# Magneto-Optic Rotation by Condenser Discharge[1]

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The rotation of the plane of polarization of light produced by a condenser discharge across a spark gap has been measured when the condenser discharges through a coil surrounding various media of comparatively high Verdet constants. The set-up is similar to that used by Dr. Fred Allison except that a Lippich double field polarimeter replaces the crossed Nicols. The rotations have also been computed from the constants of the circuit, and curves show the agreement between calculated and experimental rotations to be good. Conclusions are drawn in regard to the relation of these measurements to the experiments of Allison.

THE recent experiments of Dr. Fred Allison and his collaborators[2] have attracted wide attention. The experiments here described were performed in an effort to throw more light on the physical phenomena involved in Allison's *Magneto-optic Method of Chemical Analysis*. The results to date appear to give some insight into the nature of the rotations involved. No attempt has been made to check the results reported by Allison, and except for some preliminary work in which definite "minima" were obtained for the "zero" reading of Allison's scale ($CS_2$ in both cells), the Nicol prisms were discarded in favor of a Lippich polarimeter in order that the net rotations caused by the alternating field might be observed in both magnitude and direction.

## Description of Apparatus

Except for minor changes and the substitution of the half-shade polarimeter for the crossed Nicols the set-up is similar to that described by Allison.[2] Fig. 1 is a schematic diagram of connections. $T$ is a Thordarson resonant spark transformer rated at 1 k.v.a., 25,000 volts maximum output at 110 volts primary. Current from the high side of this transformer is rectified by the G. E. Type KP-2 kenetron and charges the condenser $C$ each sixtieth of a second. The condenser upon acquiring sufficient potential to break down the spark gap $S$, discharges through the coil $L$ or $L'$ and the resistance $R$ and the inductance $L''$. Light from the spark passes through the filter $F$ and into the Lippich half-shade polarizer $N_1N_2$, then traverses a path of about 10 cm in a material surrounded by the coil $L$, and thence to the analyzer $N_3$. During such time as a current flows through the coil $L$ a magnetic field is impressed on the material inside the coil and rotation of the plane of polarization of the light beam results (Faraday Effect). The average or net rotation may be measured

[1] F. G. Slack and W. M. Breazeale, Phys. Rev. **40**, 1052A (1932).

[2] Fred Allison, Phys. Rev. **30**, 66 (1927). Fred Allison and E. J. Murphy, J.A.C.S. **52**, 3796 (1930). Fred Allison, Ind. and Eng. Chem. **4**, 9 (1932)' Fred Allison, Edna R. Bishop, Anna L. Sommer and J. H. Christensen, J.A.C.S. **54**, 613 (1932). Fred Allison, Edna R. Bishop and Anna L. Sommer, J.A.C.S. **54**, 616 (1932). Fred Allison, J. H. Christensen and George V. Waldo, Phys. Rev. **40**, 1052A (1932).

by means of the analyzing Nicol $N_3$. $L'$ is a dummy coil provided to offer a path of equal impedance when $L$ is cut out of the circuit for the purpose of taking zero settings on the polarimeter. $L''$ is ordinarily out of the circuit but is used when it is desired to obtain a variation in impedance by induc-

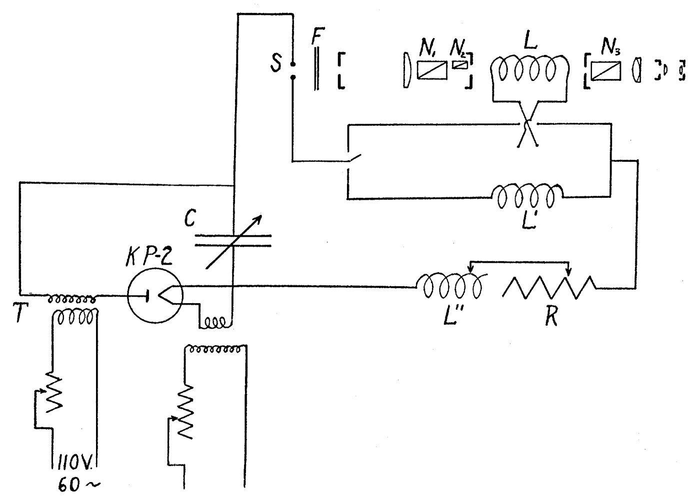


Fig. 1. Diagram of apparatus.

tance change. $R$ is used to vary the resistance of the oscillating circuit and is also normally out of the circuit.

Occasionally it was desired to measure net rotations due to two coils operating in series or in parallel and with their fields acting on separate specimens to produce opposing or aiding rotations. Fig. 2 is a diagram of the par-

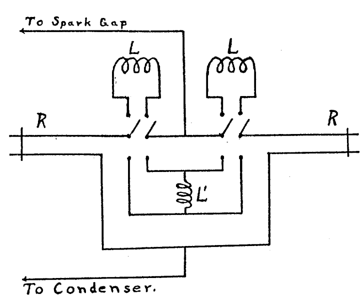


Fig. 2. Connections for two coils.

allel connections for this set-up. Two resistance trolleys $R$ are then used, one in series with each coil. The rest of the apparatus is the same as shown in Fig. 1.

Some of the constants of the apparatus are as follows: For Fig. 1 the coils $L$ and $L'$ have 59 turns of No. 16 D.C.C. copper wire, are 12 cm long by 4.5 cm in diameter and measure 0.045 millihenries. The inductance coil $L''$ is wound with 325 turns of No. 18 D.C.C. wire and measures 0.66 mh. It is tapped at several points. The condenser $C$ consists of 20 plates of glass 0.3 cm thick covered with 25 cm squares of tin foil, giving a total capacity of 0.022 mfd. The capacity is varied by removal of the condenser plates. The resistance $R$ consists of two straight wires stretched overhead and about 20 cm apart. The resistance is varied by a trolley which slides along on these wires. The wires are No. 25 chromel "$C$" (6.85 $\omega$/meter) and have a total length of about 16 meters, though somewhat longer ones have been used in obtaining some of the results reported herein. The material under test when a liquid ($CS_2$ normally) is contained in a glass cell 11.2 cm long and 2.5 cm in diameter, with thin cover glass ends sealed on with water glass. This cell is centered inside coil $L$. The spark gap, horizontally placed, has $\frac{1}{8}$ inch magnesium electrodes spaced from 0.25 to 0.30 cm apart. The filter $F$ consists of Jena glass $BG_4$ plus $GG_3$ (each 2 mm) filters. These transmit principally the magnesium spark line 4481A and a small amount of the lines at 4703, 4391, and 3835A. Investigation by more complete filtering has shown that these faint lines do not affect the rotations. The polarimeter is a Schmidt and Haensch instrument with the Lippich half-shade polarizer giving a double field. The vernier may be read to 0.01 degree.

When the set-up in Fig. 2 is used it is necessary, due to the construction of the polarimeter, to use smaller coils and cells. In this case the active and dummy coils had 37 turns of No. 16 wire, measured 0.025 mh, and were 8 cm long by 4.5 cm in diameter. The glass cells used with these coils were 8 cm long and 2.5 cm in diameter. The rest of the apparatus was not changed.

In making all readings the procedure was first to make a zero setting on the polarimeter analyzer with the dummy coil $L'$ in the circuit, then with coil $L$ thrown into the circuit the oscillatory discharge of the condenser passes through the coil and produces a magnetic field which acts on the material in the cell. The plane of polarization of the light is rotated in accord with this field and a brightening of both polarimeter fields is observed, the brightening of one field being more pronounced. The analyzer is set to bring the two fields to equal brightness and the net rotation read from the scale. As recorded under "Results" such observations have been made for various circuit constants. The spark gap length and transformer primary voltage have been held approximately constant for the data given, the latter being about 60 volts, controlled by a series rheostat.

## Theory

Oscillations will normally exist in the discharge circuit, the frequency and damping depending on the constants of the circuit. Normally the oscillations are damped out after a few cycles. Examination of the spark in a rotating mirror, mounted on the shaft of a synchronous motor, shows that there are one or more trains of waves per cycle, the number depending on the primary voltage, the spark gap, and (to a lesser extent) on the circuit constants. Experiment shows the number of trains per cycle to have little or no effect on the rotations observed.

A relationship between the circuit constants and the rotations was derived as follows: First, the current-time curves for the oscillating circuit were plotted using the equation for damped sinusoidal oscillations;

$$i = [Ee^{-Rt/2L}/L(1/LC - R^2/4L^2)^{1/2}] \sin (1/LC - R^2/4L^2)^{1/2}t \qquad (1)$$

where $i$ is the current at any time $t$, and $E$ is the initial voltage to which the condenser is charged. This assumes exponential damping which assumption was verified by cathode-ray oscilloscope observations.

The rotation was found to be proportional to the difference between the first and second current peaks (positive and negative, respectively). Fig. 3 shows the rotations due to the first peak, $i_1$ (positive), to the second peak $i_2$ (negative), and the net rotation, proportional to $i_1 - i_2$, obtained by subtracting the lower from the upper curve as the resistance $R$ is varied. In calculating these curves the peak currents were computed assuming $E = 8000$ volts. A rheostat in the transformer primary reduced the secondary voltage to about this value, although the nature of the spark gap controls the break down potential.

The maximum value of the magnetic field is given by:

$$H = 0.4\pi ni \qquad (2)$$

where $n$ = No. turns per cm of the coil and i = peak current in amperes from Eq. (1). The rotation in degrees is equal to the field strength multiplied by Verdet's constant $V$ and by the length of the cell, $l$: $\Theta = HVl = 0.4\pi nilV$.

Above about 90 ω the circuit ceases to oscillate and hence the second peak does not exist. Here in calculating the currents Eq. (1) no longer holds and the following is used:

$$i = \frac{EC}{2}\left\{\left[1 + \frac{R/2L}{(R^2/4L^2 - 1/LC)^{1/2}}\right]\left[-\frac{R}{2L} + \left(\frac{R^2}{4L^2} - \frac{1}{LC}\right)^{1/2}\right]e^{[-R/2L+(R^2/4L^2-1/LC)^{1/2}]t} + \left[1 - \frac{R/2L}{(R^2/4L^2 - 1/LC)^{1/2}}\right]\left[-\frac{R}{2L} - \left(\frac{R^2}{4L^2} - \frac{1}{LC}\right)^{1/2}\right]e^{[-R/2L-(R^2/4L^2-1/LC)^{1/2}]t}\right\}.$$

Since, in order to obtain agreement between calculated and observed curves of rotations as the resistance $R$ is varied, it is necessary to shift the calculated curve approximately 2.5ω along the resistance axis, this value has been taken in all calculations as the resistance of the spark gap and circuit exclusive of the added resistance $R$.

The mechanical process causing the rotations appears to be as follows: Suppose the first half cycle of the current wave causes a clockwise rotation which causes a maximum brightness of the right-hand polarimeter field proportional to the first current peak. The second peak causes a counterclockwise rotation which brightens the left-hand field, but as the second peak is less than the first the increase in brightness of the left field is not so great as that of the right-hand field. Persistence of vision causes subsequent changes of the field due to the rest of the wave train to pass unnoticed. This cycle repeats itself sixty times a second. Hence the first two peak currents determine the character of the observed fields. The net rotation is measured by setting the analyzer to bring the two fields to equal brightness.

## Results

Curves similar to the solid curve of Fig. 3 were computed for various circuit constants and compared with the experimentally-determined points. The experimental points are plotted as circles and Fig. 3 (curve 3) shows the agreement between calculated and measured rotations as $R$ is varied. Fig. 4 shows the rotations as calculated (smooth curve) and as measured (plotted points) as a function of capacity change, $R$ and $L$ being held constant. Curves

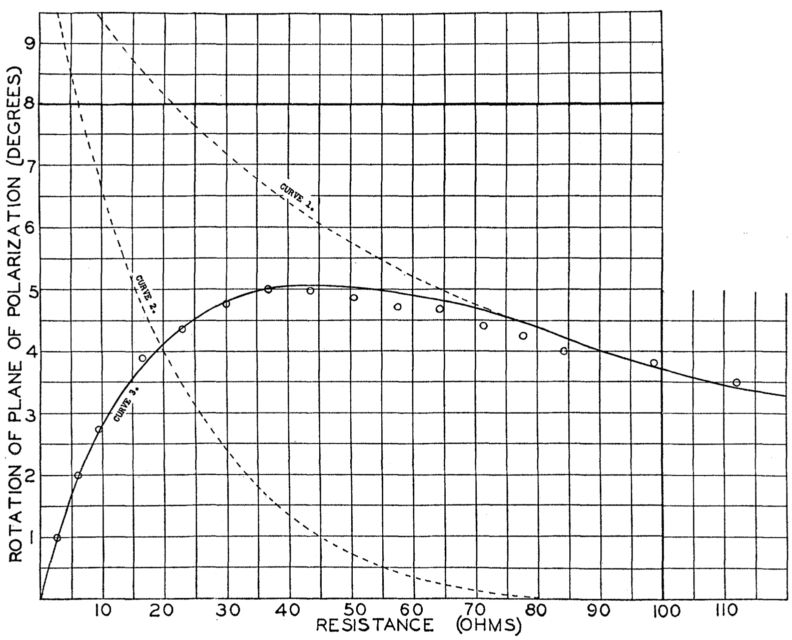


Fig. 3. Rotation-resistance curve. Curves 1 and 2, respectively, are calculated rotations due to first and second current peaks. Smooth curve 3 is difference between curve 1 and curve 2. 00000 experimental points. ($L=0.045$ mh; $C=0.022$ mfd.)

are shown for two different values of trolley resistance $R$, *viz.*, $R=0$ and $R=7.5\ \omega$. Fig. 5 shows the relations for these same values of $R$ when $C$ is held constant and $L$ varied. The disagreement for the larger values of $L$ in the curve for $R=0$ is probably due to a slight change in resistance of the spark gap at lower frequencies. It was necessary to correct for skin effect in the coil to obtain agreement at the high-frequency end of the curve. The agreement in the curve for $R=7.5\ \omega$ is better since small changes in gap resistance do not have so much effect with a larger value of $R$.

As may be seen from the curves the experimental points show very fair agreement with the computed smooth curves. This indicates that the assumption that the rotation is proportional to the difference between the first two peaks (positive and negative) is valid.

When two different materials are used in the two cells of Fig. 2 with opposite field directions cancellation of the rotation does not occur with equal

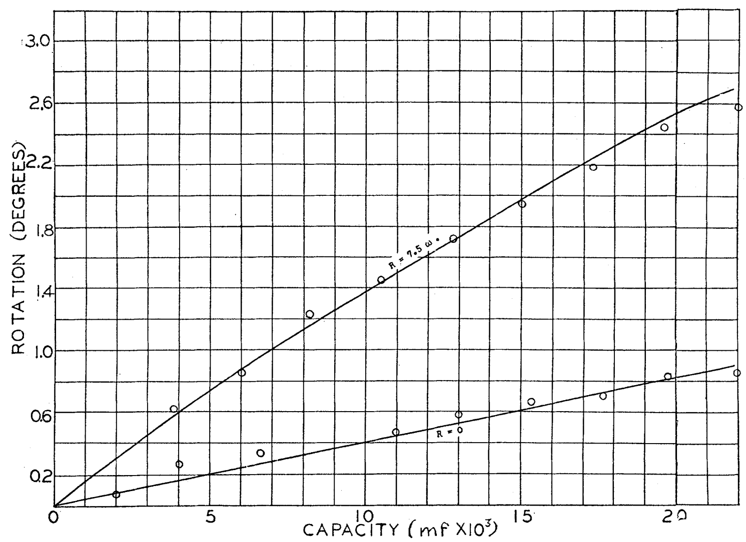


Fig. 4. Rotation-capacity curves. $L=0.045$ mh; $R=7.5\ \omega$ and $R=0\omega$. Smooth curves calculated.

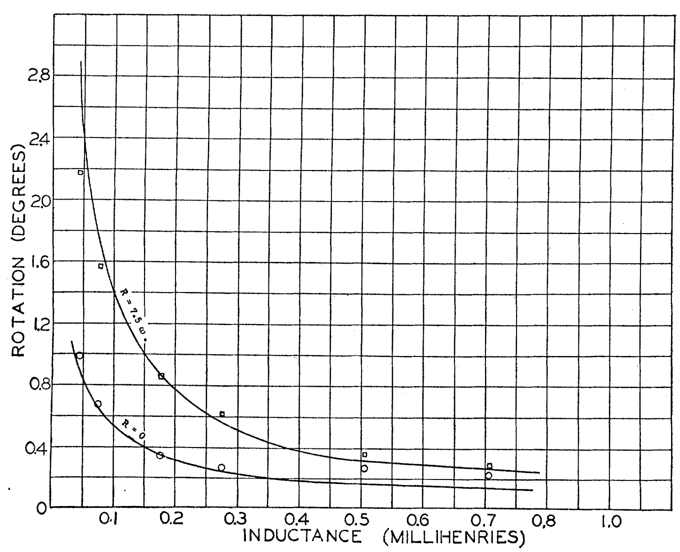


Fig. 5. Rotation-inductance curves. $C=0.022$ mfd; $R=7.5\omega$ and $R=0\omega$. Smooth curves calculated.

resistances in each trolley. However, for any setting of one trolley a setting of the other may be found for which the net rotation is zero. This setting is independent of the direction of the fields of the two coils. It is different for different materials compared to the same standard. It is probable that calculation of the rotations as above, considering the parallel circuits and proper Verdet constants, would account for these readings and further work on this is contemplated.

No rotations could be observed when the light source was constant except when a synchronous rotating disk cut off the light while no discharge current was passing through the coil. Apparently the rotated part of the light was too small to be observable except in this case.

The cause of the asymmetrical rotations reported previously[1] has been found due to the unequal intensity of the two light beams after passage through the prisms of the Lippich polarizer. This difference does not affect readings when the rotation is constant but calculations show that it produces a difference of the order of magnitude of that found in the case of the oscillating rotations.[3] The curves shown herein have not been corrected for this error since it would not appreciably affect the agreement between calculated and measured rotations.

## Conclusion

The results of these experiments indicate that a polarimeter may be used to measure the magneto-optic rotations produced by a condenser discharge when the spark gap of the discharge circuit is used as light source. These rotations may also be calculated from the constants of the circuit so that fair agreement results.

In the case of different materials used in two cells zero readings were obtained by proper adjustment of trolley resistance. These readings could not be correlated with the time lags given by Allison[2] though this was hardly expected considering the high-resistance trolley here used. Change in length of a low-resistance trolley had no observable effect on the rotations measured. This leads to the conclusion that the polarimeter, in spite of its ability to measure the magnitude and direction of the rotations, is not so sensitive to time effects (change in length of wire path) as the crossed Nicols. With the Nicols any rotation of the plane of polarization of the light produces the same effect, that is a brightening of the single field. If two opposing fields are used it is thus necessary that they cancel each other at every instant in order to produce a minimum of light. For this to be the case the resultant time constants of the parallel paths of the discharge currents would need to be identical. These include the dielectric effect, Faraday effect time lag, Verdet constant, etc., for the materials. This would require the very sharp accurate settings for minima obtained by Allison, and as found by him would depend upon the properties of the material in the cells.

In conclusion, the authors wish to express thanks to Dr. Fred Allison for his kindness in demonstrating his apparatus upon several occasions and for supplying the details of his circuits. Thanks are also due to Mr. Wilson W. Woodcock, Jr. for assistance in the early stages of this work.

[3] Thanks are due to Professor E. O. Lawrence and members of the Physics Department of the University of California for opportunity to check this work with a triple-field polarimeter resulting in the discovery of this difficulty. Especial thanks are due Dr. Harold Washburn for his assistance and suggestions.