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Gustaf W. Elmen

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I.—*Electric Double-Refraction in Carbon Disulphide at Low Potentials*

BY GUSTAF W. ELMÉN

When light polarized at an angle of forty-five degrees to the lines of force is passed through certain dielectrics, between two parallel electrodes, they become double-refracting. The difference of phase, δ , between the two components of light at right angles and parallel to the lines of force, as represented by Kerr and verified by later investigators, is

$$(1) \quad \delta = \pm \frac{BP^2l}{a^2}$$

where B is the electro-optic constant, depending on the dielectric, l the length, and a the distance between the plate electrodes in centimeters, and P the difference of potential between the electrodes in C.G.S. units.

From data obtained in this investigation, there seems to be a decided variation from the above law for low potentials. As the potential was decreased from about 200 volts per millimeter of distance between the electrodes, the decrease of δ was in a smaller ratio than the decrease of P^2 .

In determining the electro-optic constant, either a high potential or a sensitive system of measuring δ must be used. In the

investigations of Kerr,¹ Quincke,² Lemoine,³ and Schmidt,⁴ high potentials were employed. The difference of phase was measured by means of a Babinet's compensator, and the potential, supplied either by a static machine or an induction coil, by means of an electrometer. The difference in the values of B obtained by different observers and also of the values obtained by the same observer, as in the case of CS_2 , where the values of Quincke vary by one part in five, Schmidt points out as probably due to the difficulty in measuring high potentials with a sufficient degree of accuracy. To eliminate this error he used two sets of electrodes on the same axis of rotation as the beam of light and set at right angles, so that the effect of one set was compensated by that of the other. This, however, gives only relative values, and some other method must be depended upon for absolute measurements.

A sensitive system of determining the difference of phase has been used in this investigation. In place of the Babinet's compensator, an elliptic half-shade polarizing system⁵ was employed. With this system, as used in this particular problem, values of δ equal to $.0001\lambda$ could be observed. In measurements taken the lowest value recorded is $.00025\lambda$. This brought the potential that could be used down to less than 100 volts per millimeter of distance between electrodes of 47 cm. length. For CS_2 with the same length of electrodes the smallest value recorded by Quincke is over 3,000 volts per millimeter of distance. The potential was supplied by a storage battery of about 1,400 volts, and as the smallest potential used was less than 200 volts, a range of seven times this voltage was at the writer's disposal. The potential was measured by means of a voltmeter which had been calibrated so that the possible errors for the lowest potentials were less than 1 per cent.

The half shade system consisted of two thin mica sections. One, the "sensitive strip" S (fig. 1), placed next to the polarizing

¹ J. G. Kerr, *Phil. Mag.* (4), 50, p. 446, 1875; (5), 8, pp. 85 and 229, 1879; (5), 9, p. 157, 1880, and (5), 13, pp. 153 and 248, 1882.

² G. Quincke, *Wied. Ann.*, 10, p. 729, 1883.

³ J. Lemoine, *Compt. Rend.*, 122, p. 835, 1896.

⁴ W. Schmidt, *Ann. d. Physik.*, 7, p. 142, 1902.

⁵ D. B. Brace, *Phys. Rev.*, vol. 18, p. 70, vol. 19, p. 218, 1904.

Nicol N , covered half of the field and was placed with its principal axis at an azimuth of forty-five degrees to the plane of vibration of the polarized light. The edge of this strip was parallel to the faces of the electrodes, thus making the vanishing line parallel to the greatest dimension of the field of view. When electrodes of greatest length (127 cm.) were used, this strip was placed between the compensator and the analyzer, as the distance was too long to give good definition. The second section, the "compensator" C (fig. 1), was placed next to the analyzing Nicol N' , and covered the whole field. This section was mounted on a circle with a vernier that could be read to minutes. The position of the strip was changed several times, so that readings were obtained from different parts of the circle and thus eliminated any possible instrumental errors.

A forty-eight candle power Nernst "glower," one centimeter long and one millimeter in diameter, was first used as light-source L (fig. 1). Later, observations were taken with sunlight passed through a spectroscope and observations were taken for red ($620 \mu\mu$), green ($540 \mu\mu$), and blue ($490 \mu\mu$) light. By means of a condensing lens A (fig. 1) the light was passed through the polarizing Nicol, the "sensitive strip," the liquid between the plate electrodes E (fig. 1), through the compensator, analyzer, and thence to a focus O within the observer's eye. When sunlight was used the light was strong enough to allow the use of a short focus telescope with small magnifying power placed next to the analyzer. One of the electrodes was grounded and the other connected to the storage battery. V is a voltmeter, connected across the electrodes.

A thermometer was placed in the liquid and read before and after observations were taken. The measurements were taken at room temperature.

The order of the compensator was found by comparing it with a quarter-wave plate. The compensator was set for a match, and the quarter-wave plate placed in the field so that it produced no effect. The compensator was now rotated through an angle of five or ten degrees and the quarter-wave plate rotated until the intensities of the two halves of the field were again the same. Then,¹ if N' , θ' and N , θ are the orders and the degrees respectively through which the two plates are rotated

$$N'\theta = N\theta'$$

$$(4) \quad \text{or} \quad N = \frac{N'\theta}{\theta'}.$$

Having thus found the order of the "compensator" for a certain wave-length, its order for any other wave-length was found by means of the curve of differential dispersion of mica.²

The wave-length for which the quarter-wave plate produced a retardation of $\lambda/4$ was determined in the following manner: A beam of sunlight polarized at forty-five degrees to the principal axis of the plate was passed twice through the plate and then through a second Nicol with its plane parallel to the polarizer. The beam was analyzed by means of a spectroscope. The spectrum contained a black band corresponding to a retardation of half a wave-length. The plate used was found to correspond to

¹ D. B. Brace, *Phys. Rev.*, vol. 18, p. 73, 1904.

² E. J. Rendtorff, *Phil. Mag.*, May, 1901, p. 545.

$\lambda = 560 \mu\mu$. In fig. 2, A and A' are the two Nicols, B the quarter-wave plate, C a mirror silvered on the first surface, and S the spectroscope.

In taking observations, "the compensator" was set for a match, and then the plate electrodes charged and the "compensator" rotated until a match was again obtained. Then if θ is the angle through which the "compensator" was turned, N the order of the "compensator"

$$(2) \quad \delta = \frac{4N\theta}{180} = \frac{N\theta}{45} \text{ when } \theta \text{ is small}$$

$$\text{and from (1)} \quad \frac{N\theta}{45} = \pm \frac{BP^2l}{a^2} \quad (3)$$

For the same potential the settings of the mica "compensator" were approximately the same for all the colors used, showing that for the small differences of phase produced, the electric differential double refraction of CS_2 is approximately the same as the differential double refraction of mica.

Two lengths of plate electrodes were used. The first made of nickel-plated brass strips 47 cm. long and 1.5 cm. wide. They were connected to the wires leading to the ground and the battery by two rods, screwed into the plates, and taken out through glass tubes 5 cm. long, welded on the sides of the containing tube. Small glass strips were placed between them at the edges at intervals and held in position by fish glue. The electrodes were placed in a tube 2.5 cm. in diameter and extended 1 cm. from each end. On the ends of the tube were fastened squares of glass in which holes 1 cm. in diameter had been bored, and then covered with thin cover-glasses. These cover-glasses were tested for double-refraction after they were glued on, for it happened in several cases that the drying of the glue produced enough strain in the glass to be observed.

It was found quite difficult to obtain perfectly parallel metal strips for the longer electrodes, viz., 127 cm., so that plate glass strips were used instead. A thick coating of silver was deposited on one side of each plate, and the silvering carried over at the

opposite ends, where contact was made by a couple of brass clamps which also served to hold the plates in position. Copper wires were soldered to these clamps and taken out through holes bored in the end plates of the tube. The electrodes were separated in the same way as before. They rested without support in the tube containing the liquid. Fig. 3 shows a vertical and an end view of the electrodes. The formation of A_2S when the electrodes were in contact with CS_2 was slow, and they could be used for some time without resilvering.

Fig. 3

The liquid used was CS_2 . The ordinary commercial CS_2 was found to have a great number of small particles in it which would vibrate between the electrodes when the charge was put on, so that it was found very difficult to maintain a high difference of potential between them. It was therefore found necessary to clarify the liquid by filtering it through a porous cup which was fastened into the neck of a glass flask by means of plaster of Paris. Immediately below the neck was a hole in the flask into which a glass tube was cemented. This tube was connected to a vacuum pump, and thus the liquid was forced through the porous cup. The filtering of the CS_2 did not, however, seem to appreciably change the electro-optic constant of the liquid. Table I gives the manner in which each recorded value of B in the following tables was obtained. For voltages below 200 volts per millimeter distance between electrodes, each value of B is the mean of twenty observations instead of nine. Tables II and III give mean values obtained with the brass electrodes with $a=.2545$ cm. and $a=.184$ cm. Table IV gives values obtained with the silvered electrodes. The values between the three sets agree fairly well. Table V gives values obtained for different colors. For the same value of P for different wave-lengths, θ remains approximately the same, and in calculating the value of B it was only necessary to multiply the value of B , obtained from

equation (3), by the ratio of the order of the "compensator" $\left[N = \frac{1}{43.8} \right]$ determined by means of the quarter-wave plate for that particular value of λ , which, in this case, was $560 \mu\mu$, while the order for any other colors used was obtained by interpolating from the curve obtained by Rendtorff.

In fig. 4 the values of $B \times 10^{-7}$ are plotted as ordinates and $\frac{P}{a \times 10}$ as abscissae. The curve is approximately a straight line until about 200 volts per millimeter of distance, when it turns and seems to become almost asymptotic to the ordinates. On obtaining these low values the errors of observation were of course large, owing to the smallness of the effect, and at first it was thought that the large deviation from the law was due to some systematic error. To eliminate such possible errors, the apparatus was taken down and remounted under different con-

ditions. This, however, did not give any difference in values obtained for B .¹

There is a great similarity between B , the constant of electric polarization in CS_2 , as determined by means of double-refraction, and μ , the permeability, as determined by means of magnetic induction, and this suggests that possibly the double-refraction in liquids under electric strain is due to a state of polarization analogous in nature to that which takes place in a magnetic substance when in a state of polarization.

TABLE I
 $l=47$ cm. $a=.2545$ cm.

TEMP.	VOLTS	READ. OF COMP. WITH POT. ON.	READ OF COMP. WITH POT. OFF.	$B \times 10^{-7}$
19°C	1360	354°17'	6°13'	
		354°38'	6°18'	
		354°15'	6° 5'	
		354°32'	6°16'	
		354°16'	6°	
		354°19'	5°54'	
20°C		354°15'	5°58'	
		354°17'	5°51'	
		354°24'	6° 6'	
	Mean.	354°22.5'	6° 4.5'	
Rotation = 11°42'				4.05

¹It might be suggested that the readings of the voltmeter do not give the true drop in potential within the liquid owing to a possible polarization at the electrodes, analogous to that within electrolytes, which, at the low potentials used, might make itself evident. This could be determined by varying the distance of the electrodes and comparing the observations for the same drop of potential. This conclusion does not seem to be borne out by the data in tables 2 and 3 where $a=.2545$ cm. and .184 cm. respectively.

TABLE II

 $l=47$ cm. $\lambda=560 \mu\mu$ $a=.2545$ cm.

TEMP.	VOLTS	0°	$B \times 10^{-7}$
23.5°C	1389	11.66°	3.88
19.5°	1360	11.68°	4.05
18.5°	1345	11.6°	4.11
20°	1043	6.77°	3.94
19°	995	6.28°	4.07
20°	880	4.74°	3.94
21°	720	3.16°	3.92
22°	649	2.58°	3.93
19°	556	2.16°	4.53
22°	531	1.8°	4.09
20°	357	1.1°	5.53
19°	324	.74°	4.52
20°	324	.84°	5.13
19.5°	283	.76°	6.04
24°	252	.65°	6.77
22°	252	.68°	6.56
22°	247	.62°	6.51
19.5°	244	.77°	8.29
19°	243	.53°	5.88

TABLE III

 $l=47$ cm. $\lambda=560 \mu\mu$ $a=.184$ cm.

TEMP.	VOLTS	0°	$B \times 10^{-7}$
23°C	876	8.7°	3.78
25°	861	8.24°	3.71
23°	418	2°	3.82
25°	242	.74°	4.22
23°	193	.58°	5.19
25°	191	.53°	4.56
25°	191	.46°	4.23

TABLE IV
 $l=127$ cm. $\lambda=560\mu\mu$ $a=.656$ cm.

TEMP.	VOLTS	0°	$B \times 10^{-7}$
19°C	1364	4.84°	4.08
20°	1355	4.88°	4.17
20°	1334	4.38°	3.85
20.5°	1328	4.27°	3.84
18°	1314	4.53°	4.11
20°	1017	2.8°	4.25
20°	1017	2.87°	4.35
19.5°	1040	2.9°	4.17

TABLE V
 $l=47$ cm. $a=.184$ cm.

λ in $\mu\mu$	TEMPERATURE	VOLTS	0°	$B \times 10^{-7}$
620	23°	807	7.6°	3.00
	23°	525	3.1°	2.93
	23°	240	.73°	3.17
	23°	190	.6°	4.32
540	23°	997	11.75°	4.13
	23°	841	8.5°	4.16
	23°	543	3.4°	4.20
	23°	242	.78°	4.88
490	23°	191	.6°	5.96
	23°	955	11.5°	5.51
	23°	670	5.38	5.64
	26°	387	1.67	5.23
	26°	250	.66°	5.33
	26°	190	.5°	6.39