(For Counsellor's use only)

Grade . . . . Name . . . .

Evaluated by . . . . Enrolment Number . . . . .

EXPERIMENT 12

STUDY OF INTERFERENCE OF POLARISED LIGHT

12.1 INTRODUCTION

When you studied polarised light you first made many interesting observations using linearly polarised light only. You found such light could be represented as a time- varying vector. This vector pointed in the direction of polarisation, and was perpendicular to the direction in which the light traveled.

Now we ask the question, "How can two such beams be combined?". What are the rules? What, are the limitations ? The answers come from the subject of interference of polarised light.

* Demonstrate the properties of doubly - refracting plates, in regard to polarised light velocities.

* Demonstrate some white - light effects of interference of polarised light, and correctly explain them according to interference principles.

* Demonstrate quarter-wave-plate and half-wave-plate interference, using birefringent plates, polarisers and a spectrograph.

12.2 APPARATUS

2 nos. - Polaroid eye-pieces
2 nos - holder; with graduated angle scale.
1 nos - slotted connector tube
4 nos - sample holders, to fit into connector tube,
1 no - student spectrograph with prism.
1 no - red-plastic filter.
1 roll- 'CELLOTAPE'
1 no - white-light source, tube light or 60 w bulb.
1 no - +10 cm focal-length lens, and lens-bolder

12.3 STUDY MATERIAL

GENERAL FEATURES OF DOUBLE REFRACTION

The optical effects known as "interference of polarised light" are the result of a special property of some materiak. This property is called "birefringence" or "double refraction". This is just a technical word which means that' light in such materials travels at different velocities, depending on the following.

1. The direction of travel and
2. The direction of polarisation of the light.

What is the relation between the velocity of light and the index of refraction? The actual velocity v is given by c/n, where c=velocity in free space, n is index of refraction.

Since there are two directions of polarisation, and each has a separate velocity (or refractive index), the property is called birefringence, and depends on **the direction of travel.**

Lots of materials have this property. Some are crystals, Calcite and tourmaline are two examples. But several transparent plastics have the property also, specially when they are stretched or squeezed. Plastics are easy to get, so we will use them in the experiments to be done later.

There are a lot of complicated observations possible with these effects, and their explanation is often confusing. We will use one particularly simple situation. It will be very direct to analyse and explain. It also has some very important technical applications.

A fact about birefringence.

In almost all doubly-refracting materials there is just one direction along which light waves having either direction of polarisation travel at the same velocity (have the same index of refraction).

This direction is called the optic axis. Please note this "axis" is not a single line, but a direction in the material. A linearly polarised beam of light travelling in the material can be considered as two beams, in phase.

We are going to make an important simplifying assumption, which will agree with the conditions we will encounter in the experiment.

Assume that the optic axis of the doubly-refracting material Lies in the plane of the surface of the material.

Then the two beams consist of one whose direction of polarisation is perpendicular to the optic axis, and called the O-ray, and another whose plane of polarisation is parallel to the optic axis, pnd called the E-ray. These two letters come from the words "Ordinary" and "Extraordinary", which are the traditional names of the two beams or rays.

Together they combine to form the original beam.

Sometimes this idea is described by saying the following, for thk special case assumed.

A beam of linearly polarised light is resolved into two components, one polarised parallel to the optic axis (E-component), and one polarised perpendicular to the optic axis (O-component).

The two ways of looking at this idea give the same result.

How do tbe two waves travel in a doubly-refracting material?

Well, one component, with a plane of polarisation perpendicular to the optics axis, is found to travel at the same speed in all directions (0-component). This is shown in the Fig.12.1, by "Huygens construction".

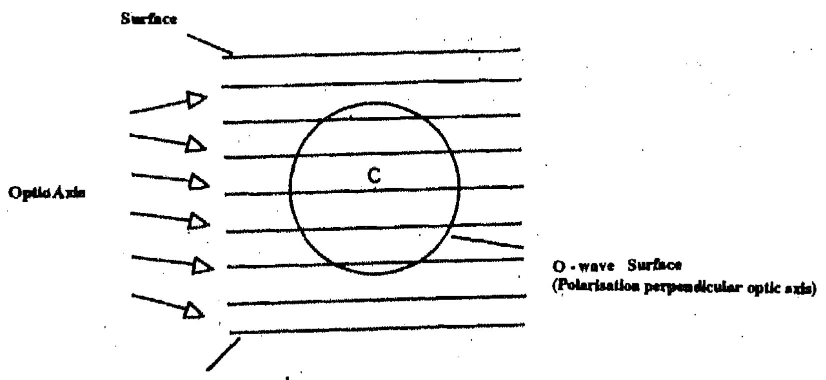

Fig.12.1

Just imagine a brief spark of light at the point C sends light in all directions. After a time it will reach the points on a wave-surface. Since the velocity is the same .PN in all directions, this surface will be a sphere (a circle in tbe Fig.12.1.) This wave is called the ordinary wave, or 0-wave, or 0-wave surface.

different velocities in different directions. The same, along the optic axis, and greater for other directions (this is called 'negative birefringence:, because the E-component index of refraction is less than the O-component). The Huygens construction is shown in the Fig.12.2.

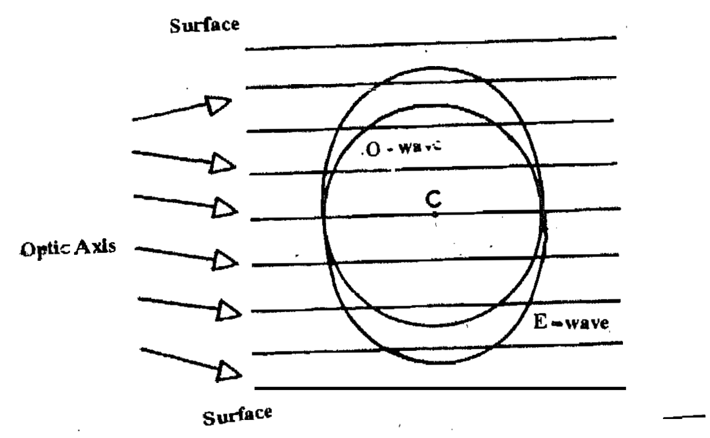

Fig.12.2

The construction gives a Fig.12.2 as shown, and the new wave is called the extraordinary wave, or **E-wave.**

OUR SPECIAL CASE

There are lots of geometric situations possible, some of which lead to very complex ideas. Luckily there is one very simple setup which explains a lot. It is also very important practically. We will stick almost entirely to this situation. Here it is.

The doubly-refracting material is a sheet (layer) of thickness d.

The optic axis is parallel to the layer surface.

The beam of linearly polarised light is incident perpendicular to the surface.

With these restrictions in mind we can draw a Fig. 12.3 showing rays of light inside a negative birefringent material.

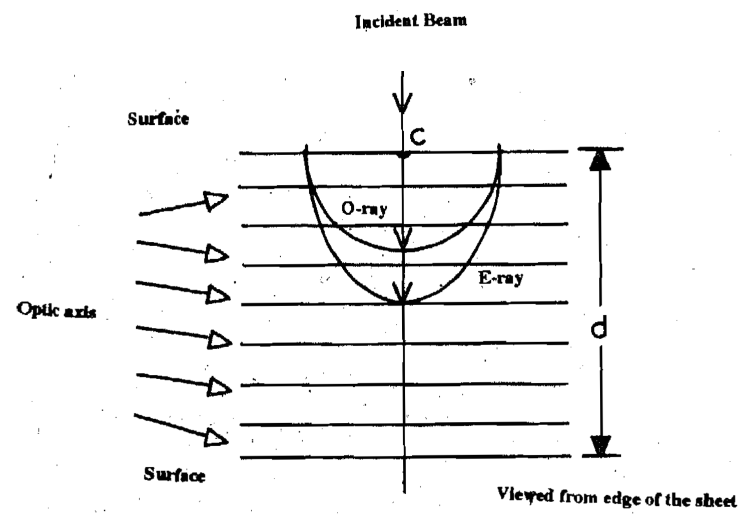

Fig.12.3

Notice a few simple aspects of the Figure 12.3.

1. The incident beam is not deflected by refraction. That means all the light goes straight through the sheet.

2. Some of the light (O - ray) travels at a relatively slow velocity $V_o = c/n_o$, where n_o is called the **ordinary** index of refraction. This ray goes straight through the crystal, and is called the slow ray, or **O** - ray.

3. Some of the light (E-ray) travelsata relatively fast velocity $V_E = c/n_E$. Where n_E is called the extraordinary index of refraction. This ray goes straight through the crystal also, but is called the E - ray, or fast ray.

The O - ray and E - ray were in phase when they were incident, but one emerges before the other in time. Hence a phase difference has been created.

QUANTITATIVE PHASE SHIFTS

How much? Here is one way to calculate. Please follow the argument, as well as the algebra!

1. How much time corresponds to one full oscillation of the light?

Well, $\lambda * \nu = V$, where λ = wavelength of the light
ν = frequency of the light
vibration.
V = velocity of the light. This has the special symbol c for light traveling in free space.

So, time for one oscillation is inverse of the frequency, hence:
P = time for one oscillation = $1/\nu = \lambda/V$

2. How much phase is this? (Remember your wave-studies)

Ans: The phase for 1 oscillation is $2 * \pi$ radians.

3. What is the time difference between **O** and E rays?

dT = time-difference = (time for **O-ray** to go through the layer of thickness d)
MINUS
(time for the **E-ray** to go the same distance).

$= d/(\text{O-velocity}) - d/(E\text{-velocity})$

So the result is that the time-difference is:

$T = d/(V_O - d/V_E)$

Now remember from the definition of index of refraction:
$n_O = c/V_O$ and $n_E = c/V_E$

Hence: $T = d(n_O - n_E)/c$

4. To find what phase this corresponds to, use the rule of proportions.

Time for 1 oscillation /Time between O and E rays = $2 * \pi/\gamma$
where y is the phase change we want to know, in radians.

So, by algebra: $\gamma = 2 * \pi * d * (n_O - n,) / \lambda$

What is the meaning of the equation just derived?

The **O** and **E** rays travel through a birefringent material perpendicular to the optic axis for a distance d and get a phase difference of $2 * \pi * d * (n_O - n_E)/\lambda$.

INTERFERENCE

But this is by no **means the end** of the possibilities, when **linearly-polarised** light is incident on **the material** as above, one part acts as an O-ray and one part **acts as** an E-ray. The Fig.12.4 shows the situation.

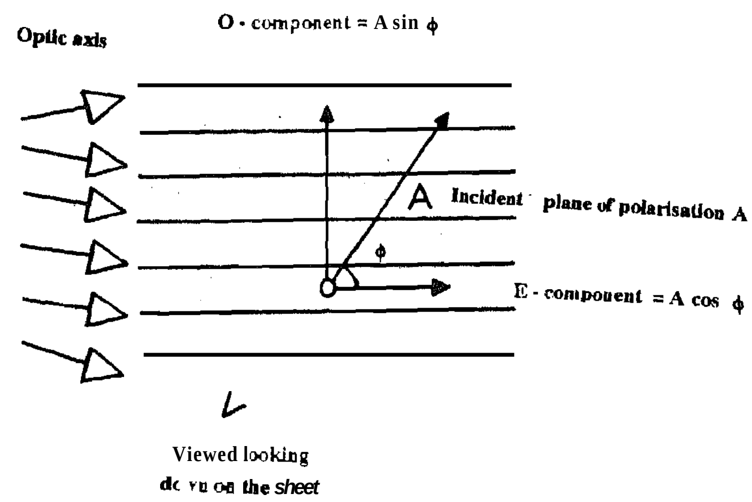

Fig.12.4

A linearly-polarised wave of amplitude A is incident perpendicularly to a material witboptic axis in **the** plane of the surface, and with the plane of the polarisation at the angle ϕ to the optic axis. This divides into two parts as follows.

1. **A component** $E=A * \cos\phi$ with plane of polarisation parallel to optic **axis** and moving with velocity V_E.

2. **A component** $O=A * \sin\phi$ **with plane of polarisation perpendicular to optic axis** and moving with velocity V_O.

These two components move **through the material and can be** observed as they leave the crystal.

When the **two** components **leave, they** recombine. **This is interference !** If the phase-**difference** is $2 * \pi$ or $4 * \pi$ **etc., then** the emerging wave is unchanged. Or, if it is π or $3 * \pi$ then the emerging wave is **plane-polarised** also, but in another direction !

As an example, suppose the original plane of polarisation is at angle 0 to the optic axis, and the **phase-difference** γ is π, or $3 * \pi$, etc., what is the angle of the emerging plane?

The diagrams below show both the incident and **the** emerging situation.

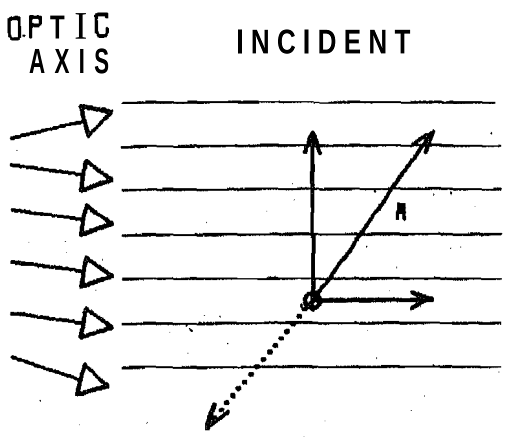

Fig.12.5

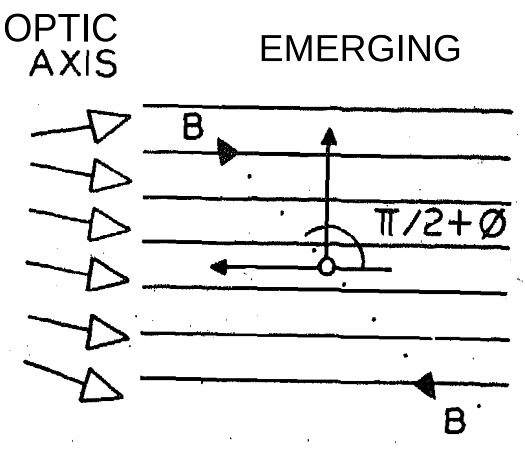

Fig.12.6

Here the vector **describing** the emergent light has a head which moves on a line B-B'.

Well, as an aside, how does the head of the vector move if the phase-change is **not** one of the special cases above?

The answer is: the head moves on an **elliptical** path, and the light is called "elliptically polarised".

Of course you know that a special case of an ellipse **is a** circle. If two conditions **are** satisfied:

$\phi = \pi / 4$, so that $\sin \phi = \cos\phi$
and
phase-difference= $y = \pi / 2$ or $3 * \pi / 2$, etc.

then the ellipse will be a circle, and the light emerging will be "circularly polarised",

Your experiment is going to investigate the effects above, by putting a birefnngent plate betweenan **analyser, crossed with a polariser. So let** us find **out what we can expect to see. There** are many possible **predictions,** depending on circumstances!

Case 1: Monochromatic light
Polaroids crossed.
Birefringent sheet of thickness d.
Indexes of refraction n_0 and n_E.
Optic axis at an angle ϕ to **polariser** axis.

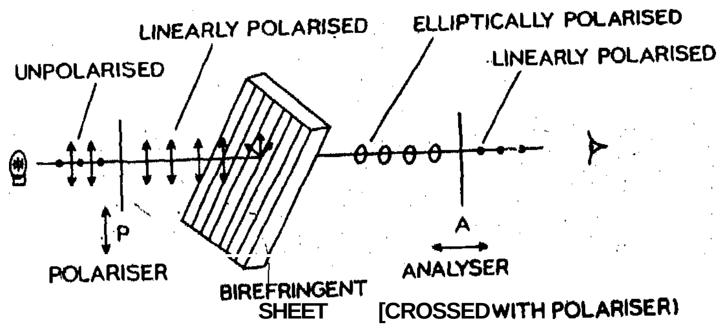

Fig.12.7

QUESTION. What are the **amplitudes** of the **two** components in the **analyser** direction7 (refer to the previous Figure 12.6)

ANS: Each has the value A $\sin \phi \cos \phi$

You will see the two components have thesameamplitude. These are the components that will come out of the analyser, but they will have a phase difference which determines what we see through the analyser of Fig.12.7.

The table below shows some possibilities.

Yhase Difference	Situation	What we see through Analyser
$2*\pi$, or $4*\pi$, etc.	The components are out of phase, and destructively interfere.	No light
π, or $3*\pi$, etc.	The components are in-phase so add for biggest value.	Maximum intensity
Other phase differences	The components are partly in phase, so add for lesser value.	Intensity between zero and brightest.

We will test this prediction in the experiment.

Case 2: White Light
Polaroids crossed,
Other conditions same as Case 12.

Now to predict the result for this case we have to calculate the quantitative effect of phase-difference on the transmitted intensity.

This just means starting in the right place, doing a lot of trigonometry, and getting a compact and useful answer.

To start, you have to begin with two vectors each of size $E = A * \sin\phi * \cos\phi$ but with a phase difference of $(\gamma + \pi)$, since when is zero the two are oppositely directed, from the Fig.12.6. So, the transmitted intensity is the square of the sum of the two vectors.

This is the start mentioned above.

The final result of the mathematics is the following expression.

A, = intensity coming out of the analyser

$= 4E^2 * \sin^2\phi * \cos^2\phi * \sin^2\phi\ (\gamma/2)$

Where ϕ = angle of polariser w.r.t. optic axis.
y =phase difference between emerging O and E rays.
$= (2*\pi*d) * (n_O - n_E)/\lambda$

This is a very useful expression to use in predicting the result of several experiments.

CASE 3: Like Case 2, but λ is allowed to vary. This means the white light is spread out by a spectrometer.

Probably, if d is more than a few wavelengths, there will be some value of λ for which $\gamma = 0$, or $\pi/2$, or π, etc. For these values, no light emerges from the analyser. That means the light from the birefringent plate is linearly polarised, with plane perpendicular to the analyser plane.

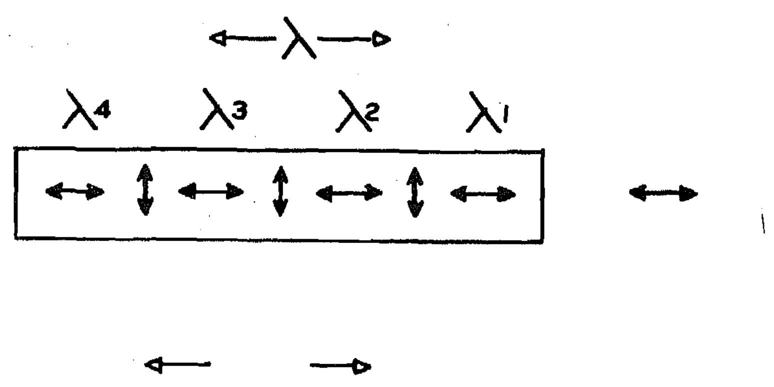

Fig.12.8

Similarly there will be values of λ for which $y = \pi/2$, or $3 * \pi/2$, et. For these values maximum light emerges from the analyser. The light from the birefringent layer is linearly polarised, with plane parallel to the analyser plane.

In-between the light will be elliptically polarised as it emerges from the birefringent layer, The result is as suggested in Fig.12.9.

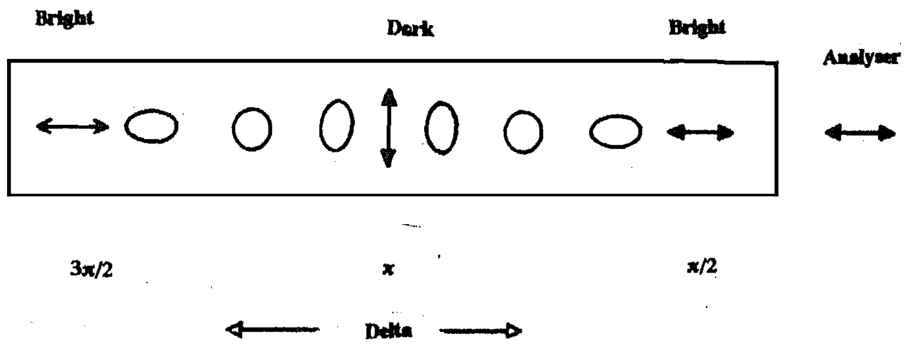

Fig.12.9

This in turn should give rise to an intensity as shown in Fig.12.10.

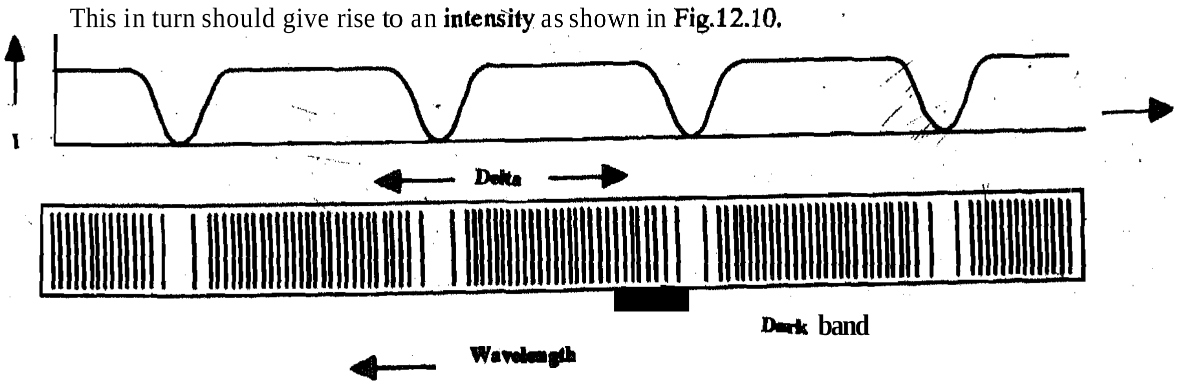

Fig.12.10

CASE 4: White-light
Thin birefringent film
(Only one dark band)

Then, through the analyser all colours will come except the blocked colour! The light will appear coloured, by the absence of a certain colour. These effects are very beautiful. In the experiment you will see several examples of this idea.

Suppose the analyser plane is now turned 90°, to be parallel to the plane of the the polariser. This will change the situation a lot.

Try yourself to sketch here the intensity versus wavelength curve to expect, and what colour may be expected. You can check in the experiment, about your own expectations.

PUT YOUR SKETCH HERE

ONE LAST REMARK

For the case of monochromatic light, with polarised light incident 45" on a birefringent plate with optic axis in the surface, there is a thickness for which the emergent light is just rotated by 90°. You have seen this described above, for positions where $y = \pi$. Such plates retard the O beam by a half-wave-length, and are called half-wave-length plates. There are also plates called quarter-wave plates.

What is the polarisation for light coming out of a quarter-wave plate?

It is circularly polarised.

REFERENCE:

Jenkins and White **Fundamentals** of **Optics**
McGraw-Hill (any edition) Chapter on "Interference of Polarised Light".

12.4 PRECAUTIONS:

Care with the optical parts is as usual: treat them gently, and keep them clean!

In setting up the spectrograph, make sure the light is travelling straight through the apparatus. The easiest way to assure this is to place your eye at each place possible, looking back toward the source.

12.5 EXPERIMENTS

Throughout, the birefringent material to be used is ordinary 'cellotape'. During manufacture the process gives a birefringent plastic with optic axis in the plane of the tape, and in the long direction of the tape. You will be using this material in several ways. The 'sticky' material has no polarising properties ! Only the plastic tape–itself has the properties.

12.5.1 CASE 1

Assemble a 'polarimeter' from the parts. Two Polaroids and scale should be fixed, one on each end of the tube for holding the samples and the filter.

Make sure the red filter is in place.

Prepare 4 glass slides, with 1, 2, 3, 4 parallel-placed layers of cellotape stuck on, respectively.

Start with polariser set at 0^o, and analyser "crossed" with it, so no light emerges.

Place the sample with one layer in the connector tube, look at a light source, and record what you see, in terms of brightness. Then set the polariser at 45°, cross analyser, insert sample and again record brightness.

Proceed this way for 90^o, 135^0, 1800 settings of the polariser.

Fill in the Table with your results, for all four samples.

TABLE

Polariser	Angle	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
0						
45						
90						
135						
180						

Now make a sample with two parallel layers and a third layer stuck on cross-ways (perpendicular).

Repeat the observations with this sample (Sample 5).

Does it behave like any of the other samples?

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Can you give any explanation?

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12.5.2 CASE 2

Use the same arrangement and samples as Experiment 1 except remove the red filter. Now, crossed Polariser + Analyser may not give complete dark, but some dim colour. Record this.

Now, repeat the observations of 12.5.1 but record for each sample and angle some estimate of the colours seen. Note any colour-similiarities or colour-complements especially.

TABLE 1
(CROSSED POLAROIDS)

Polariser	Angle	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
0						
45						
90						
135						
180						

Again, compare Sample 5 results with other samples.
Rotate the Analyser until it is parallel to the Polariser and again note colours observed.

TABLE 2
(PARALLEL POLAROIDS)

Polariser	Angle	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
0						
45						
90						
135						
180						

Please note any ways in which the "crossed" table and the "parallel" table have similarities.

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12.5.3 CASE 3

In this experiment you just set up a prism spectrograph instead of your eye. The arrangement is as shown.

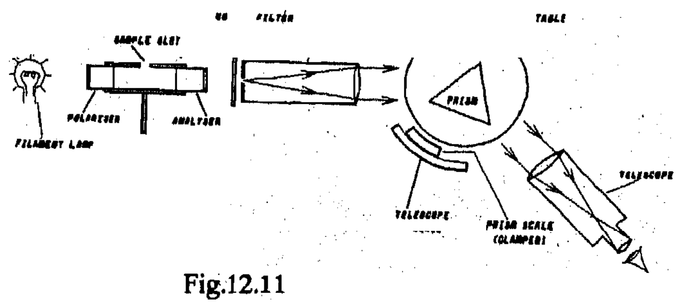

Fig.12.11

Again insert the 5 samples one-by one and sketch the spectrum observed, for the two **polarisations** suggested, especially to note black regions, for crossed polariser and analyser.

Sample 1, **polariser** set at 0°

VIOLET BLUE GREEN YELLOW RED

Sample **2,** polariser set at 00

VIOLET BLUE GREEN YELLOW RED

Sample 3, **polariser** set at 00

VIOLET BLUE GREEN YELLOW RED

Sample **4,** polariser set at 00

VIOLET BLUE GREEN YELLOW RED

Sample 5, polariser set at 00

VIOLET BLUE GREEN YELLOW RED

Sample 1, polariser set at **45°**

VIOLET BLUE GREEN YELLOW RED

Sample **2,** polariser set at **459**

VIOLET BLUE GREEN YELLOW RED

Sample 3, polariser set at **459**

VIOLET BLUE GREEN YELLOW RED

Sample **4**, polariser set at 45"

VIOLET BLUE GREEN YELLOW RED

Sample 5, polariser set at **45"**

VIOLET BLUE GREEN YELLOW **RED**

After you have **completed** this, please try to point out at least a few **examples** where the thickness-variations **or/and** the wavelength variation agree with what is expected in the **Study** Material.

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Any cases you find which contradict the expectations of the study material?

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12.6 CONCLUSIONS

Write in your own **words** what you have found in this experiment, especially if your observations agree with the expectations of the Study Material.