CHAPTER IV

ANOMALOUS TRANSMISSION (BORRMANN EFFECT) IN ABSORBING CHOLESTERIC LIQUID CRYSTALS

1. Anomalous transmission of X-rays

This chapter is conoerned with another striking phenomenon, namely, the anomalous transmission of light (or Borrmann effect) exhibited by absorbing oholesterics. Borrmann (1941) disoovered a remarkable effect in the transmission of X-rays when a perfect absorbing crystal is eet for Bragg reflection. Away from the Bragg setting, a crystal of sufficient thickness shows oonsiderable reduation in the transmitted intensity due to photoelectric absorption. When it is set for Bragg reflection one expects a further reduation in the transmitted intensity as there is an additional lose due to reflection. Borrmann, using a quartz crystal of 0.2 mm thickness and FeK_{α} radiation, disoovered an enhancement in the transmitted intensity instead of reduction. Also the transmitted ray had a slight lateral shift with respect to the

incident ray, instead of being collinear with it, in such a way that it appeared as though inside the crystal the energy travelled along the Bragg planes. This effect can be explained qualitatively as follows. At the Bragg setting standing waves are eet up inside the medium due to the interference between the primary and Bragg reflected waves and its nature (i.e., position of nodes and antinodes) depends on the phaae difference between the two wavee. When the medium is absorbing the phase difference changes and for some angle of incidence the nodal planes of the standing wave coincides with the atomic planes (figure 1). Therefore the atomic electrons aee a reduced electric field and this results in a decrease of photoelectric absorption. Due to the standing wave nature, the component of the Poynting vector normal to the Bragg plane vanishes so that the energy flows parallel to the planes and this results in the alight lateral shift of the transmitted X–ray with reepect to the incident ray.

This effect, in principle, can occur at any wavelength in an absorbing system having periodicity

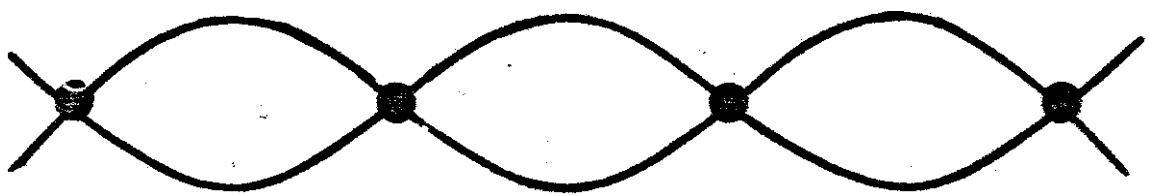


Figure 1: A qualitative picture of the Borrmann effect in X-rays. The nodes of the standing wave coincide with the atomic positions giving minimum absorption.

that matches with the wavelength of the inoident radiation. But, so far, an optical analogue of Borrmann effeot does not appear to have been observed.

2. Anomalous transmission in cholesterics

For the oocurrence of this effeot, it may appear necessary to have atratification of the absorption centres with periodicity matching with the wavelength of light. In cholesterics the wave sees a continuously twisted medium and the reflected oiroularly polarissd wave has the same sense as that of the incident wave which will not result in a conventional standing wave consisting of nodes and antinodes. The standing wave pattern in cholesterics is of a different type; interference between the reflected circularly polarized light and the primary circularly polarized light of the same sense gives a linearly polarized wave whose azimuth rotates at the same rate as the director in the medium. The angle made by the electric vector of the standing wave with respect to the director depends on ψ, the phaae difference between the inoident and

reflected right circularly polarized light. For a cholesteric of semi-infinite thickness ψ oan be worked out as follows using dynamical theory.

From (10) in Chapter 3, the ratio of the amplitudes of the reflected and primary waves

$$\frac{S_o}{T_o} = -\frac{iQ\, f_m(y)\, \exp(i\varphi)}{f_m(y)\exp(i\varphi) - f_{m-1}(y)}$$

$$= -\frac{iQ}{1 - \frac{f_{m-1}(y)}{f_m(y)}\, e^{-i\varphi}}$$

Now

$$\frac{f_{(m-1)}(y)}{f_m(y)} = \frac{\sin h(m-1)\xi}{\sin h\, m\xi}$$ (from equation 13, Chapter III)

$$= \cosh\xi - \coth m\xi \sinh\xi$$

For a semi-infinite sample, $\cosh\xi - \coth m\xi \cdot \sinh\xi \approx \cosh\xi - \sinh\xi = e^{-\xi}$. Therefore

$$\frac{S_o}{T_o} = \frac{-iQ}{1 - e^{-i\varphi} \cdot e^{-\xi}} = \frac{-iQ}{1 - e^{-(i\varepsilon + \xi)}} \qquad (1)$$

$$\sim \frac{-iQ}{i\varepsilon + \xi} = \frac{Q/\varepsilon}{1 \pm \left[\frac{Q^2}{\varepsilon^2} - 1\right]^{\frac{1}{2}}} \cdot e^{-i\,\pi/2}$$

(In the, reflection band ξ is real)

Separating this into an amplitude factor and a phase factor

$$\frac{S_o}{T_o} = \frac{Q/\varepsilon}{\left[\frac{Q^2}{\varepsilon^2} - 1 + 1\right]^{\frac{1}{2}}} \cdot e^{-i\,\pi/2} \cdot e^{-i\tan^{-1}\left\{\pm 1/[(Q^2/\varepsilon^2 - 1)]^{\frac{1}{2}}\right\}}$$

Therefore

$$\gamma = \frac{\pi}{2} \pm \tan^{-1} \frac{1}{\left[\frac{Q^2}{\varepsilon^2} - 1\right]^{\frac{1}{2}}} \qquad (2)$$

The dependence of γ on $\varepsilon(\lambda)$ 4s given in figure 2.

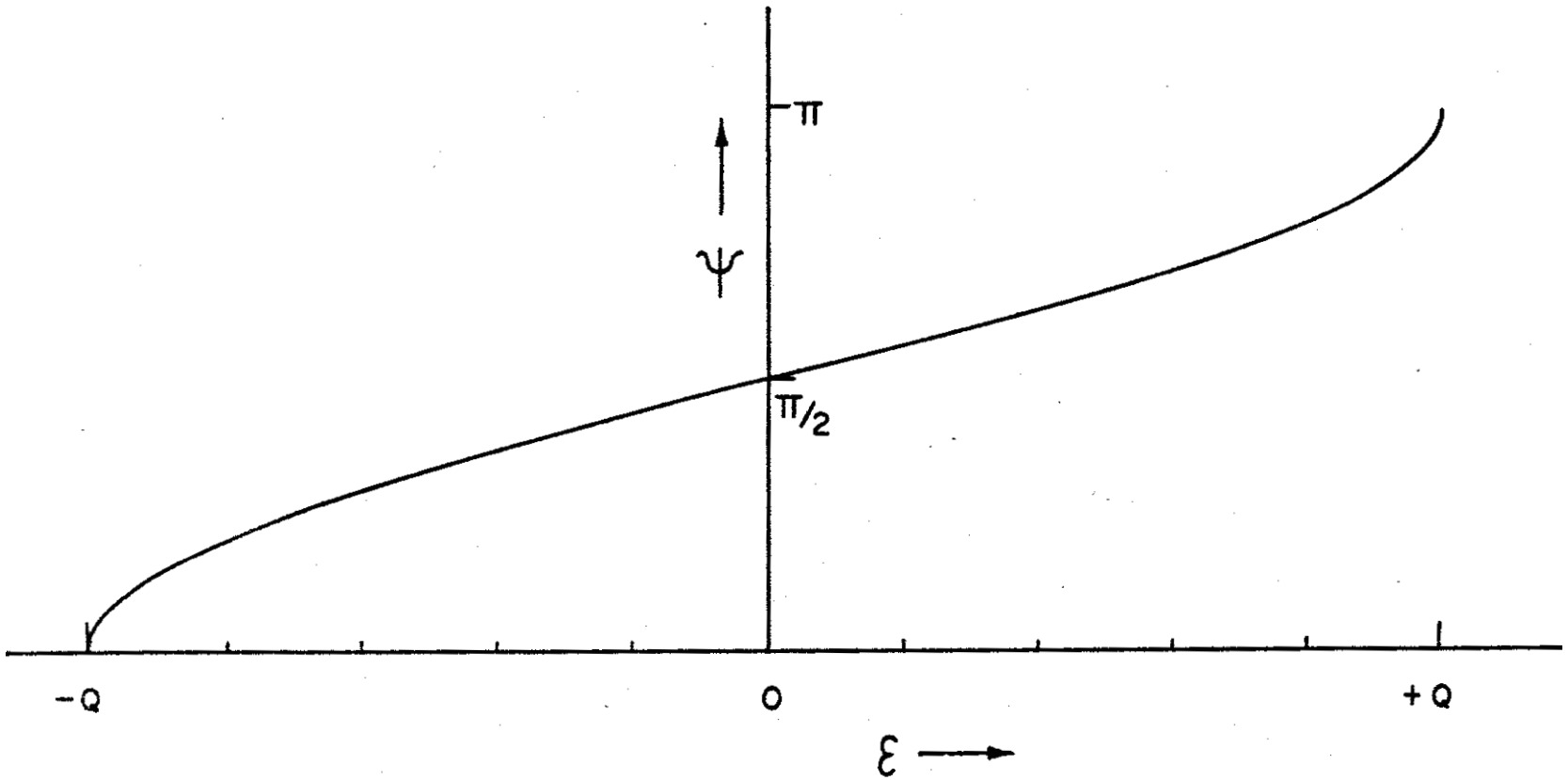


Figure 2 m e phase of the reflected wave with respect to the primary ware plotted as a function of $\varepsilon(\lambda)$.

When $\varepsilon = Q, \Psi = \pi/2 + \pi/2 = \pi$

$\varepsilon = 0, \Psi = \pi/2 + 0 = \pi/2$

$\varepsilon = -Q, \Psi = \pi/2 - \pi/2 = 0$

Thus the phase of the reflected wave with respect to the primary wave varies from 'π' to '0' starting from the shorter wavelength edge to the longer wavelength edge of the reflection band. Hence the electric vector in the medium makes an angle π/2 with respect to the director at the shorter wavelength edge and along the director at the longer wavelength edge. Ehe refractive index and the absorption coefficient in the direction of the director (i.e., long axis of the molecule) is assumed to be greater than that in the direction perpendicular to it. Than the electric vector of the standing wave experiences minimum attenuation at the shorter wavelength side and maximum attenuation at the longer wavelength side of the reflection band. As a result of this, there occurs an anomalous increase in the transmitted intensity on the shorter wavelength side which is over and above the normal attenuation. One finds that in

cholesterics the optimum conditions to observe Borrmann effect are satisfied not exactly at the centre of the reflection band but at one edge of it, this being similar to the X-ray case where the effect occurs not at the Bragg angle but at a slightly different angle.

3. Dynamical theory of absorbing oholeaterice

In %hischapter the dynamical theory is applied to explain the Borrmann effect in absorbing cholesterics (Chandrasekhar et al. 1973). It is assumed that the layers are linearly dichroic in addition to being linearly birefringent and that the principal axes of the two coincide with eaoh other. Therefore parameters like μ, Q, φ_r, φ_L become complex. If $\hat{\mu}_1$ and $\hat{\mu}_2$ be the principal complex refractive indices of each layer, then the reflection coefficient $\hat{Q}$ and the phase retardation $\hat{\varphi}$ per pitch also become complex; i.e.,

$$\hat{Q} = \pi \frac{\Delta \hat{\mu}}{\hat{\mu}}$$

$$\hat{\varphi}_R = \frac{2\pi}{\lambda} \hat{\mu}_R P = \frac{2\pi}{\lambda} \hat{\mu} P - \frac{\pi(\Delta \hat{\mu})^2 P^2}{4\lambda^2}$$

$$\hat{\varphi}_L = \frac{2\pi}{\lambda}\hat{\mu}_L P = \frac{2\pi}{\lambda}\hat{\mu}P + \frac{\pi(\Delta\hat{\mu})^2 P^2}{4\lambda^2}$$

Here

$$\Delta\hat{\mu} = \hat{\mu}_1 - \hat{\mu}_2 \qquad \hat{\mu}_1 = \mu_1 - ik_1$$

$$\hat{\mu} = \frac{1}{2}(\hat{\mu}_1 + \hat{\mu}_2) \qquad \hat{\mu}_2 = \mu_2 - ik_2$$

k_1 and k_2 are the principal absorption coefficients.

All the equations obtained for non–absorbing media are still valid for absorbing systems excepting that $\hat{Q}$, φ_R, $\hat{\varphi}_L$, $\hat{\mu}_R$, $\hat{\mu}_L$ replace Q, φ_R, φ_L, μ_R and μ_L respectively. For example, for a thick specimen, the refleation coefficient R for the right circular wave, the wave vectors $\hat{K}_R$ and $\hat{K}_L$ of the circular waves are given by

$$R = \left| \frac{\hat{Q}}{\hat{\varepsilon} \pm (\hat{\varepsilon}^2 - \hat{Q}^2)^{\frac{1}{2}}} \right|^2 \qquad (3)$$

$$\hat{K}_R = \frac{2\pi + \hat{\xi}/i}{P} \; ; \quad \hat{K}_L = \frac{(2\pi\hat{\mu}_L)}{\lambda} \qquad (4)$$

Here

$$\hat{\varepsilon} = \frac{2\pi}{\lambda}(\hat{\mu}_R P - \lambda)$$

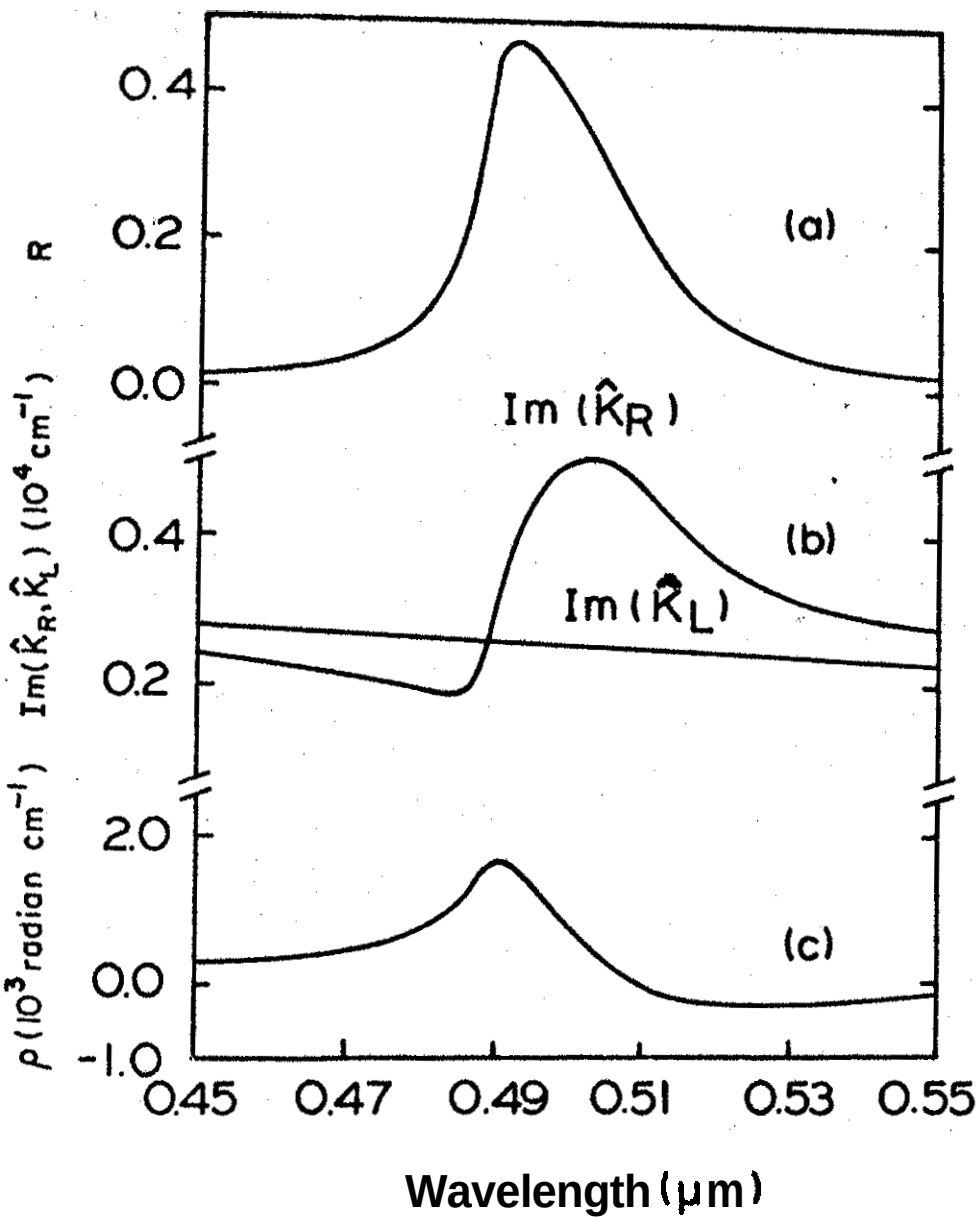
$$\hat{\xi} = \pm (\hat{Q}^2 - \hat{\varepsilon}^2)^{\frac{1}{2}}$$

Figure 3 presents the dependence of R, the imaginary parts of $\hat{K}_R$ and $\hat{K}_L$ on wavelength. Here $k = \frac{1}{2}(k_1 + k_2) = 0.02$ and $\Delta k = k_1 - k_2 = 0.028$. The interesting result is that on the shorter wavelength side $\mathrm{Im}(\hat{K}_R)$ is lees than $\mathrm{Im}(\hat{K}_L)$, i.e., the right circular wave is less attenuated than the left circular wave, whilst on the longer wavelength side the opposite is true.

The transmitted intensities T_R and T_L for the right and left oircular waves through an absorbing cholesteric film of thickness mP for unit incident intensity are given by

$$\left.\begin{aligned} T_R &= \left| \frac{1}{\exp(i\hat{\varepsilon})\,\dfrac{\sinh m\hat{\xi}}{\sinh \hat{\xi}} - \dfrac{\sinh (m-1)\hat{\xi}}{\sinh \hat{\xi}}} \right|^2 \\ &\approx \left| \frac{\hat{\xi}\,\mathrm{cosech}\, m\hat{\xi}}{i\varepsilon + \hat{\xi}\coth m\hat{\xi}} \right|^2 \\ T_L &= \left| \exp(-m\hat{\varphi}_L) \right|^2 \end{aligned}\right\} \qquad (5)$$

Figure 3: The calculated values of (a) reflection coefficient R, (b) imaginary parts of $\hat{K}_R$ and $\hat{K}_L$, (c) rotatory power δ, plotted as functions of λ for an absorbing semi-infinite medium.

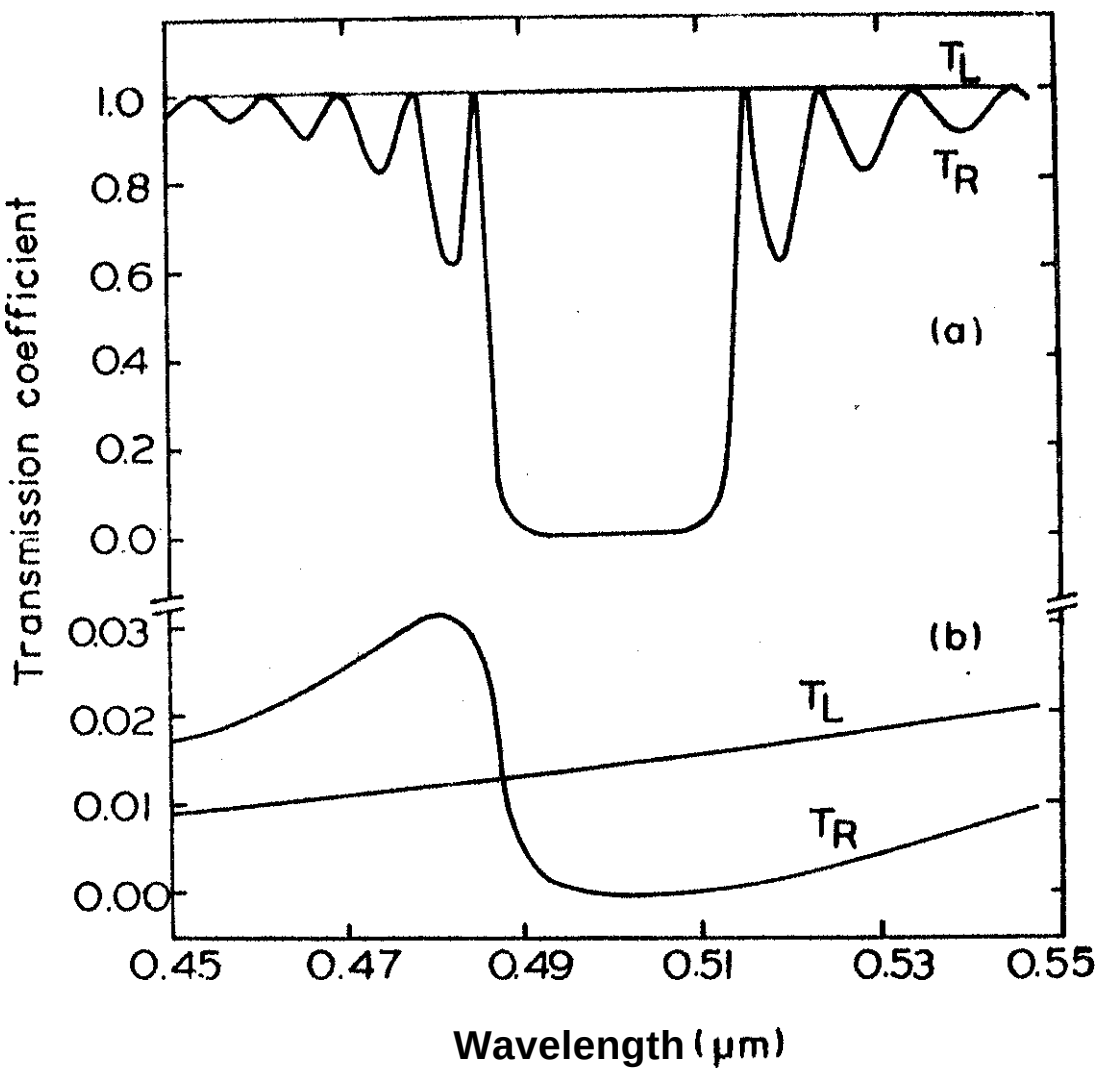

0.4
0.2
0.0
R
(a)
Im ($\hat{K}_R$)
0.4
0.2
(b)
Im ($\hat{K}_L$)
2.0
0.0
-1.0
(c)
ρ (10^3 radian cm^{-1})
Im($\hat{K}_R$, $\hat{K}_L$) (10^4 cm^{-1})
0.45
0.47
0.49
0.51
0.53
0.55
Wavelength (μm)

The theoretical dependence of T_R and T_L on wavelength are shown in figure 4 for both non-absorbing and absorbing cases for a film of thickness 25 P. The structure being right-handed, the right circular oomponent is reflected, and hence in the non-absorbing film ($k = \Delta k = 0$) T_R is always lass than T_L. On the other hand, in the absorbing caee, T_R hae an enhanced value on the shorter wavelength side of the reflection band which is the Borrmann effeot in cholesterics. It can be shown that T_L will exhibit an anomalous increase for a left-handed structure (i.e., negative β) and also that the enhanced transmission will occur on the longer wavelength side of the reflection band if Δk is negative.

4. Experiments

To observe the optical analogue of Borrmann effeot in a cholesteric the molecules (layers) should have a linearly dichroic band in the visible region and this intrinsic absorption band should be wider than the Bragg band. Normally the compounds that exhibit cholesterio texture do not absorb in

Figure 4: The transmitted intensities T_R and T_L for right and left circular waves (for unit incident intensity) for a film of thickness 25P (a) now absorbing, (b) absorbing. The enhanced transmission for the right circular component in (b) is the analogue of the Borrmann effect.


Transmission coefficient
1.0
0.8
0.6
0.4
0.2
0.0
0.03
0.02
0.01
0.00
T_L
T_R
(a)
(b)
T_L
T_R
0.45
0.47
0.49
0.51
0.53
0.55
Wavelength (μm)

the optical region. However, as explained in Ohapter II, it is possible to induce linear diohroism in the layers in a cholesteric by dissolving linearly dichroic molecules (Saeva and Wysokhi 1971). The solute moleoules arrange themselves locally in the order prevalent in the medium and therefore determine the absorption and linear dichroic properties of the medium.

Experiments were oarried out on thin films of cholesteryl nonanoate in which was dissolved small quantities of p-azoxyanisole (PAA) or n-p-methoxybeneylidene-p-phenylaxoaniline (MBPAA) (Nityananda et al. 1973, Suresh 1976). PAA and MBPAA have strong linearly dichroic bands around 0.36 μm and 0.38 μm respeotively. Pure oholesteryl nonanoate is left handed and has a Bragg refleotion band at 0.36 μm at 88.5°C. The temperature corresponding to the Bragg reflection band 0.36 μm decreases slightly with addition of small quantities of either YAA or MBPAA. The mixture is also left handed and reflects left circularly polarized light at the reflection band. The experimental procedure is to adjust the sample temperature so

that the reflection band of the cholesteric mixture coinaidee (as closely as poseible) with the absorbing band of the solute molecules.

The sample was taken between two optically flat ($\sim \lambda/10$) fused silica plates and by careful displacement of the plates well oriented plane texture cholesteric could be obtained. The thickness of the sample and the concentration of the solute molecules play an important role in observing Borrmann effect. A thick sample does not give well oriented specimen by oover slip displaaement and a very thin sample does not have sufficient number of pitches to give a well defined Bragg refleotion. Also a very small percentage of the solute molecules will not show the effect prominently and on the other hand a high percentage of the solute molecules does not transmit any detectable intensity. By trials it was found that a sample thickness of about 6 μm and solute concentrations in the range 1 to 4 per eent are suitable to observe the effect. In all the experiments the sample thickness was fixed using a mylar spacer of thickness 0.25 mil ($\approx$ 6.4 μm).

A parallel beam of intense white light from a tungsten lamp was passed through a circular polariser and the sample. The transmission speotrum was recorded photographically using a quarts spectrograph (Hilger E 498.305/49645). The speotra for left- and right-circularly polarised light were recorded on the same photographic plate (one above the other) under identical conditions (see figure 5). Miorodensitometer tracings were then obtained from the developed plates and the relative intensities were evaluated using previously calibrated relative intensity-density curves for the source speotrum. The relative intensities thus evaluated giver a measure of the transmission ooefficient of the sample. The constant of proportionality involved in the relative intensity was eliminated by calculating the circular dichroism defined as

$$D = \frac{T_L - T_R}{T_L + T_R + 2(T_L T_R)^{\frac{1}{2}}} \qquad (6)$$

where T_L and T_R are transmitted intensity for left-

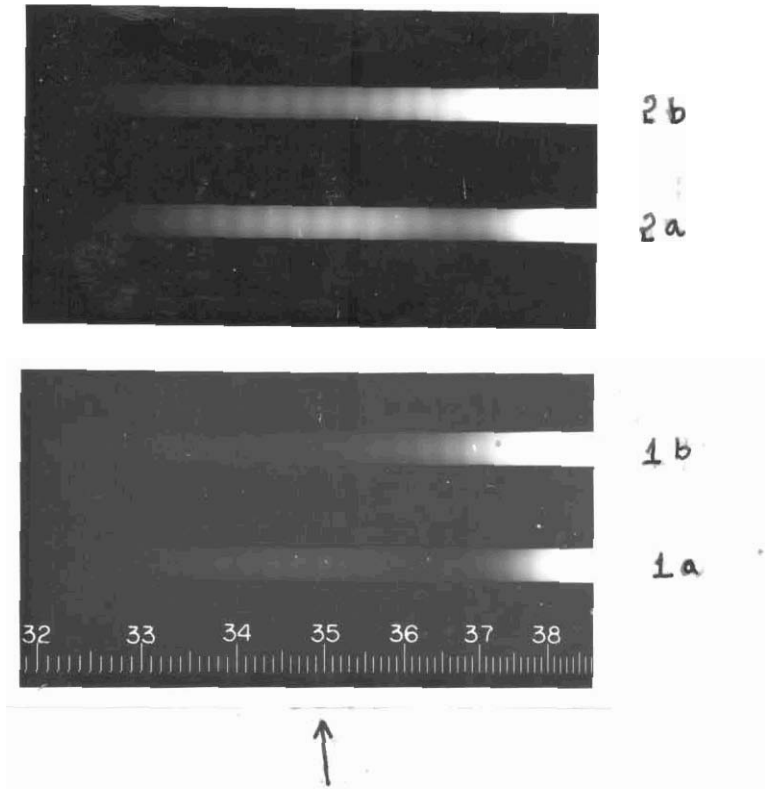


Figure 5

A typical transmission spectrum showing the Borrmann effect: (1) for a short exposure tine, (2) for a longer exposure time. In both the cases 'a' is for the left circular wave which exhibits anomalous transmission, and 'b' is for the right circular wave which undergoes normal attenuation. The fringes are due to the channelled spectrum of the quarter wave plate. The wavelength scale is also given in the same plate. The reflection band is around 3600 Å. 3hr region of enhanced transmission in 'a is indicated by the arrow.

and right-circularly polarized light respectively.

The raw microdensitometer traces for non-absorbing sample are presented in figure 6. The two traces do not cross, indicating that the ciroular dichroism does not change sign. Pigure 7 gives the two traces for 2.45% PAA (by weight) in cholesteryl nonanoate. For this composition, the maximum value of $\Delta k = 0.03$. The Bragg reflection occurs at about 0.355 μm, as indicated by hhe dig in the transmission for left circular light. At shorter wavelengths, the transmission has actually risen above that for right circular light. Figure 8 gives the transmitted intensities (in arbitrary units) and figure 9 gives the circular dichroism for the same sample. Figure 10, 11 and 12 present the results of a similar experiment on 4.25% MBPAA, the Bragg reflection being at about 0.4020 μm.

In interpreting the experimental transmitted intensity curve8 (figure 8) one must recall that the linear dichroism Δk is a function of wave-length having a maximum and falling off on either side. Since the experimental curves (figure 8)

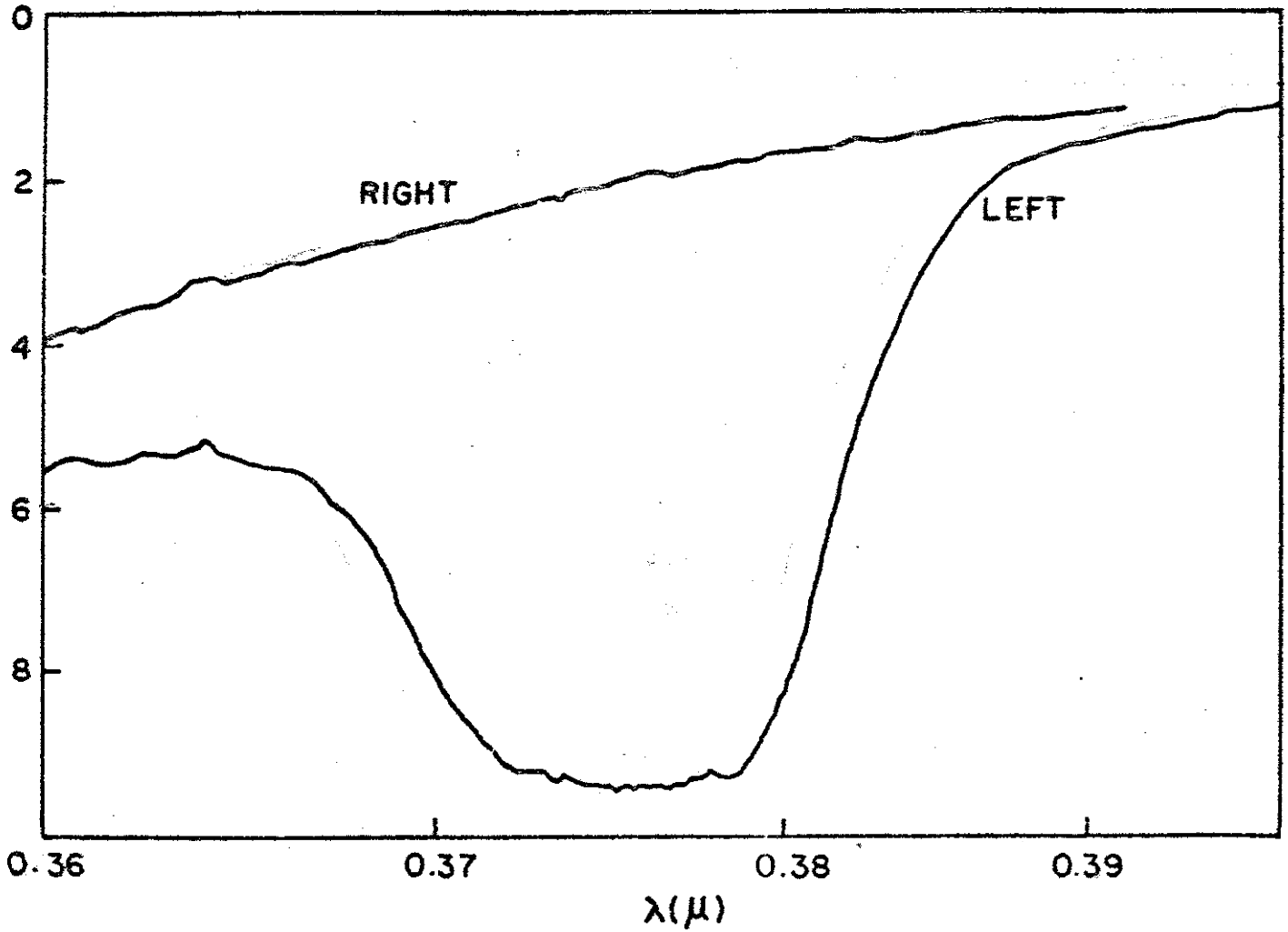

0
2
4
6
8
RIGHT
LEFT
0.36
0.37
0.38
0.39
λ(μ)

Figure 6: Raw microdensitometer traces for a non-absorbing sample (purr cholesteryl nonanoate) showing qualitatively the behaviour of the transmitted intensity as a function of wavelength for the two circular polarisations. Sample thickness $\approx$ 6.4 μm.

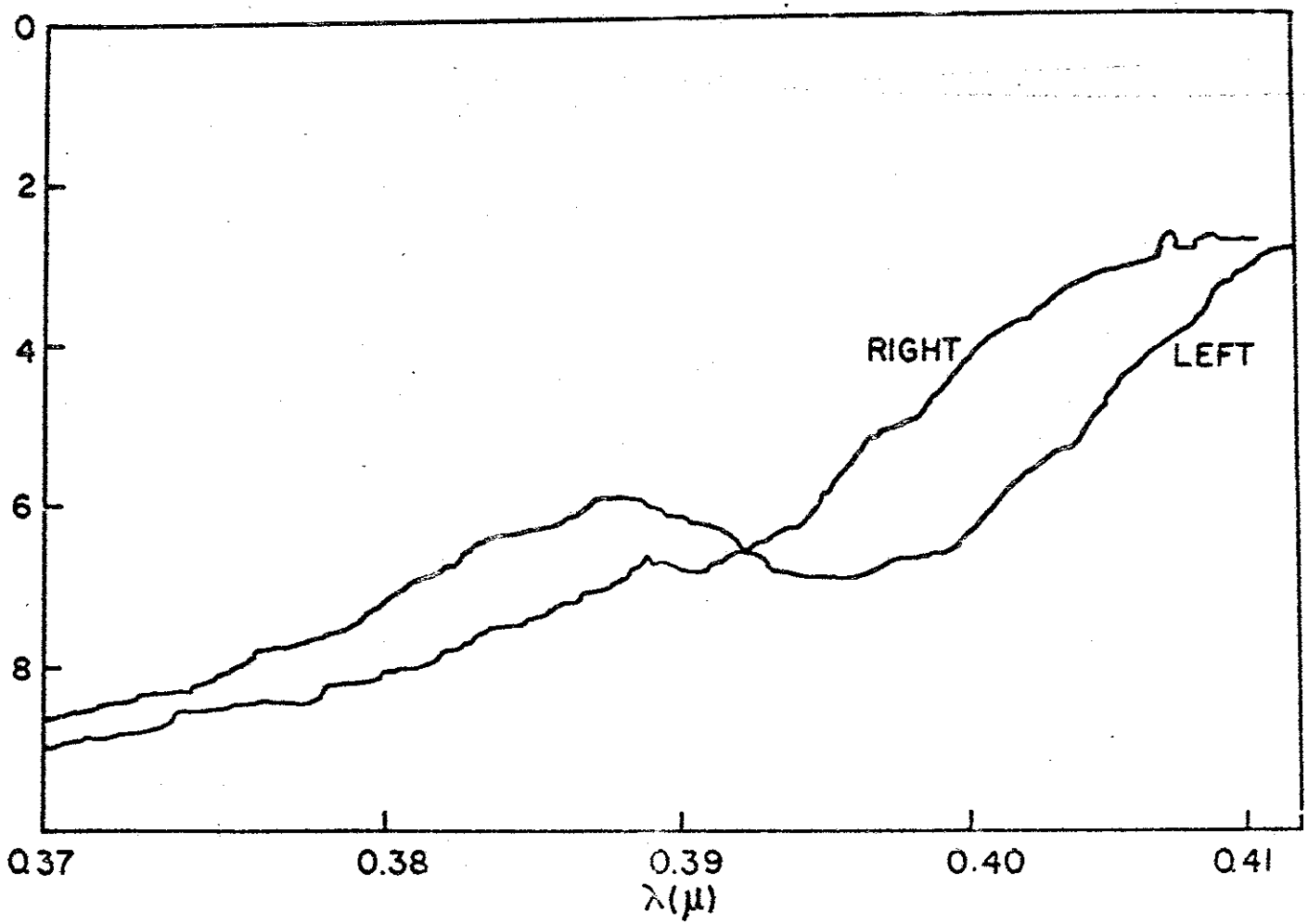


Figure 7: Microdensitometer traces for the two circular polarisations. Sample: 2.45% PAA in cholesteryl nonanoate.

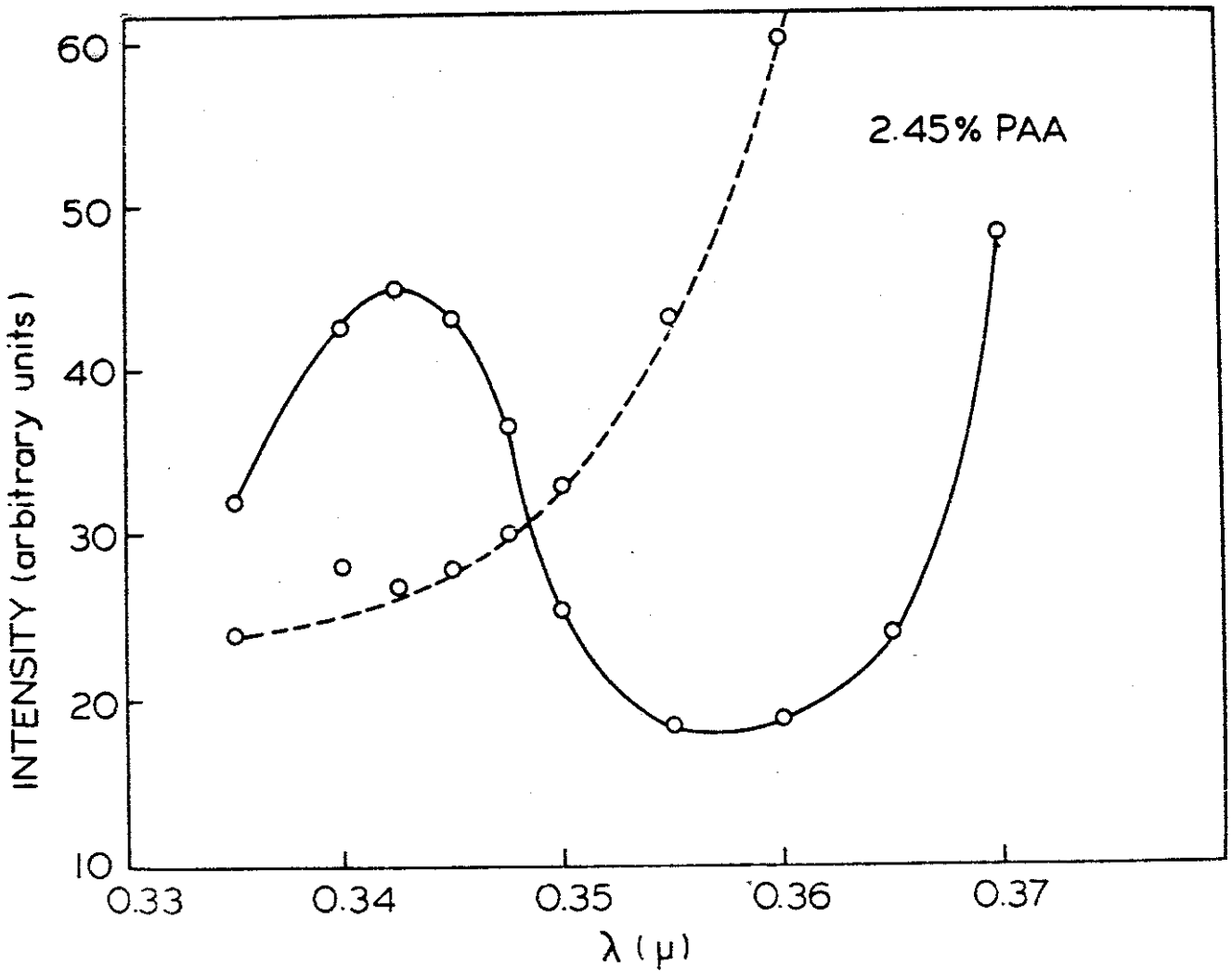

60
50
40
30
20
10
INTENSITY (arbitrary units)
2.45% PAA
0.33
0.34
0.35
0.36
0.37
λ (μ)

Figure 8: Transmitted intensity for the two circular polarisations (arbitrary units). The dashed line is for right circular polarisation and the solid line for left circular.

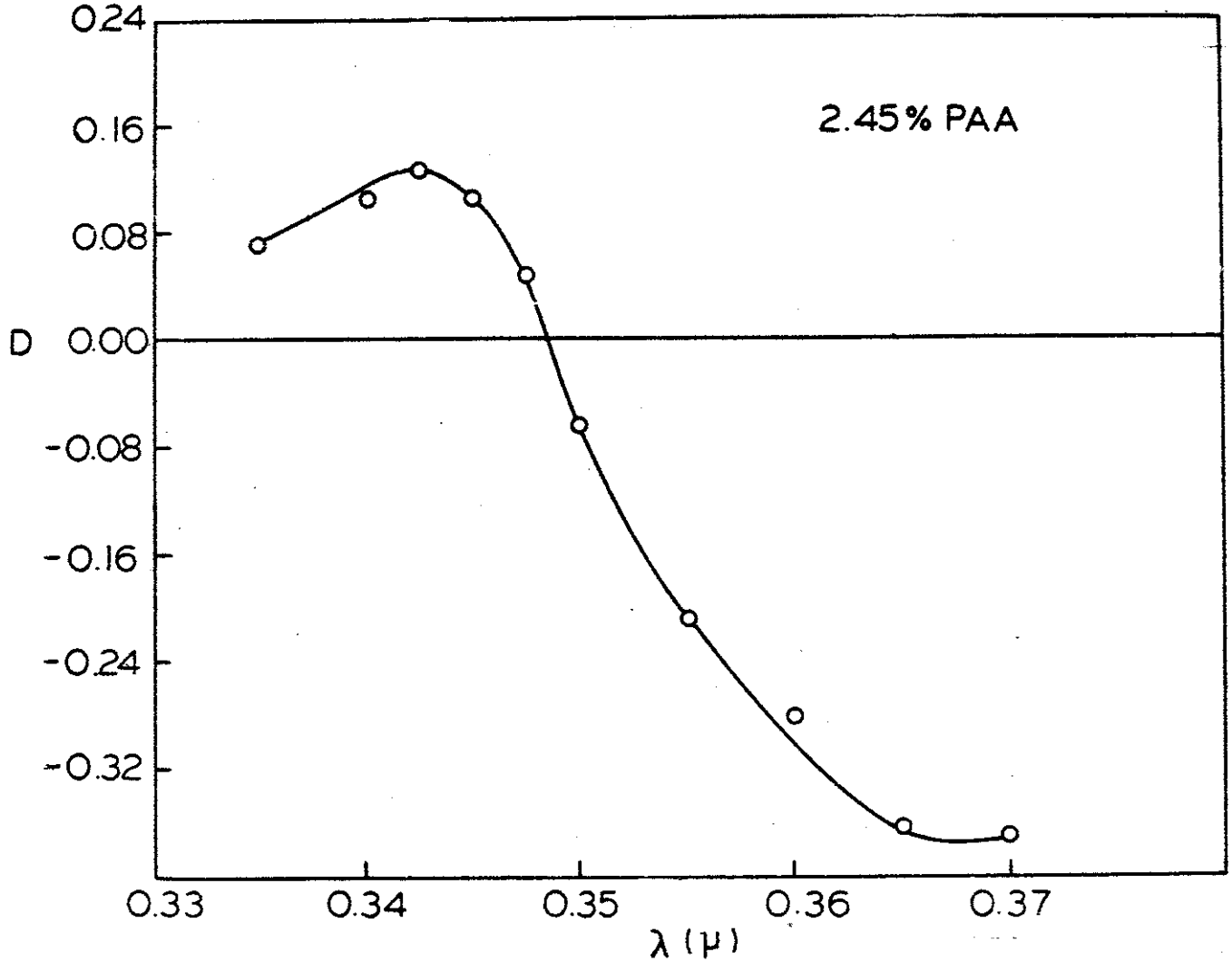


Figure 9: Circular dichroism as a function of wavelength for a sample of thickness ≈ 6.4 μm.

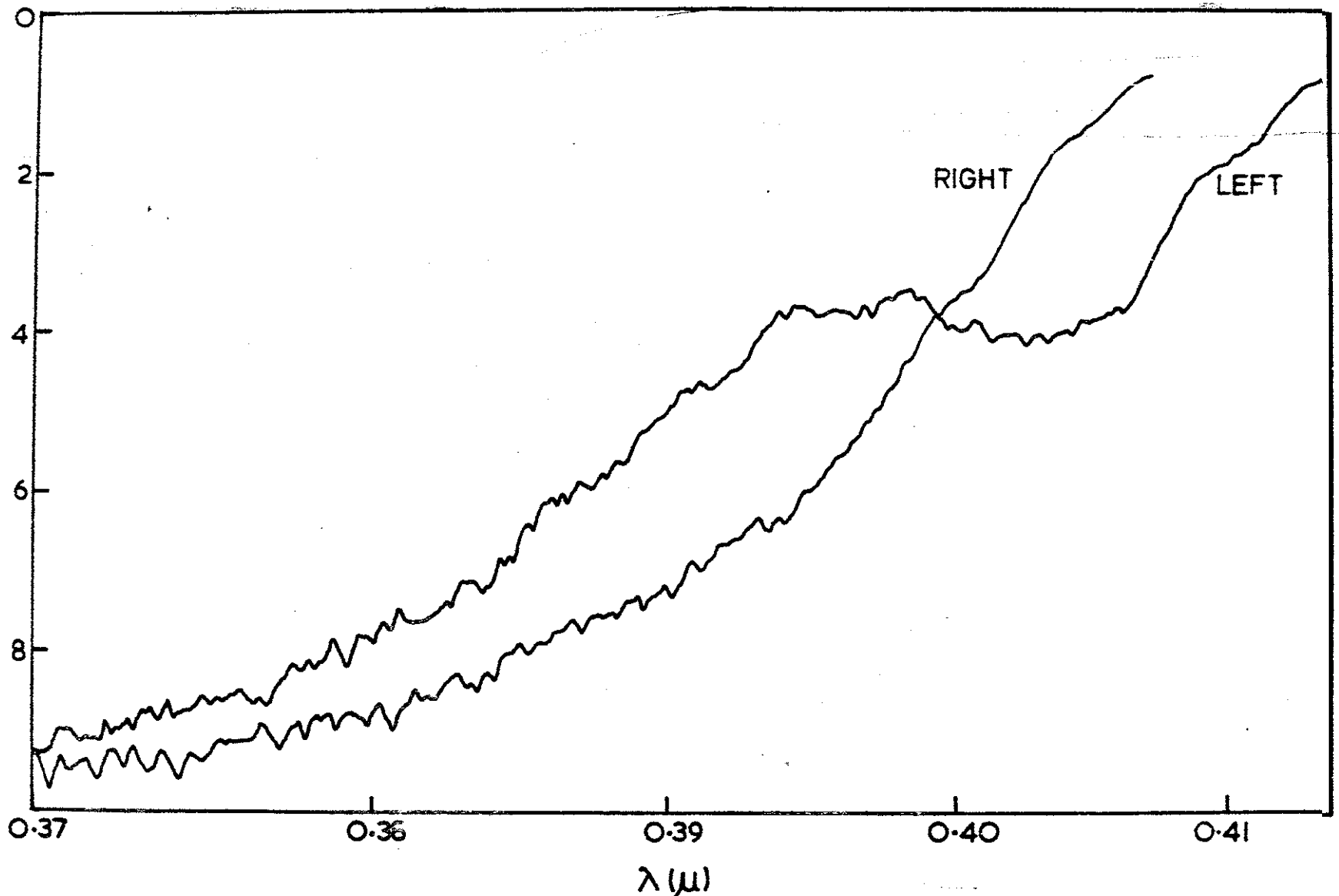


Figure 10: Microdensitometer traces for the two circular polarisations.
Sample: 4.25% MBPAA in cholesteryl nonanoate.

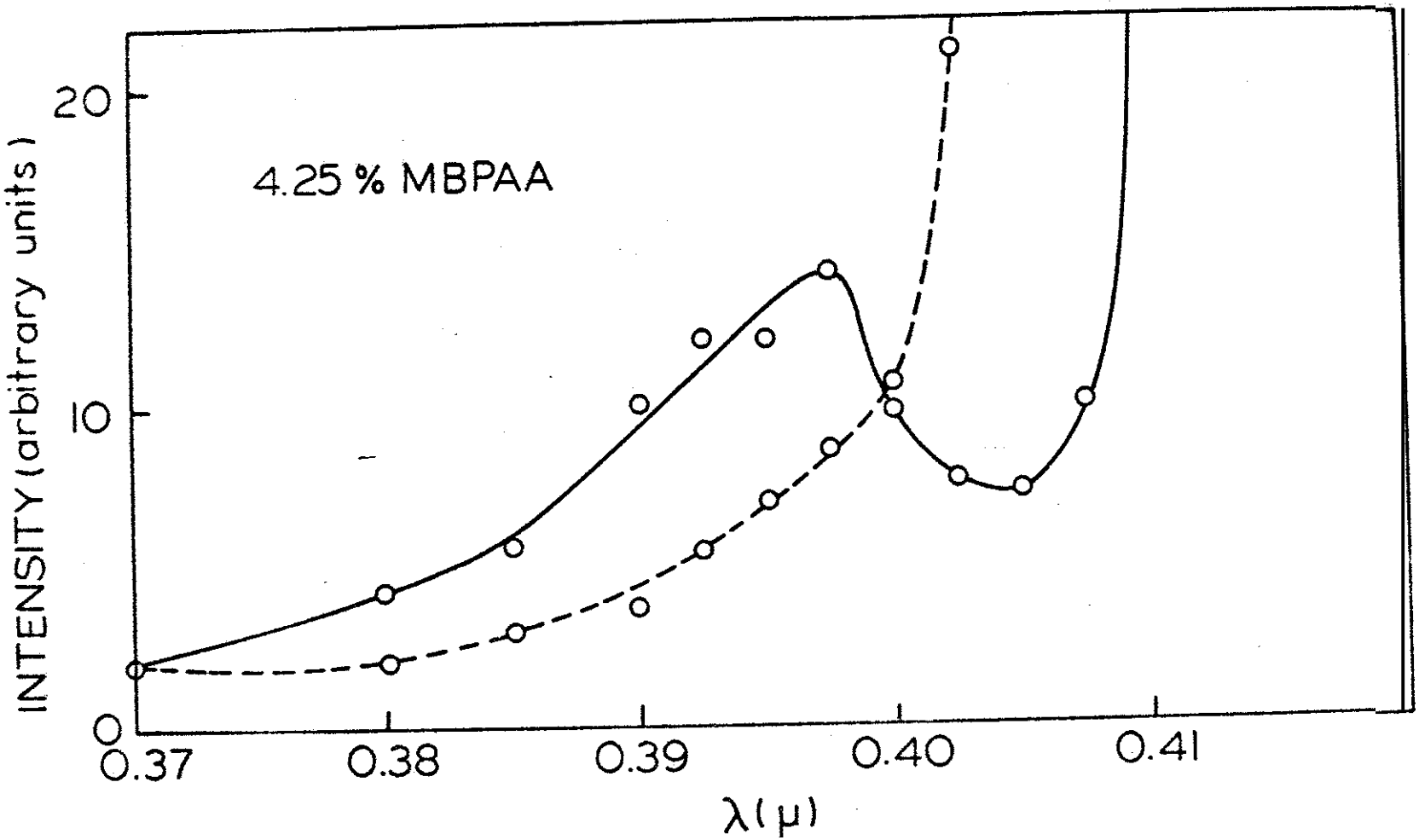


Figure 11: Transmitted intensity in arbitrary units as a function of wavelength. The dashed line is for right circular polarisation and the solid line for left circular.

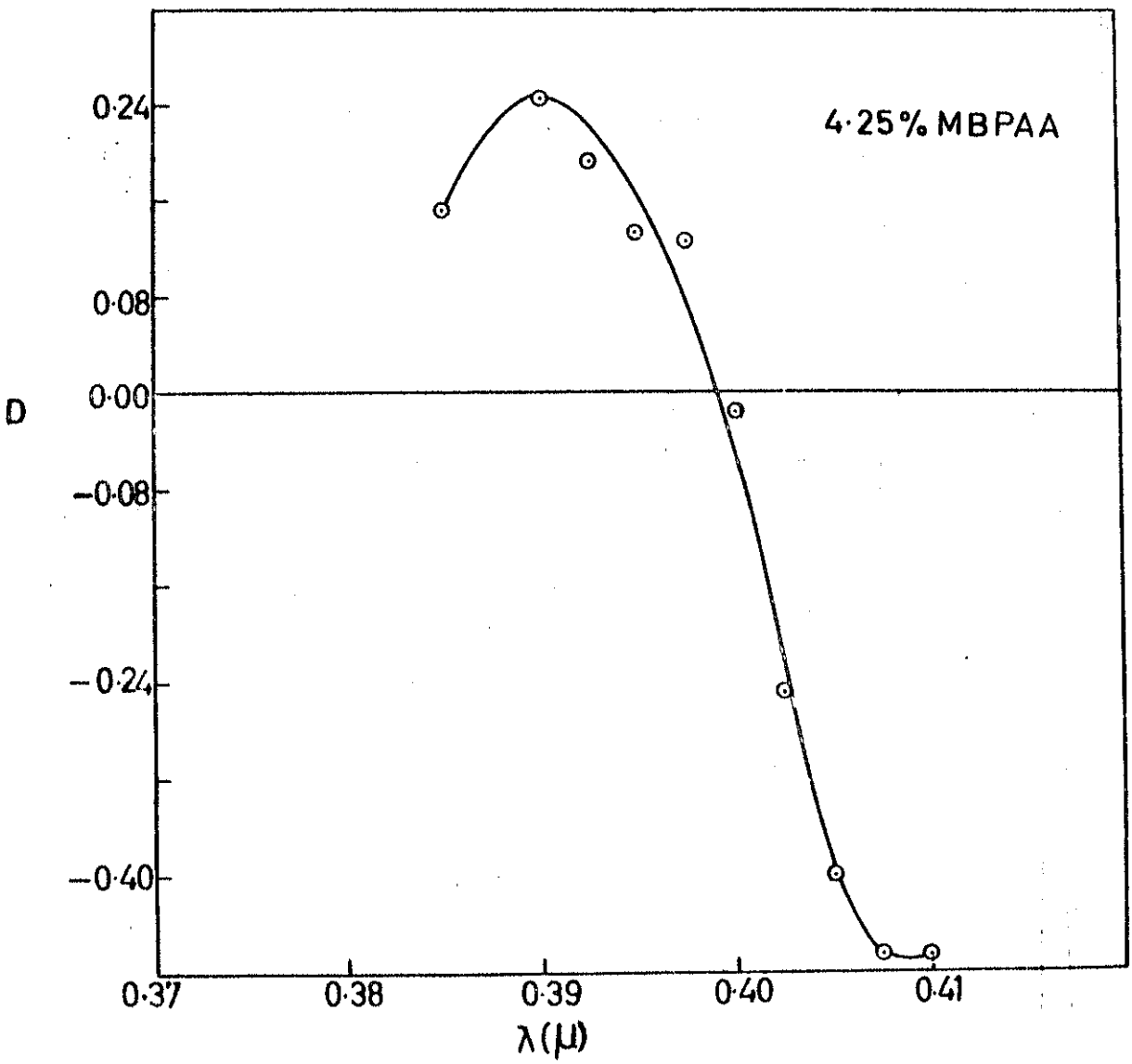


Figure 12: Circular dichroism as a function of wavelength for a sample of thickness ≈ 6.4 μm.

depend critically on the relative position of the refleution band and on the linearly dichroic band of the eolute moleculee, one does not expect it to resemble very closely the theoretical curves (figure 4) computed for conetant Δk. However, the circular dichroism curves (Figures 9 and 12) do ehow a positive maximum at shorter wavelengths which falls off st longer wavelengths, characteristic of the Borrmann effect.

5. Dependence of anomalous transmission on the concentration of eolute molecules.

With a view to making a more detailed comparison with the theory we shall now present studies carried out on thin films of mixtures of cholesteryl nonanoate and p-azoxyanisole (PAA) of different concentrations. PAA was used because the polarized ultraviolet absorption spectra of thie compound have been reported (Maier and Saupe 1956) from which k and Δk could be evaluated and used in the theoretical calculations. All experiments were performed on films at thickness 6.4 μm (with mylar spacers of 0.25 mil). The sample was prepared by

the method explained in seotion 4. The light source was aniodine-quartz lamp whioh has high intensity down to 0.3 μm. The position of the refleotfon band of the medium with respect to the absorption band of' the solute moleoules is very critical in determining the anomalous transmission profile. With increase in the concentration of PAA, it becomes more and more difficult to locate the centre of the reflection band since the setting in of the anomalous transmission alters the shape of the normal Bragg refleotion profile. Moreover the reflection band itself depends on the concentration of PAA and on the temperature. The position of the reflection ban&, looated by the minimum in the transmission spectrum, was adjusted (as closely as possible) to coincide with the absorption band of the solute molecules by varying the temperature. To evaluate the transmitted intensities and circular dichroism D, the same method described in section 4 was followed.

Figure 13 presents experimental curves of D as a funotion of wavelength for 0, 0.98, 1.76 and

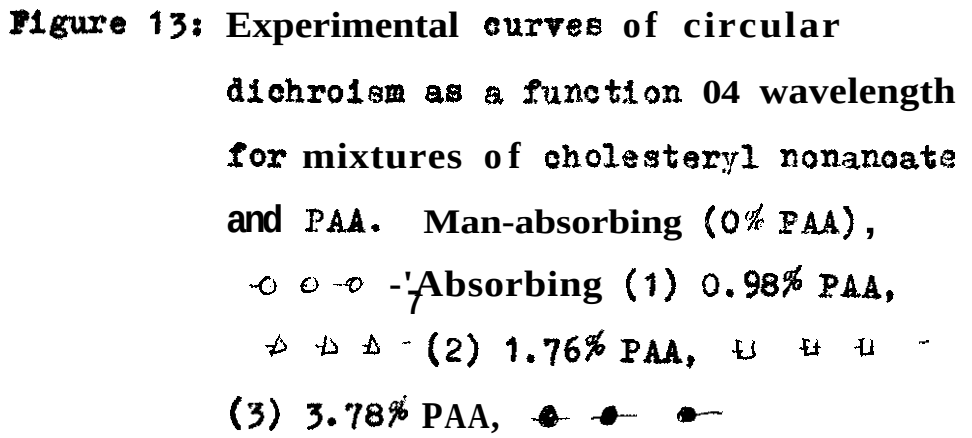
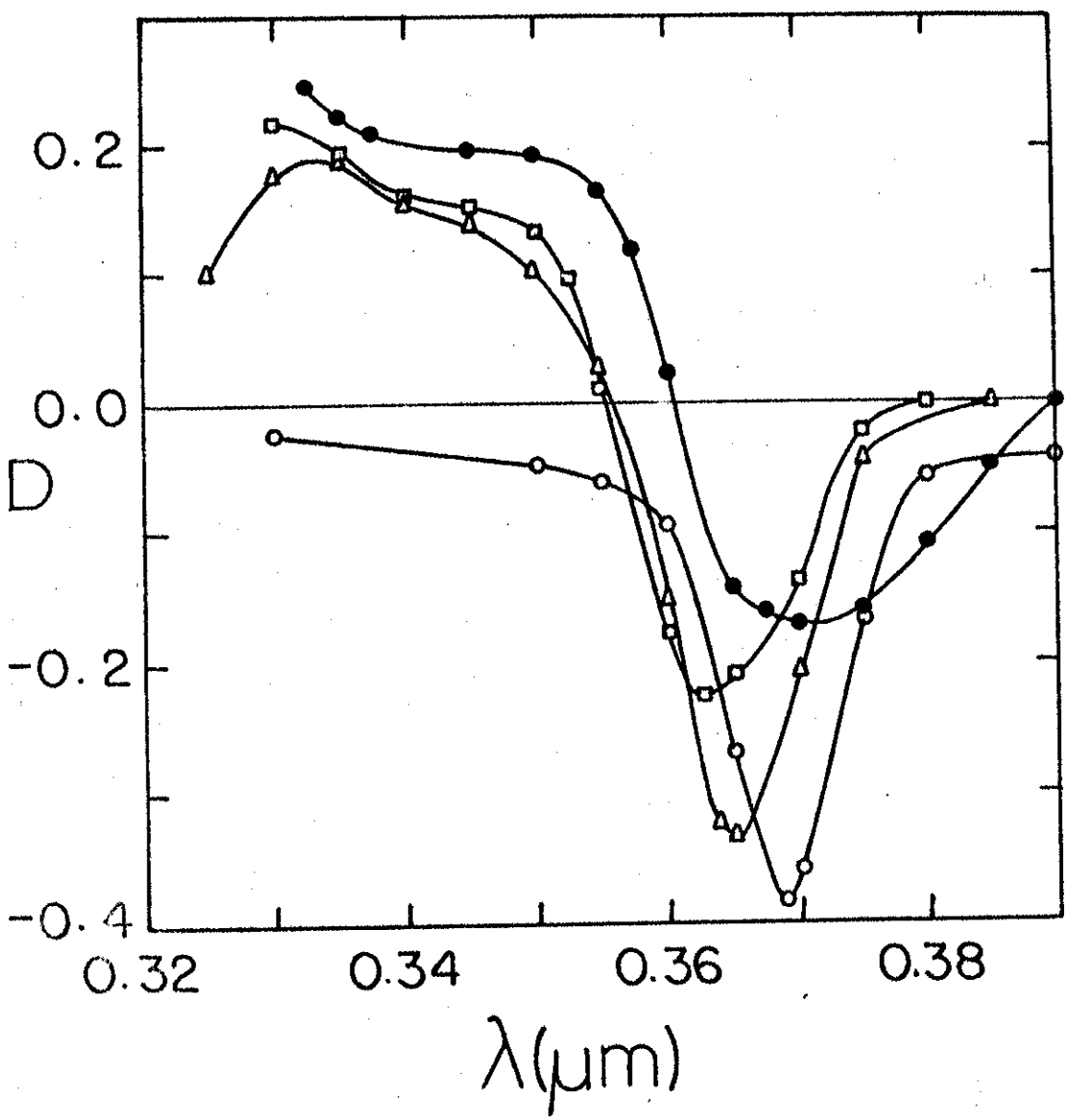


Figure 13: Experimental curves of circular dichroism as a function 04 wavelength for mixtures of cholesteryl nonanoate and PAA. Man-absorbing (0% PAA), Absorbing (1) 0.98% PAA, (2) 1.76% PAA, (3) 3.78% PAA,


0.2
0.0
D
-0.2
-0.4
0.32
0.34
0.36
0.38
λ(μm)

3.78% PAA (by weight) concentration. The curves give the following features:

a. In absorbing cholesterics, D changes sign at the lower wavelength aide of the reflection band, whereas for the non–absorbing cholesterics (0% PAA) D is always negative.

   The change of sign in D for the absorbing case is due Lo the anomalous transmission of the left circularly polarised light which is enhanced at the lower wavelength side and attenuated at the higher wavelength side of the reflection band. The right circularly polarised light Buffers only the normal attenuation,

b. With increase in the concentration of PAA the magnitude of tho negative peak decreases while the positive aide indicates an increasing trend.

c. The half width of the negative peak increases with increasing RAA concentration.

6. Comparison with theory

In section 3 while writing down the equations for anomalous transmission it was assumed that the absorbing system is a right handed cholesteric whereas the cholesteryl nonanoate and PAA mixture used in the experiments adopt a left handed helix. Here the left circularly polarised light undergoes Bragg reflection and anomalous transmission. From (5) the transmitted intensities of the left- and right-circularly polarized light are given by

$$T_L = \left| \frac{\hat{\xi} \operatorname{cosech} m\hat{\xi}}{i\hat{\varepsilon} + \hat{\xi} \coth m\hat{\xi}} \right|^2 \qquad (7)$$

$$T_R = \left| \exp(-m\hat{\varphi}_R) \right|^2$$

where m = number of pitches in the sample thickness. Using equations (7) and (6) the theoretical values of D versus wavelength were computed. The above calculations were made on a IBM 360 computer using Fortran IV language. (I am grateful to Dr. G.S.

Ranganath for his help in writing the computer programme.) The absorption coefficients of the cholesteryl nonanoate + PAA mixture around 0.36 μm were assumed to be only due to that of PAA. The molecular extinction coefficient ϵ for PAA in the isotropic phase ($\bar{\epsilon}$) and in the nematic phase for the electric vector polarised perpendicular to the director ($\epsilon_\perp$) were taken from the data of Maier and Saupe (1956). The maxima of absorption in the two cases are at 0.34 and 0.355 μm respectively. ϵ is related to the absorption coefficient k by the general equation

$$k = 2.303\ \epsilon c\lambda/2\pi$$

where c = concentration of PAA, λ = wavelength of Light. The absorption profiles were fitted approximately to a Gaussian of the form

$$= k_{max} \cdot \exp\left[-\left(\frac{\lambda - \lambda_{max}}{\Delta\lambda}\right)^2\right]$$

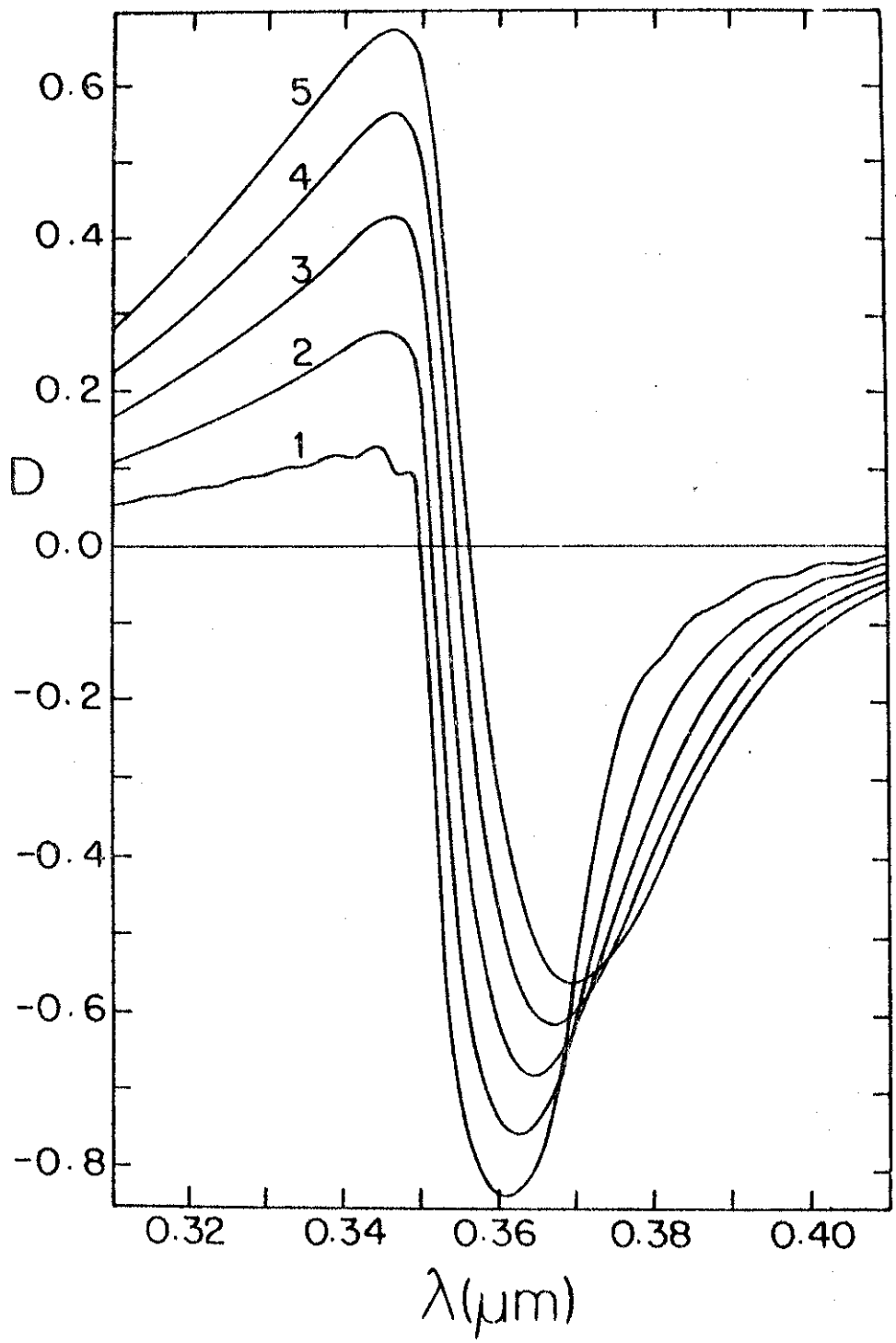
Using the experimental values of $\bar{\epsilon}$ and $\epsilon_\perp$ along with the above expressions, $k = \frac{1}{2}(k_1 + k_2)$ and $\Delta k = (k_1 - k_2)$ were calculated as a function

of wavelength and concentration. The other parameters used in the calculations were P = 0.24 μm, $\lambda_o = \mu P = 0.36$ μm (i.e., $\mu = \frac{\mu_1 + \mu_2}{2} = 1.5$), m = 25 and $\Delta\mu = 0.07$. The dispersion of μ and $\Delta\mu$, as well as the dependence of k and Δk on temperature were neglected. Theoretical curves of D computed for a few typical values of k and Ak are presented in Figure 14.

To check the theory quantitatively is difficult owing to experimental difficulty of adjusting the refleotion band to coincide exactly with the absorption band of the molecules. A slight deviation can drastically change the anomalous transmission profile. For example the Borrmann effect is less prominent in Figure 9 than in Figure 13 for comparable concentrations of PAA since in the preliminary experiments (Figure 9) the refleotion band waa not as carefully adjusted to coincide with the absorption band of the solute molecules as in the case of the later experiments (Figure 13). Ideally, the experiment should have been performed with solute molecules with a very broad linearly dichroic absorption band, but there

Figure 14: Theoretical curves of circular dichroism as a function of wavelength for a few values of k and Δk.

1) $k = 0.0125$, $\Delta k = 0.0157$ (1% PAA)
2) $k = 0.0250$, $\Delta k = 0.0314$
3) $k = 0.0375$, $\Delta k = 0.0471$
4) $k = 0.0500$, $\Delta k = 0.0628$
5) $k = 0.0625$, $\Delta k = 0.0785$


0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
D
5
4
3
2
1
0.32
0.34
0.36
0.38
0.40
λ(μm)

are few euah rnoleoulea. Nevertheless, it is gratifying that there is qualitative agreement between experiment and theory. In particular the prediction that with increasing oonoentrstion of PAA, the positive peak in the circular dichroism curve should increase in magnitude and the negative peak ahould decrease in magnitude but increase in half width is borne out by experiments.

Referenaee

Borrmann, G. 1941 Z. Phys. 42, 157

Chandrasekhar, S., Ranganath, G.S. and Suresh, K.A. 1973 Proceedings of the International Liquid Crystals Conferenoe, Bangalore - Pramana Suppl. 1, 341.

Mafer, W. and Saupe, A. 1956 Z. Physik. Chem. (NF) 6, 327.

Nityananda, R., Kini, U.D., Chandrasekhar, S. and Suresh, K.A. 1973 Proceedings of the International Liquid Crystals Conference, Bangalore - Pramana Suppl. 1, 325.

Saeva, P.D. and Wysocki, J.J. 1971 J. Amer. Chem. Soa. , 5928.

Suresh, K.A. 1976 Mol. Cryst. Liquid Cryst. 35, 267.