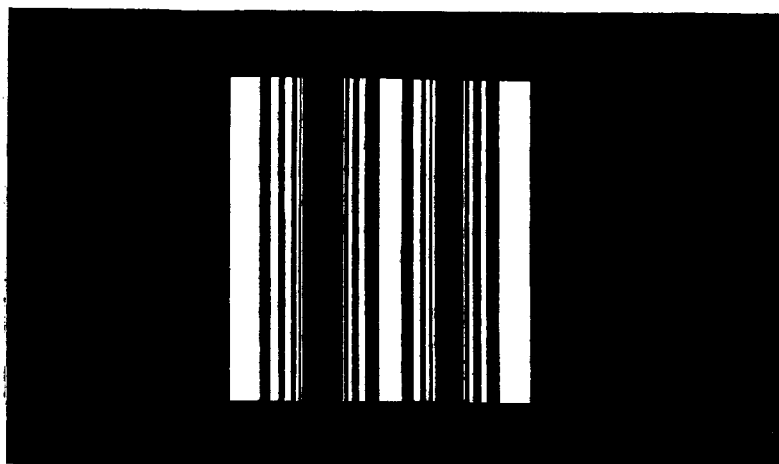
A lump of sodium the size of a walnut is melted in an iron crucible, and poured out into a V-shaped trough made of thin sheet iron. As soon as the bar is solid it is placed in the iron tube, one end of which has been previously closed with a small piece of plate-glass cemented on with sealing-wax. The tube is introduced into the magnet, the sodium bar pushed to a position midway between the helices, and the other end closed with a piece of glass in a similar manner. The ends of the tube should be coated while hot with sealing-wax before the introduction of the sodium. One has then only to wave a Bunsen flame over them and press on the piece of glass, previously heated; the sealing-wax should come into optical contact with the glass to insure an air-tight joint. The tube is now connected with an air-pump which will produce a vacuum of a millimetre or two. If the air-pump leaks, it is a good plan to place a glass stopcock between the pump and tube to prevent the entrance of traces of air after exhaustion. For purposes of demonstration it is sufficient to heat the tube gradually with a Bunsen burner turned down low. In the present work, however, where constancy of temperature was essential, electrical heating was invariably used; the tube was wrapped with a thin sheet of asbestos board, around which was wound a spiral of iron wire, and the whole subsequently covered with an asbestos jacket.

The light from an arc-lamp, made parallel by a lens, is passed through a Nicol prism, the steel tube, and a second nicol, after which it is brought to a focus by means of a second lens upon the slit of a spectroscope. In the present case, the instrument in question was a concave grating of 14-foot radius, the observations being made both visually and by means of photography.

We will now consider briefly the phenomena which are presented when the sodium vapour is formed in the magnetic field. The nicols are crossed and the spectrum vanishes completely. The magnet is now excited and the Bunsen burner placed under the tube, the tip of the flame barely touching it. In a few minutes we see two bright yellow lines exactly in the position of the D lines. The light constituting these lines comes, however, from the crater of the arc, as we can easily see by intercepting the beam. The lines are in reality double, though they appear single with low resolving powers, while even with the 14-foot grating their duplicity

cannot be made out when they first appear. As the density of the vapour increases, the components separate, four lines being distinctly visible. This condition is shown in Plate V. fig. 1 *a*. The lines are formed by the constituents of the white light bordering the two absorption-lines, which having suffered a rotation of  $90^\circ$  in the magnetic field, is enabled to pass the second nicol. The lines continue to separate, becoming broader, and presently we see between them a second pair of lines, for which the rotation is  $270^\circ$ , the two dark regions between representing rotations of  $180^\circ$ . This stage is shown in fig. 1 *b* and *c*, Plate V. In fig. 1 *b*, the two inner  $90^\circ$  lines are beginning to fuse together, the centre being partially dark however. In fig. 1 *c*, the fusion is complete and the centre of the system of lines is bright. With a further increase in the vapour-density, the outer lines ( $90^\circ$ ) separate still further, and widen out into broad flares of light, and other lines appear between them, corresponding to larger rotations, the system resembling a set of diffraction fringes, as shown in fig. 2. The centre of the system, as I

Fig. 2.



shall designate a point midway between  $D_1$  and  $D_2$ , becomes bright and dark in succession, as is shown in the succeeding figures of Plate V. fig. 1. Only a few of the inner lines show in the photographs, as they are very close together, and the vibration of the building prevented their resolution in the photograph. They could be distinctly seen with the eye-piece, and accurate settings of the cross-hair could be made. Their position with respect to the D lines was very accurately determined by means of a filar micrometer, settings being

made on the dark lines between as well. A little practice was necessary before a complete series of readings could be taken without error, but consistent results were finally obtained. The method adopted was as follows. A current of given strength was turned into the iron spiral, and as the vapour-density increased the alternations of brightness and darkness at the centre were counted. No measurements were commenced until a steady state was reached, which was indicated by a fixed condition at the centre. The positions of the bright lines and dark spaces were then measured, the readings being taken down by an assistant. If at the end of the series any change was found to have occurred at the centre, it was rejected. As soon as the series was completed, the heating current was shut off, and the tube allowed to cool. During this process the alternations of brightness at the centre were counted, and if the number of changes differed from that originally recorded the series was thrown out. The rapid changes which occur as the tube cools, especially an unjacketed tube, are most interesting; the centre of the system changes from bright to dark with great rapidity. The largest number of complete alternations observed was eight, corresponding to a rotation of 1440 degrees, one alternation (*i. e.* from bright to bright) corresponding to 180. The whole thing lasts but a few seconds, the bright band "winking" almost as fast as one can count. We can, as it were, see the plane of polarization actually turning around and around, for four complete revolutions. Beyond this point the absorption becomes too strong to admit of further observations between the D lines, but readings may be taken above and below them in the spectrum, with vapours of very great density.

When the vapour acquires a considerable density, a most magnificent bright-line spectrum appears in the red and green-blue region. Each bright line corresponds to a dark line in the absorption spectrum, but only a small percentage of the dark lines appear to exercise a rotatory power. Some of the strongest absorption-lines are absolutely unrepresented in the magnetic rotation spectrum, which indicates that there is some radical difference in the absorbing mechanism.

Much time has been spent in a further photographic study of the channeled absorption spectrum, a piece of work which was commenced three years ago by the writer in collaboration with Mr. J. H. Moore. It has since been found that the presence of hydrogen, nitrogen, or carbonic acid modifies the appearance of the absorption spectrum. The photographs previously obtained were made by passing the light through

a steel tube containing sodium vapour in an atmosphere of hydrogen, under which condition the absorption spectrum has a most beautiful shaded appearance, being made up of fluted bands, each band containing a very large number of fine lines. If the hydrogen is removed, and the sodium vapour formed *in vacuo*, the fluted appearance disappears almost entirely, although the individual lines remain. Many new lines appear, however, which are broader and more distinct than the others, and these lines appear to coincide with the bright lines in the rotation spectrum. This point will be more fully investigated in the future, the work on the absorption spectrum not having been completed at the present time.

Returning now to the measurements obtained in the vicinity of the D lines, we will discuss them in their bearing on the theory of magnetic rotation.

The rotation has been measured over a considerable range of wave-lengths in the case of very dense vapours, by the method described in the previous paper. In brief this method consisted in rotating one of the nicols through various angles and measuring the position of the two dark bands which move, the one up, the other down the spectrum. The dispersion of the 14-foot grating was too great for this part of the work, and a large plane grating was accordingly combined with a pair of telescope objectives of six-foot focal length. A very brilliant spectrum was obtained in this way, and the dark bands were not so broad but that the cross hairs of the micrometer could be set on the centre of the band with a fair degree of accuracy. Readings of the rotation were obtained throughout the region comprised between  $\lambda=5840$ , and  $\lambda=5932$ . The dark bands cannot be pursued with accuracy to greater distances from the D lines, on account of their increased breadth. It will be understood from what has been said in the previous paper, that these dark bands retreat from the D lines when one of the nicols (originally parallel) is rotated towards the position of extinction. The bands enter the red and green regions when the nicols are very near the crossed position, under which circumstances the bright lines appear, and completely obliterate all trace of the dark bands, which by this time have become very broad. The rotation for the wave-lengths corresponding to the dark bands, is the angle through which one of the nicols has been rotated, measured from the crossed position.

The values found with vapours of various density are recorded in the following table. The tables are designated by the magnitude of the rotation midway between the D lines.

CENTRE 30°.	CENTRE 90° <i>con.</i>	CENTRE 450°.	CENTRE 540° <i>con.</i>
5897.1 90	5894.5 270	5902.1 30	5888.0 630
5896.8 180	5894.4 180	5902.2 40	5887.8 540
5896.5 270	5893.34 90	5900.3 60	5887.4 450
5895.4 270	5891.9 180	5899.4 90	5887.1 360
5895.3 180	5891.5 270	5898.7 180	5886.7 270
5894.9 90	5891.3 360	5898.0 270	5886.1 180
5893.2 30	5891.1 450	5897.7 360	5884.6 90
5891.4 90	5890.86 640	5897.5 450	5883.2 60
5890.9 180	5889.0 450	5897.3 540	5881.5 40
5890.6 270	5888.8 360	5894.8 900	
5889.3 270	5888.5 270	5894.7 810	
5889.0 180	5888.2 180	5894.5 720	CENTRE 720°.
5888.7 90	5887.5 90	5894.2 630	5875.0 20
	5886.96 60	5894.0 540	5876.3 25
	5886.5 40	5893.2 450	5880.5 50
	5886.0 30	5892.3 540	5881.4 60
	5884.8 20	5892.1 630	5882.6 80
CENTRE 50°.		5891.8 720	5883.2 95
5898.4 30		5891.5 810	5885.7 180
5897.8 45	CENTRE 180°.	5888.3 720	5887.0 270
5897.6 60	5901.3 20	5888.1 630	5893.5 720
5897.3 90	5900.3 30	5887.9 540	5899.0 180
5897.0 180	5899.4 40	5887.7 450	5900.8 97
5896.7 270	5899.0 60	5887.4 360	5901.8 80
5895.3 270	5898.2 90	5886.9 270	5902.8 61
5894.9 180	5897.7 180	5886.1 180	5903.6 50
5894.6 90	5897.3 270	5884.7 90	5908.0 25
5893.2 50	5897.1 360	5883.2 60	5909.7 20
5891.9 90	5896.9 450	5881.7 40	
5891.4 180	5894.9 540	5880.3 30	
5891.0 270	5894.7 450		
5889.1 270	5894.5 360		
5888.7 180	5894.1 270	CENTRE 540°.	CENTRE 960°.
5888.3 90	5893.2 180	5902.8 40	5903.9 60
5887.8 60	5891.9 270	5901.5 60	5902.0 90
5887.6 45	5891.6 360	5900.1 90	5900.2 180
5886.9 30	5891.3 450	5898.8 180	5899.6 270
	5891.2 540	5898.3 270	5899.2 360
CENTRE 90°.	5888.6 540	5898.0 360	5898.8 450
5899.7 20	5888.4 450	5897.7 450	5893.4 960
5899.3 30	5888.2 360	5894.4 720	5886.6 540
5898.8 40	5887.9 270	5893.7 630	5886.3 450
5898.3 60	5887.5 186	5893.5 540	5885.9 360
5897.8 90	5886.8 90	5892.4 630	5885.1 270
5897.45 180	5886.2 60	5892.1 720	5884.5 180
5896.8 360	5885.4 40	5891.8 810	5881.8 90
5895.3 451	5884.6 30	5891.7 900	5880.0 60
5895.0 360	5883.2 20		

A number of photographs of the spectrum with the dark bands in different positions were made with a large three-prism spectrograph, recently constructed for the study of the fluorescence spectrum (Pl. V. fig. 2). It was at first thought that by measuring the positions of the bands on the negatives, more accurate results could be obtained than by visual observations; but the reverse proved to be true, though fairly good curves were obtained. The density of the vapour was



much greater than that employed for the visual observations, and the dark bands were found to be symmetrical with respect to the D lines, that is the rotation was the same at points in the spectrum at equal distances (measured in wave-lengths) to the right and left of the D lines. This was not the case with less dense vapours, the rotation being greater in the vicinity of  $D_2$  than in the vicinity of  $D_1$ . The rotation constant of  $D_2$  was found to be about double that of  $D_1$ ; but since the direction of rotation is the same on opposite sides of the absorption-bands, the effects of the two bands are additive, and lack of symmetry will be less noticeable with very dense vapours, where the measurements are made in a region not very close to the lines.

*Verification of the Rotatory Dispersion Formula.*

Drude, in his *Lehrbuch der Optik*, has given two formulæ for the magnetic rotatory dispersion, the first of which, developed from the hypothesis of molecular currents, calls for an anomalous effect on crossing the band, and obviously does not apply to sodium vapour. The second, developed from the Hall-Effect Hypothesis, predicts rotations of similar sign and equal magnitude for wave-lengths symmetrically situated in the spectrum, with respect to the centre of the absorption-band. The formula deduced for the rotation is

$$\delta = \frac{1}{n} \left( \frac{a}{\lambda^2} + \frac{b\lambda^2}{(\lambda^2 - \lambda_m^2)^2} \right).$$

In the case of sodium vapour  $n$  differs so little from unity that it can be left out of account. Investigations of the refractivity of the vapour by the writer, have shown that with very dense vapour (comparatively speaking) the value of  $n$  may be as great as 1.3 in the immediate vicinity of  $D_2$ , but calculations showed that in all of the cases dealt with in the study of the magnetic rotation,  $n$  was practically equal to unity. When working very near the D lines the vapour was extremely rare, while observations made with denser vapours covered regions not very near the absorption-lines. Since, moreover, the rotation is zero for very short waves, the first term in the formula drops out, i. e.,  $a=0$ . Precisely the same thing was done in the case of the ordinary dispersion formula, since the refractive index was found to be unity for very short waves\*. The similarity in the sign of the rotation on opposite sides of the bands results from the fact that the

\* See previous paper on the "Dispersion of Sodium Vapour," this Journal, vol. viii. p. 293 (1904).

quantity  $(\lambda^2 - \lambda_m^2)$  (which changes sign on crossing the absorption-band) is squared. An attempt was first made to verify the simplified formula by writing  $\lambda_m = 5893$ , *i. e.*, assuming the D lines to be a single absorption-band. The value of the constant could then be determined from a single observation, and the rotations for different values of  $\lambda$  calculated. The calculated values agreed very closely with the observed on one side of the double absorption-band, but the agreement on the other side was very poor. This was at once seen to be due to the fact that the rotatory power of the two lines was very different, and the following formula was consequently adopted :—

$$\delta = \frac{a\lambda^2}{(\lambda^2 - \lambda_{D_2}^2)^2} + \frac{b\lambda^2}{(\lambda^2 - \lambda_{D_1}^2)^2}.$$

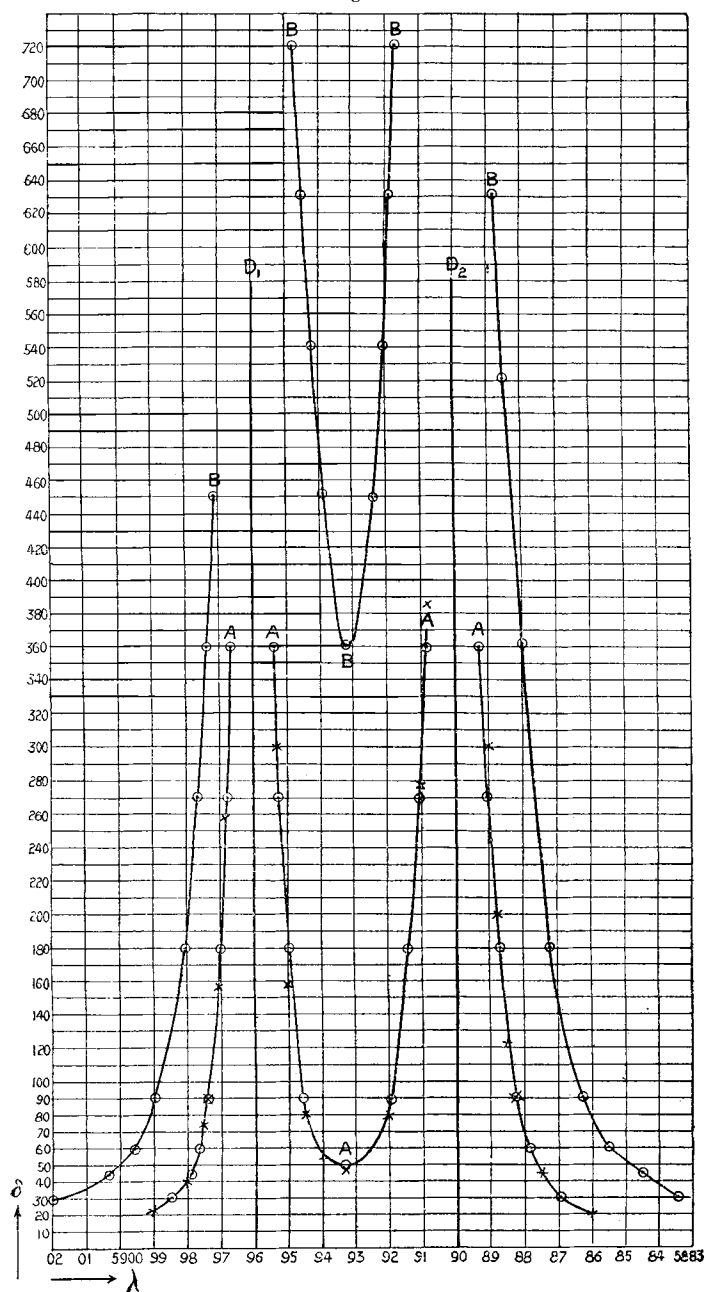
The constants  $a$  and  $b$  were calculated from two observations of  $\lambda$ , one greater than  $D_1$ , the other less than  $D_2$ . In almost every case the ratio  $\frac{a}{b}$  was found to lie between the limits 1·8 and 2·03. Writing  $D_1 = 5896$  and  $D_2 = 5890$ , the values of the constants  $a$  and  $b$  for vapours of different densities are recorded in the following table. The densities are defined by the magnitude of the rotation for a wave-length midway between  $D_1$  and  $D_2$ .

Density .....	$a$ .	$b$ .	$a/b$ .	Centre Rotation Calc.
Centre $\bar{c} = 50^\circ$ .....	1123	587	1·9	$51^\circ$
„ „ $90^\circ$ .....	2217	1350	1·65	$98^\circ$
„ „ $180^\circ$ .....	4309	1860	2·3	$161^\circ$
„ „ $360^\circ$ .....	5111	2571	1·98	$205^\circ$
„ „ $450^\circ$ .....	9279	4545	2·03	$369^\circ$
„ „ $540^\circ$ .....	10326	4607	2·24	$392^\circ$
„ „ $720^\circ$ .....	12750	7100	1·8	$538^\circ$
„ „ $960^\circ$ .....	23873	10333	2·6	$893^\circ$

The “centre” as defined above does not in fact fall at  $\lambda = 5893$ , but at  $5893\cdot5$ , *i. e.*, when the bright bands unite, the point of unison lies nearer  $D_1$  than  $D_2$ . This is owing to the fact that the expansion of the bands from  $D_2$  is more rapid than from  $D_1$ .

It was found that if the constants  $a$  and  $b$  were calculated from different pairs of readings, there was considerable difference between the values, a circumstance which indicates either that the formula is at fault, or that the observations were not sufficiently accurate. We are dealing with very steep curves, as will be seen by reference to fig. 3, and

Fig 3.



small errors in wave-length readings will make large errors in values deduced from them. The severest test of all is to calculate the rotation at the centre from values of the constants determined from two medium values of  $\delta$  (say 90 or 180) outside of the D lines. This has been done in each case, and in almost every case the calculated value has turned out too small. I have given all of the tables of data thus far obtained, and some of them are doubtless less accurate than others. By means of an improved heating coil (which is in process of construction), of porcelain and strip platinum, I hope to be able to hold the conditions more nearly steady and obtain still more accurate results. It will also be necessary to secure greater rigidity of the grating. For large rotations at the centre, say above 180, we cannot be quite sure of the exact value, as the best that can be done is to regulate the heat so that the condition at the centre is either of maximum brightness or darkness. Errors of say 15 or 20 degrees can be made easily. It is quite possible too that the formula is incomplete. It seems more than likely that the molecular currents play some part, and that the formula built up on the hypothesis of the Hall effect is incomplete. As we shall see presently, however, it represents the rotation outside of the D lines with a surprising degree of accuracy, while between the lines it gives in most cases a curve which is elevated somewhat above the experimental curve. It is possible that the refractive index plays some part, though I regard this as very doubtful. Midway between the D lines the refractivity is equal to unity, rising and sinking rapidly to the right and left of this point. It is not worth while to experiment further with the formula until still more accurate data are at hand, which I am confident of obtaining in the autumn.

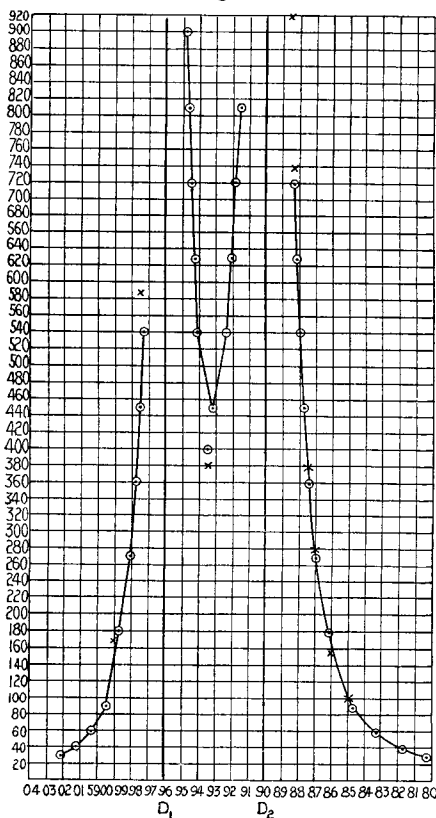
Another matter still to be determined is whether the variation of the ratio  $\frac{a}{b}$  results from errors, or whether it increases with the density of the vapour, as appears to be the case. These points will be taken up again in the second paper.

For densities giving rotations of 50°, 90°, and 180°, at the centre, the calculated value agrees with the observed to within the probable experimental error, for, as I have said, it is impossible to fix the rotation at the central band to within say 15. In the case of denser vapours the discrepancies are much too large to be attributed to errors of this sort.

Outside of the D lines the calculated values agree remarkably well with the observed, even in the case of the densest vapour used, as will be seen by referring to the

curves shown in figs. 3 & 4. The observed values are represented by circles, the computed by crosses. The observed values are, of course, for values of  $\delta$  which are multiples of 90. In the computations, values of  $\lambda$  were selected, which

Fig. 4.



could be accurately represented by five figures, consequently we judge of the accuracy with which the formula represents the dispersion by seeing whether the calculated values fall on the curve determined by experiment. The computations are easily made. One has but to determine the value of

$$\frac{\lambda^2}{(\lambda^2 - \lambda_{D_2}^2)^2} \quad \text{and} \quad \frac{\lambda^2}{(\lambda^2 - \lambda_{D_1}^2)^2}$$

for wave-lengths in the region under investigation. These terms being independent of the vapour-density, can be used

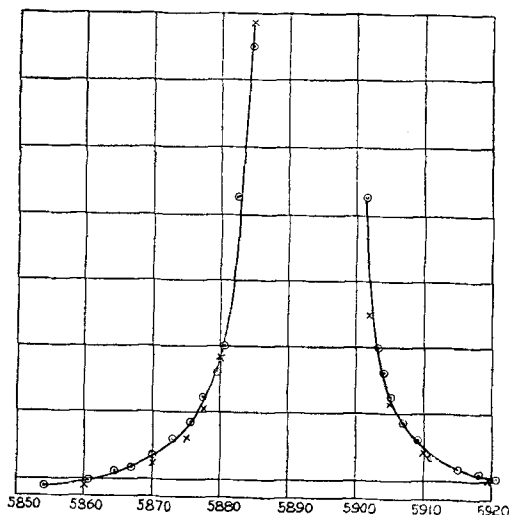
in all cases, the rotations being found by multiplying them by the constants  $a$  and  $b$  as determined for a particular density, and adding the two products.

On fig. 3 will be found two curves, A and B, for centre rotations of  $50^\circ$  and  $360^\circ$ . The values of  $\delta$  calculated for the curve A, will be seen to fall in most cases exactly upon the curve of observed values.

Fig. 4 shows that the agreement is also good for a density giving a rotation of  $450^\circ$  at the centre.

Fig. 5 represents the rotatory dispersion of the densest vapour investigated by visual methods. The bright band

Fig. 5.



between the D lines had disappeared completely owing to absorption. This corresponds to a rotation at the centre of about 1500, since 1440 is the largest rotation actually observed. The observed values in this case were obtained with the plane grating and long focus telescope-lenses of five inches aperture. The positions of the broad, dark bands were measured with a micrometer eyepiece for different settings of the nicol, and readings were also taken on the narrow bright and dark bands lying between the broad ones and the D lines, whenever they were distinct enough. In this case, the calculated values lie on a curve slightly lower than the observed curve. This may be due to the fact that the value of  $\lambda$  for which the rotation is equal to that of the nicol may not lie exactly at the centre of the band. On the whole, the formula may be said to represent the rotatory dispersion,

exclusive of the region between the D lines, with a fair degree of accuracy. If, however, the constants  $a$  and  $b$  are calculated from different pairs of readings on the same curve, different values are found. On this account, it seems desirable to redetermine the curves with still greater precision, which will be done in the autumn.

Vapour of a still greater density was investigated by a photographic method.

The spectrum of the light transmitted through the two nicols and the sodium tube was photographed with the three-prism spectrograph. Seven exposures were made on a trichromatic plate, with the second nicol in seven different positions. A sodium flame, burning continuously in front of the slit of the spectrograph, recorded the D lines on the plate. The tube was heated electrically, and the density of the vapour remained constant throughout the total time of exposure. Each exposure amounted to less than half a minute. One of these multiple photographs is reproduced on Plate V. fig. 2. The picture may be said to show the dispersion curve. The positions of the dark bands, which appear on each side of the D lines, were measured on the dividing engine, and the wave-lengths determined from the calibration curve of the spectrograph. For these dense vapours it was found that the rotatory dispersion curves were symmetrical with respect to a point midway between  $D_1$  and  $D_2$ . The dispersion should therefore be well represented by a single-term formula

$$\delta = \frac{a\lambda^2}{(\lambda^2 - \lambda_D^2)^2},$$

in which  $\lambda_D = 5893$ . This was found to be the case, as the following table shows.

Value of constant  $a = 135600$ .

$\lambda$ .	$\delta$ Observed.	$\delta$ Calculated.
5980	5	4.47
5950	10	10.4
5933	20	20.2
5923	40	38.0
5917	60	58.9
5912.5	90	89.2
5874	90	93.1
5869	43	43.0
5864	40	40.6
5852	20	20.2
5833	10	9.2
5814	5	5.2

The value of the constant was determined from the value of  $\delta$  at wave-length 5869, as given by the curve.

*The Bright Line-Spectrum produced by Magnetic Rotation.*

Attention has already been drawn to the remarkable bright line-spectrum which presents itself when the nicol prisms are crossed. This spectrum, which at first could only be seen with the greatest difficulty, was finally obtained of such brilliancy that it could be photographed with the 14-foot concave grating. A good vacuum was found to be the most essential condition. In the earlier work with tubes sealed off from the pump, the pressure due to the liberated hydrogen was probably responsible for the faintness of the lines. The density of the sodium vapour must be just right. If it is too rare, the rotation is insufficient to bring out the lines, if too great the absorption weakens the spectrum. When the conditions are exactly right, the lines are almost as bright and numerous as the metallic lines in the arc. Photographs of the complete spectrum were made on trichromatic plates, made by the Cramer Dry Plate Co. of St. Louis. These plates were found to be sensitive up to the red lithium line ( $\lambda=6705$ ). An exposure of fifteen minutes was sufficient with a small concave grating of about a metre radius. Two of these photographs are reproduced natural size on Plate V. fig. 4.

I have never observed a doubling of any of these lines such as occurs in the case of  $D_1$  and  $D_2$ . So great is the quantity of the light transmitted by the second nicol, that a brilliant orange-coloured image of the crater of the arc appears on the slit of the spectroscope the moment the current is turned into the magnet, notwithstanding the fact that the nicols are crossed.

Inasmuch as it seemed desirable to investigate these lines under higher dispersion and determine their wave-lengths as accurately as possible, the apparatus was transferred to the concave-grating room.

The Ruhmkorff magnet was abandoned at this point, as it was found that an exposure of four or five hours would be necessary, and the magnet became dangerously hot in half an hour, when fed with the necessary current. In its place a very large magnet, built by Professor Rowland for the study of the Zeeman effect, was used. This magnet could be fed with a 110-volt current without resistance, and operated continuously for any necessary length of time.

A steel tube nearly 3 cms. in diameter could be used with this magnet, which increased in no small degree the amount of light available. After a number of failures, a very satisfactory negative was secured with the 14-foot grating showing the rotation spectrum and the absorption spectrum side



by side on the same plate. The plate showed over 60 lines in the blue-green region, some of them so faint that they could scarcely be seen under the microscope of the dividing engine, while others were strong enough to yield prints capable of reproduction.

Another plate was exposed and a comparison iron spectrum recorded by the side of the rotation spectrum. The wave-lengths of the rotatory lines were measured on both plates, using the iron lines and the sodium absorption lines as standards. Some of the latter were redetermined, as it was found that they were much sharper when the sodium was heated in a high vacuum, than when heated in hydrogen, as in the previous work by Dr. Moore and the writer. A print obtained from the plate on which the rotatory spectrum and absorption spectrum were recorded, is shown on Plate V. fig. 5. The absorption spectrum is above. Many lines are, of course, visible on the negative which do not show on the print. The rotatory lines in many cases coincide with the heads of the groups of absorption-lines, though the centre of the line appears to be slightly displaced beyond the head of the group of absorption-lines. The displacement is, however, very slight, not more than half the width of the line. A list of the wave-lengths of all the lines visible on the negative follows. The approximate intensities are represented by numerals, 10 indicating the maximum intensity and 1 the minimum. Lines marked with an interrogation point were so faint as to be doubtful.

## Green Rotation Spectrum.

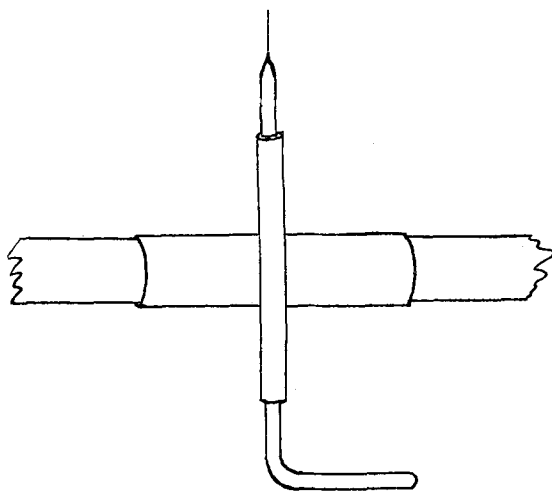
1	5225.34	1	5033.54	2	4839.56
1	5218.49	1	5025.66	9	4837.49
1	5212.02	1	5003.12 broad	2	4819.43
1	5186.70	10	5001.57	1	4814.60
1	5179.71	5	4979.34	1	4812.68
1	5172.98	1	4970.85	3	4810.16
	5171.98	1	4967.10	3	4802.62
1	5169.04	1	4964.39	5	4792.67
	5165.85	9	4962.85	3	4782.89
1	5140.71	1	4958.62	1	4777.00
2	5133.73	1	4933.93	1	4766.94
2	5126.54	3	4932.64	6	4756.69
1	5119.34	2	4924.32	1	4752.04
2	5094.78	4	4912.10	2	4738.51
7	5087.31	1	4904.67	4	4727.52
8	5079.78	1	4903.38	1	4716.90
1	5071.58	1	4896.65	1	4715.63
1	5052.83	1	4894.58	1	4703.78
1	5049.56	1	4892.77	2	4692.54
3	5048.49	2	4883.81	2	4670.30
7	5040.65	2	4865.59		

It is especially noteworthy that many, in fact most, of the strongest absorption-lines are not represented at all in the rotation spectrum. This fact is of fundamental importance, for it indicates that the absorbing mechanism is different in the two cases. Just wherein the difference lies cannot as yet be definitely stated. On either hypothesis as to the cause of the magnetic rotation, the effect will diminish as the mass of the electron increases. The lines of the rotatory spectrum may correspond to the negative electrons of small mass; the other lines in the absorption spectrum which show no rotatory power may be due to positive electrons, or at all events to some form of vibrator having a much larger mass than the negative electrons. The fact that the bright lines in the fluorescence spectrum coincide with the lines of the rotatory spectrum appears in accord with this assumption; for the agitation of the electrons by the light vibrations will be greatest for those having the smallest mass. It will doubtless be possible to speak more definitely in regard to this point, after the fluorescence spectrum has been more carefully studied. The matter will be discussed further in the paper on the fluorescence of the vapour.

The rotation spectrum in the red and orange region is more brilliant than the green-blue one, but it was found impracticable to photograph it with the 14-foot concave grating. Excellent photographs of it were secured with a small concave grating of about a metre radius. One of these, together with the absorption spectrum, is reproduced in fig. 3, Plate V. As the red lines could be *seen* without difficulty with the 14-foot grating, a method was devised for mapping them which may prove useful in other lines of work. A brass rod, on which a short brass tube had been fitted, was fastened into the grating camera just below the groove which held the plate. To the movable tube was soldered a second tube of 2 mm. bore, into which was fitted a short piece of brass rod. This rod carried a needle point. The whole arrangement is shown in fig. 6. A plate of thin glass was carefully smoked over a gas-flame, and then wiped clean with the exception of a narrow strip 4 mms. wide along the centre. This plate was inserted in the camera in place of the photographic plate, and the spectrum brought into such a position that the lines crossed the smoked strip. The positions of the lines could be accurately recorded by bringing the needle-point in contact with the glass exactly on the centre of a line

and then pushing it up across the soot-film. Intensities could be recorded approximately by varying the length of the lines. The sodium lines were also recorded on the plate in the same manner to serve as reference marks. An iron arc spectrum was then photographed together with the sodium lines, and by means of the two plates the wave-lengths of the lines of the red rotation spectrum could be determined. The

Fig. 6.



smoked plate was fixed by flowing it with a very dilute solution of collodion in ether. A print from the plate mounted "in register," with a photograph of the absorption spectrum, is shown in fig. 6, Plate V. Owing to the inequality of the absorption in the different parts of the spectrum above the D lines, it was necessary to take photographs, at three different vapour densities, to represent the entire set of lines. The prints have been carefully registered in mounting. The small percentage of lines which exercise rotatory power is very marked in this case. The position of the D lines is indicated on the left-hand end of the plate, the red being to the right. The wave-lengths of the lines in the red rotation spectrum are given in the following table:—

## Red Rotation Spectrum.

8	6005.26	3	6218.94	2	6427.45
8	6019.22	5	6230.59	7	6434.23
4	6023.45	7	6235.96	2	6435.05
5	6027.47	3	6240.19	3	6438.30
7	6031.79	5	6252.18	3	6441.62
4	6060.25	7	6255.73	3	6445.24
6	6063.91	2	6260.32	10	6449.86
7	6067.47	10	6262.55	1	6470.58
2	6075.42	6	6272.78	10	6481.89
10	6107.73	3	6283.40	10	6490.36
9	6108.25	3	6283.84	7	6501.45
4	6113.59	10	6314.14	3	6515.69
2	6113.81	6	6317.09	4	6545.91
10	6125.67	10	6323.81	3	6555.71
10	6139.17	2	6358.65	5	6556.66
8	6162.74	10	6374.11	7	6579.55
2	6166.10	4	6379.24	8	6609.80
6	6172.32	10	6386.50	7	6623.96
4	6179.92	6	6399.79	3	6676.88
8	6183.93	3	6405.84	4	6692.60
9	6196.93	8	6419.69	4	6745.61
8	6216.56	3	6426.85	5	6761.19

The fact that the rotatory effects of the vapour only manifest themselves in a vacuum is of fundamental importance. The exact nature of the changes which occur when an inert gas is admitted have not as yet been determined. The fact that no trace of the red or green rotation spectrum could be seen when the vapour was formed in an atmosphere of hydrogen at atmospheric pressure, and that only a very slight restoration of light was visible at the D lines, led me to infer that the rotatory power had been destroyed. On experimenting with helium light, however, it was found that the rotation measured in degrees was the same after the admission of the hydrogen as before, the intensity of the transmitted light being however very much less. On this account it seems probable that the effect of the chemically inert gas is to modify the absorbing power of the gas. It has been found that the presence of hydrogen or nitrogen interferes in a very marked degree with the fluorescence of the vapour.

The same thing is true in the case of iodine vapour, which has been found to possess a very great rotatory power for green light, when the vapour is formed in an exhausted tube. A small bulb, containing a few crystals of iodine, is exhausted and sealed off from the pump. On placing it between the poles of the magnet between crossed nicols, a most beautiful emerald-green light is restored the moment the current is turned into the coils. The spectrum of this light has been photographed and observed visually. It resembles the absorption spectrum so closely as to lead to the belief that the narrow black lines in it are produced by absorption. Little

or no rotatory power is exhibited for red or yellow light, though this portion of the spectrum is filled with fine absorption-lines, and the blue region is also wanting in the rotation spectrum, though the absorption is strongest at this point. These effects are at present under investigation, and will be reported in a subsequent paper.

The investigation reported in the present paper is one of a series made possible through substantial aid received from the Rumford Fund, two grants having been made by the American Academy for a study of the optical properties of sodium vapour.

Much assistance has also been rendered by Mr. A. H. Pfund, for whose services I am indebted to the Carnegie Institute.

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L. *The Scintillations produced by Radium.*  
By Prof. R. W. Wood\*.

[Plate VI.]

THE scintillations of phosphorescent zinc sulphide, when subjected to the bombardment of the radium corpuscles, does not appear to have been satisfactorily explained up to the present time. Crookes regarded each flash as due to the impact of a positive electron or alpha particle, while Becquerel regards the production of light as a secondary effect resulting from cleavages of the crystals brought about by the action of the rays. Neither hypothesis, as it stands, seems quite convincing. I do not know whether any estimate has ever been made of the actual number of alpha particles emitted in unit time from a given amount of radium, but it certainly seems as if the number must far surpass the number of flashes of light as seen in the spintharoscope. As to the second hypothesis, the only argument advanced in support of it appears to be the circumstance that zinc sulphide crystals when rubbed or crushed show similar flashes of light. This argument is not very convincing, for it amounts to saying that similar effects must result from similar causes. On the other hand, the cleavage hypothesis removes the trouble regarding the number of flashes as compared with the probable number of electrons, as well as the difficulty in the conception of an appreciable flash being produced by a single electron. The experiments described in this paper were completed just a year ago, and were undertaken in the hope of settling the question of the cause of the flash. As they did not lead to sufficiently definite conclusions to satisfy me,

\* Communicated by the Author.

FIG. 1.

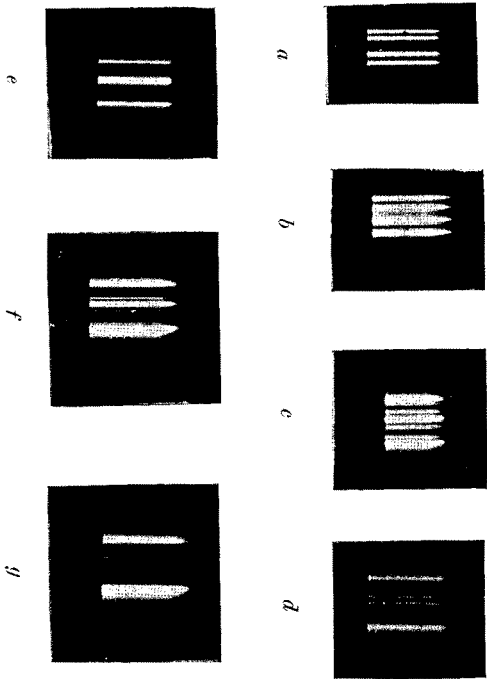


FIG. 2.

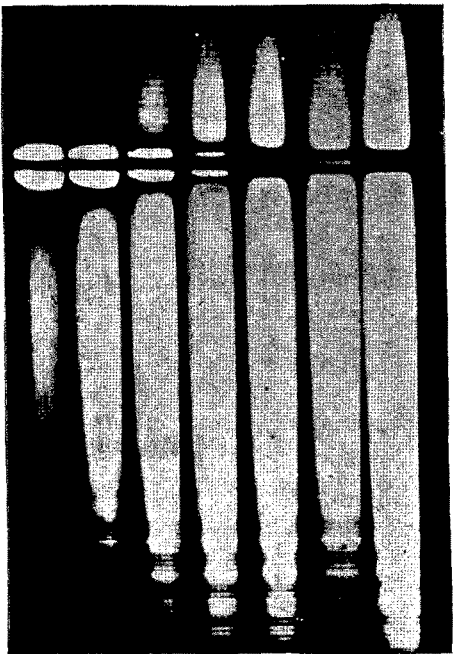


FIG. 3.

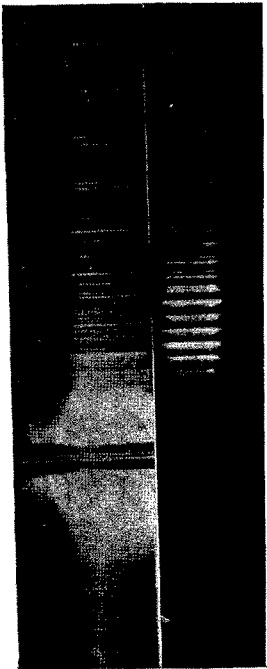
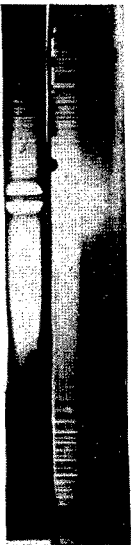
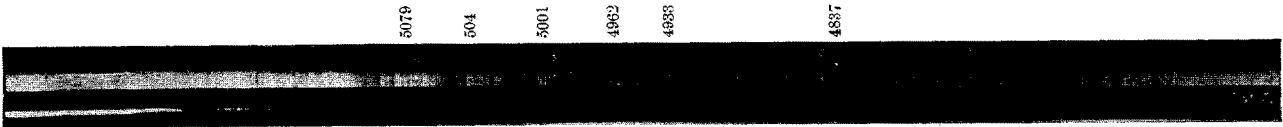


FIG. 4.



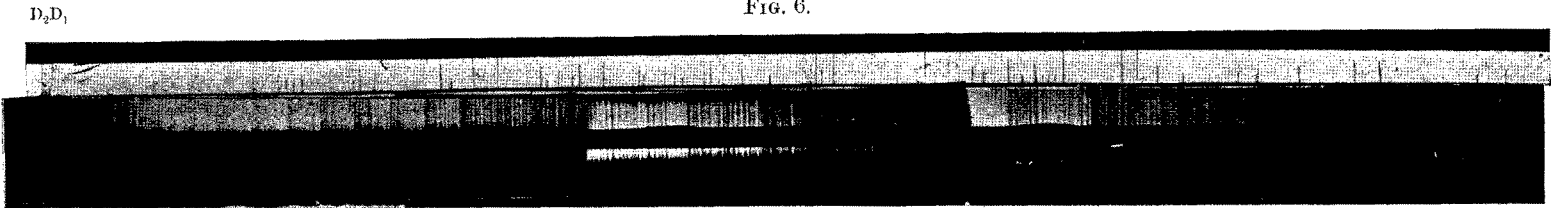
Red. Green. Blue.

FIG. 5.



Absorption.  
Mag. Rotation

FIG. 6.



Mag. Rotation.  
Absorption.