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# DETERMINATION OF THE MAGNETO-OPTIC ANOMALY OF SOME GLASSES

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## 1. INTRODUCTION

DARWIN AND WATSON (1927) have shown that in many substances the magnitude of the Faraday effect is expressible by a formula of the Becquerel type, *viz.*,

$$V = \gamma \lambda \frac{dn}{d\lambda} e/2\, mc,^2$$

where V is Verdet's constant, $e$ and $m$ are the electronic charge and mass respectively, $c$ is the velocity of light, $\lambda$ is the wavelength of light and $n$ the refractive index of the subtstance. $\gamma$ is a factor, called the magneto-optic anomaly, which is constant throughout the visible and the ultraviolet regions of the spectrum provided the contribution to the dispersive power made by the infra-red absorption bands is eliminated from the formula. No reference to the data for glasses appears in the paper of Darwin and Watson. The present investigation was undertaken to fill this gap in the literature and to find whether the Becquerel formula is valid for glasses and if so to ascertain how the magneto-optic anomaly depends on the composition of the glass. Most of our knowledge of the magneto-optic behaviour of glasses is due to du Bois (1894) and to Ingersol (1917). The former measured Verdet's constant for the sodium line $\lambda$ 5893 in nine glasses, while the latter studied the dependence of the constant on the wavelength in five glasses. The present paper records the values of Verdet's constant determined for $\lambda$ 5893, $\lambda$ 5461 and $\lambda$ 4358 with 18 optical glasses made by the firm of Schott at Jena as well as of their dispersive powers for a test of the validity of the Becquerel formula. The results disclose the existence of interesting relationships between the composition and the magneto-optic anomaly.

## 2. MATERIALS AND METHODS

The specimens studied formed a set of eighteen optical glasses presented to Prof. Sir C. V. Raman by Messrs. Schott & Co., Jena, and had the form of rectangular blocks 3 × 3 × 2 cm. having all but two of the sides polished. The thickness of each glass did not deviate by more than 0·003 cm. from 2·000 cm. Table I gives the list of glasses studied, their melting numbers, approximate composition and density as supplied by the manufacturers.

TABLE I

*List of Glasses Studied*

| Serial No. | Melting No. | Chemical composition: More than 10% | Chemical composition: Less than 10% | Density | $n$5893 | 100γ |
|---|---|---|---|---|---|---|
| 1 | 25188 | $SiO_2$, $B_2O_3$, $Al_2O_3$, $K_2O$ | $Na_2O$, F | 2·3 | 1·46693 | 67 |
| 2 | 18415 | $SiO_2$, $B_2O_3$, $K_2O$ | $Al_2O_3$ | 2·3 | 1·49340 | 67 |
| 3 | 16776 | $SiO_2$, $K_2O$ | $Al_2O_3$, $Na_2O$, CaO | 2·4 | 1·50228 | 73 |
| 4 | 23975 | $SiO_2$, $B_2O_3$, ZnO | $Al_2O_3$, $Na_2O$ | 2·5 | 1·50933 | 72 |
| 5 | 24906 | $SiO_2$, $B_2O_3$ | $Na_2O$, $K_2O$, BaO | 2·5 | 1·51714 | 71 |
| 6 | 22601 | $SiO_2$, $B_2O_3$, $Sb_2O_3$ | $Al_2O_3$, $Na_2O$, $K_2O$ | 2·7 | 1·52998 | 68·5 |
| 7 | 23125 | $SiO_2$, $Na_2O$, PbO | ZnO | 2·7 | 1·52686 | 78·7 |
| 8 | 22638 | $SiO_2$, PbO | $Na_2O$, $K_2O$ | 2·9 | 1·54495 | 77·4 |
| 9 | 24464 | $SiO_2$, ZnO, BaO | $B_2O_3$, $Na_2O$, $K_2O$, PbO | 3·1 | 1·57000 | 74 |
| 10 | 19510 | $SiO_2$, PbO | $Na_2O$, $K_2O$ | 3·2 | 1·56991 | 77 |
| 11 | 23355 | $SiO_2$, $B_2O_3$, BaO | $Al_2O_3$, $Na_2O$ | 3·3 | 1·58950 | 67·0 |
| 12 | 20672 | $SiO_2$, PbO | $B_2O_3$, $Na_2O$, $K_2O$ | 3·4 | 1·59813 | 77·4 |
| 13 | 22986 | $SiO_2$, BaO, PbO | $Na_2O$, $K_2O$, ZnO | 3·5 | 1·60620 | 76·2 |
| 14 | 23441 | $SiO_2$, PbO | $Na_2O$, $K_2O$, | 3·9 | 1·64712 | 77·6 |
| 15 | 23497 | $SiO_2$, BaO, PbO | $Na_2O$, $K_2O$, ZnO | 3·9 | 1·64917 | 77·4 |
| 16 | 23850 | $SiO_2$, PbO | $Na_2O$, $K_2O$ | 4·4 | 1·7130 | 77 |
| 17 | 23590 | $SiO_2$, PbO | $Na_2O$, $K_2O$ | 5·1 | 1·7850 | 78 |
| 18 | S1075 | $SiO_2$, PbO | $B_2O_3$, $K_2O$, $Sb_2O_3$ | 6·7 | 1·8900 | 78 |

The refractive indices of the glasses were determined with the aid of a Pulfrich refractometer. The differences in refractive indices for different wavelengths could be determined with an accuracy of 2 or 3 units in the fifth place of decimals. Even so, the dispersion values were accurate only to one or two per cent. The refractive indices were determined for λ 5893, λ 5461 and λ 4358 and the constants in the dispersion formula

$$n^2 = A + B\lambda^2/(\lambda^2 - \lambda^2_0)$$

were evaluated. The values of $\lambda \frac{dn}{d\lambda}$ for different wavelengths were calculated. As the glasses 16, 17 and 18 had refractive indices much higher than the prisms supplied with the refractometer, their dispersions are not so accurate as those of the other glasses. Table II gives the refractive indices and the values of $\lambda \frac{dn}{d\lambda}$ of the glasses for different wavelengths.

An electromagnet of the Rutherford type with the distance between the polepieces 22 mm. was used in the work. When 7 amperes were passed

TABLE II

*Dispersion Data for Glasses*

| No. | $n_{5893}$ | $n_{5461}$ | $n_{4358}$ | $\lambda\frac{dn}{d\lambda}{}_{5893}$ | $\lambda\frac{dn}{d\lambda}{}_{5461}$ | $\lambda\frac{dn}{d\lambda}{}_{4358}$ |
|---|---|---|---|---|---|---|
| 1 | 1·46693 | 1·46868 | 1·47575 | 0·02316 | 0·02482 | 0·03897 |
| 2 | 1·49340 | 1·49522 | 1·50266 | 0·02217 | 0·02509 | 0·04130 |
| 3 | 1·50228 | 1·50430 | 1·51262 | 0·02457 | 0·02879 | 0·04649 |
| 4 | 1·50933 | 1·51138 | 1·51968 | 0·02501 | 0·02912 | 0·04578 |
| 5 | 1·51714 | 1·51910 | 1·52715 | 0·02393 | 0·02782 | 0·04356 |
| 6 | 1·52998 | 1·53249 | 1·54295 | 0·03045 | 0·03584 | 0·05892 |
| 7 | 1·52686 | 1·52939 | 1·53992 | 0·03087 | 0·03592 | 0·05614 |
| 8 | 1·54495 | 1·54782 | 1·55999 | 0·03478 | 0·04103 | 0·06814 |
| 9 | 1·57000 | 1·57243 | 1·58273 | 0·02938 | 0·03481 | 0·05891 |
| 10 | 1·56991 | 1·57320 | 1·58712 | 0·03979 | 0·04712 | 0·07945 |
| 11 | 1·58950 | 1·59183 | 1·60171 | 0·02823 | 0·03331 | 0·05637 |
| 12 | 1·59813 | 1·60190 | 1·61801 | 0·04551 | 0·05408 | 0·09317 |
| 13 | 1·60620 | 1·60962 | 1·62408 | 0·04124 | 0·04883 | 0·08279 |
| 14 | 1·64712 | 1·65182 | 1·67209 | 0·05666 | 0·06754 | 0·1174 |
| 15 | 1·64917 | 1·65335 | 1·67116 | 0·05052 | 0·05986 | 0·1023 |
| 16 | 1·7130 | 1·7191 | 1·7434 | 0·074 | 0·089 | 0·159 |
| 17 | 1·7850 | 1·7932 | 1·8281 | 0·097 | 0·116 | 0·210 |
| 18 | 1·8900 | 1·8999 | 1·9430 | 0·123 | 0·149 | 0·282 |

through the coils of the magnet, a field of 17200 gauss was developed. A pair of wide-angle nicols were used as polariser and analyser and the angles measured were to 0·05 of a degree and this gave an accuracy of about ½%. It was considered that a greater accuracy was not necessary as the dispersions were accurate to 1% only. Conductivity water whose Verdet's constant is accurately known ($V_{5461}$ = 0·01547 at 25° C.) was used as the standard for the determination of the field. 1·24 cm. of water gave a rotation of 3·30° when 7 amperes were passed through the coils of the magnet. The field developed was, therefore, 17200 gauss.

A sodium lamp and a mercury point-o-lite lamp with suitable filters were used as the different sources of light for the measurement of the Verdet's constant of the glasses. If the glasses were kept exactly normal to the incident light, it was difficult to determine the true crossing position when the magnetic field was put on. This was due to the fact that light which comes to the analyser after two reflections at the surfaces of the glass was not rotated through the same angle as that which came without any reflection. To avoid this the glasses were turned through a small angle (about ½°) away from the normal position. Usually a mean of about 20 readings was taken to determine each crossing position. Table III gives the actual rotation $\rho$ due to a field of 17200 gauss), the Verdet's constant V, and the anomaly $\gamma$ for the three wavelengths $\lambda$ 5893, $\lambda$ 5461 and $\lambda$ 4358 for the 18 glasses.

TABLE III

*Magneto-optic Data for Glasses*

| Serial No. | λ 5893 | | | λ 5461 | | | λ 4358 | | |
|---|---|---|---|---|---|---|---|---|---|
| | ρ in degrees | V min./cm. gauss | γ % | ρ in degrees | V min./cm. gauss | γ % | ρ in degrees | V min./cm. gauss | γ % |
| 1 | 5·15 | 0·0149 | 64·2 | 5·80 | 0·0169 | 67·4 | 8·95 | 0·0260 | 66·3 |
| 2 | 5·10 | 0·0148 | 66·4 | 5·85 | 0·0170 | 67·8 | 9·5 | 0·0276 | 66·4 |
| 3 | 6·35 | 0·0185 | 74·6 | 7·35 | 0·0214 | 73·7 | 11·40 | 0·0332 | 71·0 |
| 4 | 6·25 | 0·0182 | 72·1 | 7·40 | 0·0215 | 73·3 | 11·25 | 0·0327 | 71·0 |
| 5 | 5·90 | 0·0172 | 71·2 | 7·00 | 0·0204 | 72·6 | 10·50 | 0·0305 | 69·6 |
| 6 | 7·25 | 0·0211 | 68·7 | 8·50 | 0·0247 | 68·5 | 13·85 | 0·0403 | 67·8 |
| 7 | 8·20 | 0·0239 | 76·7 | 9·80 | 0·0285 | 78·8 | 15·45 | 0·0449 | 79·4 |
| 8 | 9·35 | 0·0272 | 77·6 | 11·00 | 0·0320 | 77·4 | 18·25 | 0·0531 | 77·3 |
| 9 | 7·80 | 0·0227 | 76·6 | 8·95 | 0·0260 | 74·2 | 14·75 | 0·0429 | 72·3 |
| 10 | 10·65 | 0·0310 | 77·3 | 12·70 | 0·0369 | 77·8 | 21·10 | 0·0614 | 76·7 |
| 11 | 6·75 | 0·0196 | 69·0 | 7·70 | 0·0224 | 66·7 | 12·95 | 0·0377 | 66·3 |
| 12 | 12·25 | 0·0356 | 77·7 | 14·50 | 0·0422 | 77·4 | 24·80 | 0·0721 | 76·9 |
| 13 | 10·85 | 0·0316 | 76·0 | 12·95 | 0·0377 | 76·6 | 21·75 | 0·0633 | 75·9 |
| 14 | 15·10 | 0·0439 | 76·9 | 18·20 | 0·0529 | 77·8 | 31·75 | 0·0953 | 78·0 |
| 15 | 13·35 | 0·0388 | 76·3 | 16·05 | 0·0467 | 77·4 | 27·45 | 0·0799 | 77·5 |
| 16 | 19·80 | 0·0576 | 77 | 23·85 | 0·0694 | 77 | 42·25 | 0·123 | 77·0 |
| 17 | 26·15 | 0·0761 | 78 | 31·30 | 0·0910 | 78 | 56·45 | 0·164 | 78·0 |
| 18 | 33·25 | 0·0969 | 78 | 40·55 | 0·1180 | 78 | 76·75 | 0·223 | 78·0 |

## 3. DATA FOR FUSED SILICA AND QUARTZ

Cotton (1931) has determined the Verdet's constant of vitreous silica for three wavelengths, λ 5780, λ 5461 and λ 4358. The constants were redetermined for the above wavelengths as well as for λ 5893 using a plate of 8·40 mm. thickness. The values obtained were within ½% of those obtained by Cotton. $\lambda\, dn/d\lambda$ for this substance was calculated from the dispersion formula

$$n^2 = 1\cdot36112 + \frac{0\cdot74655\,\lambda^2}{[\lambda^2 - (0\cdot107044)^2]} - 0\cdot01350\,\lambda^2,$$

where λ is expressed in microns. The last term which is due to the infra-red absorption is omitted in the calculation. Table IV gives the optical and

TABLE IV

*Magneto-optic Data for Fused Quartz*

| Wavelength in A. U. | Refractive Index | Verdet's constant | | γ % |
|---|---|---|---|---|
| | | Cotton | Author | |
| 5893 | 1·4585 | .. | 0·01421 | 78·1 |
| 5780 | 1·4590 | 0·01479 | 0·01491 | 78·1 |
| 5461 | 1·4601 | 0·01671 | 0·01664 | 78·1 |
| 4358 | 1·4667 | 0·02602 | 0·02640 | 75·8 |

magneto-optical constants of vitreous silica for the four wavelengths mentioned above.

A large number of workers (1903, 1912, 1917) have devoted themselves to the study of the Verdet constant of quartz for different wavelengths in the spectrum. Actual measurements extend from 20000 A° to 2000 A°. $\lambda\, dn/d\lambda$ is calculated from the dispersion formula

$$n^2_w = 3\cdot53445 + \frac{008067}{[\lambda^2 - 0\cdot00127493]} + \frac{0\cdot002682}{[\lambda^2 - 0\cdot000974]} + \frac{127\cdot2}{[\lambda^2 - 108]},$$

where $n_w$ is the ordinary refractive index and $\lambda$ is the wavelength expressed in microns. Here also the last term is omitted in the calculation. Table V gives the Verdet's constant, and for the value of $\gamma$ different wavelengths.

TABLE V

*Magneto-optic Data for Crystalline Quartz*

| Wavelength | Refractive Index | Verdet's Constant | $\gamma$ % |
|---|---|---|---|
| 20000 | 1·5199 | 0·001266 | 71 |
| 16000 | 1·5270 | 0·002106 | 75·4 |
| 12000 | 1·5323 | 0·003727 | 75·1 |
| 8000 | 1·5383 | 0·008802 | 79·0 |
| 5893 | 1·5443 | 0·01664 | 78·9 |
| 5460 | 1·5462 | 0·01952 | 78·5 |
| 5085 | 1·5482 | 0·02257 | 77·1 |
| 4799·9 | 1·5501 | 0·02574 | 78·6 |
| 4358 | 1·5538 | 0·03081 | 78·5 |
| 4046 | 1·5572 | 0·03555 | 74·4 |
| 3612 | 1·5635 | 0·04617 | 74·5 |
| 2573 | 1·5962 | 0·1079 | 75·4 |
| 2194·6 | 1·6250 | 0·1586 | 69·9 |

## 4. DISCUSSION OF RESULTS

It will be seen from Table V that the Becquerel formula is obeyed by quartz for the visible spectrum. There appears to be a small drop in the value of $\gamma$ in the infra-red and the ultra-violet regions, but more accurate measurements are needed before the data could be accepted as indicating a real variation of $\gamma$ with wavelength in quartz. Although the data for fused quartz (Table IV) are not so extensive as those for crystal quartz, it is seen that $\gamma$ is sensibly constant in the visible region. It is worthy of remark that the values of $\gamma$ for fused quartz and crystal quartz are practically identical, and this is particularly remarkable in view of the large difference in density and refractive indices of the two substances.

An examination of Table III shows that the value of $\gamma$ is independent of wavelength in many of the glasses. Nevertheless, there are a few glasses in the list (Nos. 1, 3, 9 and 11) in which $\gamma$ is apparently not constant. Since these variations in $\gamma$ mostly occur in glasses of low dispersive power, they may be ascribed to inaccuracies in the measurement of the refractive indices. But a more probable reason is that the dispersion due to the infra-red term has not been eliminated (as has been done in quartz and fused silica) in calculating the value of $\lambda\, dn/d\lambda$ for the glasses. The variation in the value of $\gamma$ in glass No. 9 is probably too large to be explained on these lines. In general, however, one could say that most of the glasses studied obey the Becquerel formula, the $\gamma$ value of each glass being approximately constant for the visible spectrum. The mean value of $\gamma$ of each glass has been incorporated in Table I.

A study of Table I reveals many interesting facts. All the glasses which do not contain $B_2O_3$ or $Al_2O_3$ have values of $\gamma$ lying between 76% and 78%, thus differing very little from the values for fused and crystalline quartz. This is all the more remarkable when one considers the large variations in composition, density and dispersive power of the glasses. For instance, in spite of the dispersion of glass No. 18 being four times that of glass No. 7 the $\gamma$ factor is not appreciably different. The variations in content of PbO and ZnO—which are principally responsible for the large dispersion and high density in some of the glasses—do not appear to involve any noticeable variations in the magneto-optic anomaly.

The presence of $B_2O_3$ seems to have a large influence on the $\gamma$ value of a glass. All borate glasses have low $\gamma$ values, $\gamma$ being lower in glasses having a higher percentage of $B_2O_3$. Glass No. 1 and No. 2 which contain more than 10% of $B_2O_3$ have lower $\gamma$ values than glass No. 9 which has less than 10% of $B_2O_3$. The results with glass 3 seem to suggest that $Al_2O_3$ also depresses the $\gamma$ value of a glass. The simultaneous presence of $B_2O_3$ and $Al_2O_3$ is obviously the cause of the very low value of $\gamma$ in glasses No. 2, 6 and 11. It would seem that the presence of trivalent elements not only diminishes the dispersive power of a glass but also has the effect of diminishing the magneto-optic rotation in a still greater proportion, and that on the other hand, $\gamma$ is practically the same for all silicate glasses which do not contain the trivalent elements.

In conclusion, the author wishes to thank Prof. Sir C. V. Raman for his kind advice and encouragement during this investigation.

## 5. Summary

The paper records the values of Verdet's constant determined for λ 5893, λ 5461 and λ 4358 with 18 silicate glasses made by Schott & Co., Jena. The dispersive powers of the glasses have also been measured. It is found that most of the glasses obey a modified Becquerel formula, in which the multiplying factor $\gamma$ is practically constant over the visible spectrum. The $\gamma$ factor for fused quartz and crystalline quartz for different wavelengths have also been calculated. It is found that the value of $\gamma$ for both the substances is about 78%. All the glasses which do not contain $B_2O_3$ or $Al_2O_3$ have $\gamma$ values lying between 76% and 78% in spite of large variations in composition, density and dispersive power, the presence of the heavy elements like Pb, Ba and Zn in varying proportions having no influence on the $\gamma$ value. On the other hand, trivalent elements like Boron and Aluminum when present in glasses diminish $\gamma$ to values between 67% and 74% depending on the amount of $B_2O_3$ or $Al_2O_3$ present.

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