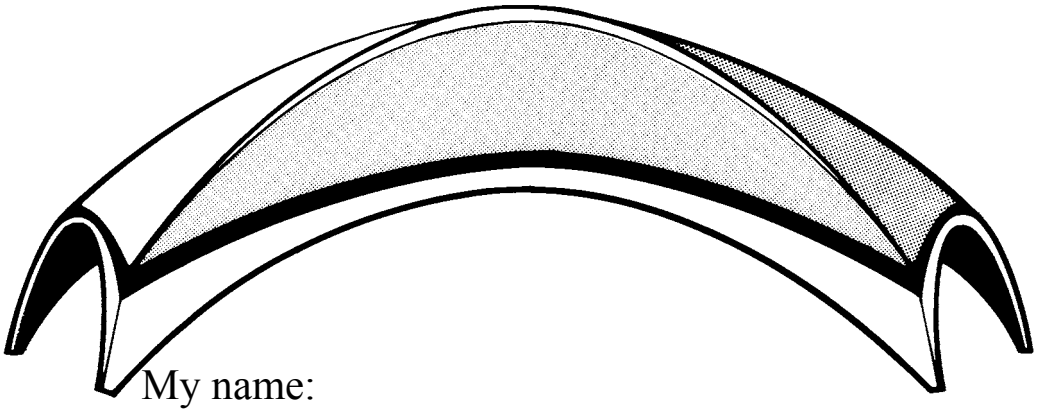
UNIVERSITY OF ABERDEEN

DEPARTMENT OF PHYSICS



My name:

Laboratory Optics

for

Advanced Higher Physics

February/March 2005

OPTICS LAB FOR ADVANCED HIGHER PHYSICS

CONTENTS

NOTE FOR STUDENTS

Please read enough of the instructions for each experiment you try BEFORE you start the experiment so that you know what you are expected to do and how you will go about doing it.

Birefringence in Minerals and Strained Plastic

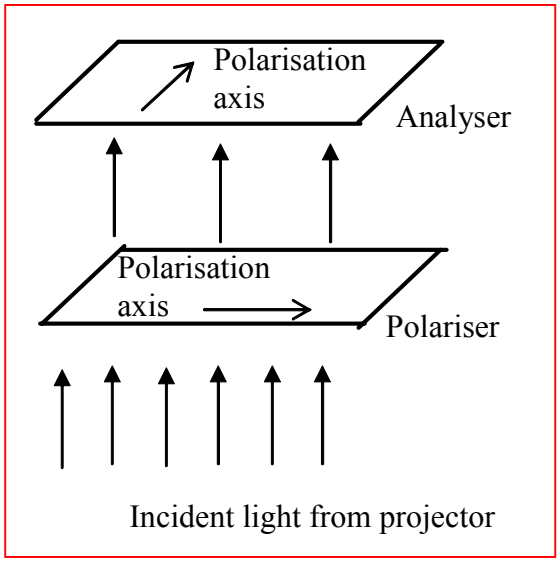
Introduction

Most minerals are *optically anisotropic*, which means that they transmit light at different speeds in different directions. That's not all they do. When an ordinary beam of light enters an anisotropic mineral it normally propagates in two waves whose polarisations are at right angles to each other. This behaviour is responsible for another name describing such materials: *birefringent*. Hence the polarisation of light transmitted through most minerals is closely linked with one of their fundamental properties. Geologists have exploited this for almost two hundred years using the *petrological microscope*. The idea is to cut your rock sample into very thin slices, so thin that they transmit light. Then look through the microscope at the effect of the mineral crystals that make up the rock on polarised light. This will give you information about the mineral or collection of minerals in your sample. That's what we'll do in this experiment. The technique enables skilled geologists to identify the composition of their rocks. The only reason that geologists use a microscope is that the mineral grains inside most rocks are very small. We'll choose a mineral sample that is naturally transparent and occurs in big slabs. You may have guessed that our mineral sample will be *mica*. Sometimes you can see quite big chunks of mica in the stones that make up Aberdeen's granite houses and garden walls.

It's not only rocks that are birefringent. Crystals of many solids are. So are plastic materials that you might think are intrinsically the same in all directions. They are frequently given anisotropy and hence birefringence by the manufacturing or moulding process that makes them. You'll see that in the samples of quite ordinary items that we've got for you.

Background

The gist of the arrangement is to look at a thin plate sample placed between polarisers, made here of Polaroid sheet. The first polariser, usually called "**the polariser"**, linearly polarises the light incident onto the sample. An **analyser** is placed between the sample and the observer looking at the specimen. If the analyser is placed at an orientation of 90° to the polariser, then for a sample of 'ordinary' isotropic material such as window glass the observer will see black, i.e. no light.



Birefringent materials have a special direction within them called the *optic axis*. For this experiment to work well the optic axis must lie in the plane of the sheet sample. For our samples this is the case. When the light enters the sample it divides into two wavefronts polarised at right angles. These wavefronts travel with different speeds and hence the *optical path length* for the two waves after crossing the thickness of the sheet will be different. Remember that optical path length is calculated as (actual length)×(refractive index). This means that the two components are likely to be out-of-phase when they reach the top of the sheet. Now linearly polarised light is characterized

by having any two components of its electric vector *in phase*. Hence the emerging light is in general not linearly polarised. It will have a component of its electric vector parallel to the direction of transmission of the analyser and this will therefore come through the top Polaroid.

Our arrangement will therefore distinguish between isotropic materials and birefringent minerals with their optic axis (approximately) in the plane of the sample.

Our incident light is white. Whatever the thickness of the specimen, for some wavelength (and hence colour) the phase difference between the two polarisations described above will be exactly 360°. For this particular wavelength, the light will emerge with the same polarisation as the incident light and hence will not be transmitted by an analyser that has been set at right angles. The device will therefore take out this colour of light and leave the transmitted light approximately the complementary colour. Hence, the birefringence not only shows up, but it produces very pretty colours in each mineral grain. The most intense **polarisation colours** are seen when the optic axis is at 45° to the orientations of the crossed polariser and analyser. This is because the transmitted waves within the crystal are of equal amplitude in this case. The skilled mineralogist can estimate the amount of birefringence from the maximum colouring observed in grains of a mineral, and hence perhaps identify the mineral itself.

Aims

- To note the use of the technical terms *anisotropy*, *birefringence*, *optic axis*, *optical path length*, *polarisation colours*, *extinction*
- To appreciate the effect of crossed polarisers on a beam of incident white light
- To use a polarised light box that makes birefringence visible
- To observe the effect of assorted birefringent objects placed in the polarised light box
- To observe that a thin mineral samples shows *extinction* at certain angles of rotation and transmits coloured light at other angles
- To characterise the polarisation colours of strips of Sellotape of different thickness
- To make up a pattern of your choice that shows up in polarised light

Safety and Handling Notes

- Don't switch off the light source at the mains. The internal fan is needed to cool the device after the light has been extinguished by the front switch.
- When the projector has been on for 10 minutes, the Polaroid and objects left on it get quite hot. Mind your fingers. Switch off the projector light if you are reading these notes and not looking at the light.
- Treat the mica sheets with care. They are fragile, quite easily broken and not easy to replace.

Action

- Relate the equipment in front of you to the schematic diagram on the first page of this section. Take off the box from the projector and switch the projector on. Place the protractor on top of the sheet of Polaroid on the projector and observe the image on the screen. Focus the image if need be using the knob on the projector lens support arm.

- Remove the protractor. Pick up the other large sheet of Polaroid and look through it at the light coming from the projector. Rotate the piece of Polaroid in your hand around about and observe that there is an orientation in which it transmits the least light and one in which it transmits the most. Write a sentence or two in the following box explaining why the second Polaroid transmits almost no light in certain orientations.

- Put the box on top of the projector with the aperture facing you and the second sheet of Polaroid covering the hole on top. Switch on the light and observe that no light reaches the screen. Place the clean round glass plate on the Polaroid. What do you see on the screen?

The glass is *isotropic*, meaning that it obeys Snell's law and does not affect the polarisation of the incident light. Remove the glass plate.

- Hold the small (grey) piece of Polaroid within the box and notice that light is now transmitted by the top Polaroid. See what happens when you rotate this Polaroid. At what orientation does it transmit the most light? Can you explain why this piece of Polaroid produces a component of light polarised in the direction of the analyser?

T
h
e objects you are about to put in have a similar effect but the reason they do so is different.

- Place the protractor in the box and observe the image on the screen. It should be quite pretty. Turn the protractor around and see if the colours change. Look into the top of the box and you will see even more intense colours.

  The protractor is birefringent because of the moulding process used in its construction. This process induces anisotropy in the plastic that particularly shows up internal strain in the material. The colours will change with the thickness of the plastic sheet and the internal strain.

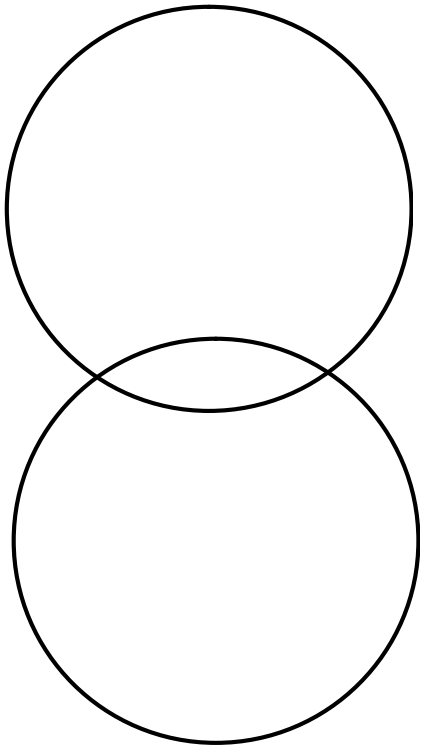
- Remove the protractor and try some of the other items: the spoon, the ruler. Have you got anything of your own you could try?

- Now look at the thin sheet of plastic. Notice that at a couple of angles it transmits no light. This happens when its optic axis lies parallel to the direction of polarisation produced by the polariser. When this happens, only one wave is produced within the sheet and there is no phase difference to change the state of polarisation. This orientation is said to produce *extinction*.

- Now try the thin and thicker pieces of mica. Handle them carefully for they are fragile. They both show extinction. Geologists note where the extinction occurs in relation to the visible edges of the mineral grains and this provides a clue to the identity of an unknown mineral.

- Now explore the birefringence of Sellotape. In the next part you will be asked to make up a coloured design of your choice using strips of Sellotape. The colours will only show when the design is placed in the polarising box. They are achieved by using different thicknesses of Sellotape. In this part you have to see first what different colours you can produce.

  On the glass disk, lay strips of Sellotape in lines or half lines of different thicknesses, i.e. different numbers of layers. It makes a difference if you put layers on top of each other in the same orientation or



not. Make a sketch here showing how you have laid out the strips. Place your disk in the polarisation box and observe the colours. Label the strips in this diagram with the colours seen.

- You are now ready to design your own picture that will just look like a few layers of Sellotape on a glass plate in ordinary light but will show up in the colours of your choice in the polarisation box. You can draw your design in the second blank circle here.

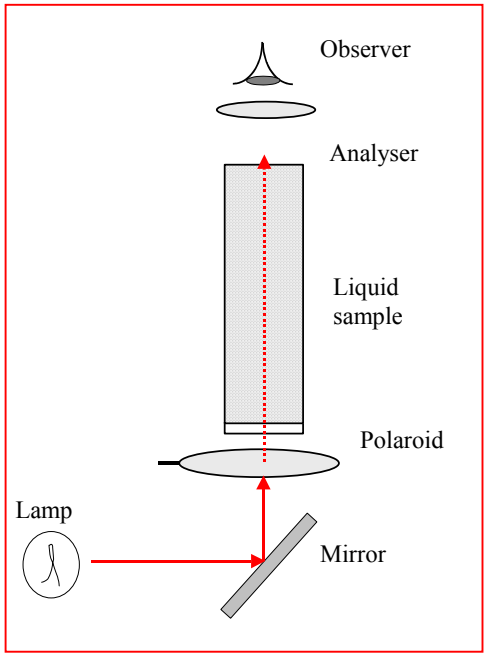
The polarisation of light is an important property. It helps geologists and materials scientists and it can help designers and manufacturers of tools and other objects to make visible what can't otherwise be easily seen, namely properties of the internal structure of the object.

The polarisation box you have used bears some resemblance to each pixel in an LCD display. The pixel is changed from light to dark by changing the influence of the material inside to polarised light. In the case of the cell, this change is controlled by an applied external electric field, created by transparent electrodes just outside the polarisers. The clever bit is finding a suitable material to put in the cell and that's why the material scientists have developed suitable 'liquid crystals'.

THE END

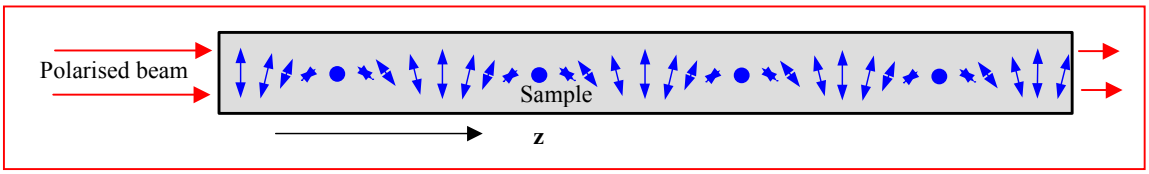
Rotation of Direction of Linear Polarisation

Background



Optical activity is the ability of materials to rotate the direction of linear polarisation of light as it travels through the material. It is of particular interest to structural chemists and biologists and it has quite a few practical applications. The archetypal example is shown by natural dextrose ($C_6H_{12}O_6$) extracted from cane or beet sugar. The illustration shows how it can be observed quite simply. Putting in dextrose (or other sugars) causes the direction of polarisation of the light to be rotated and hence some light to emerge through the top analysing Polaroid. Dextrose always rotates the direction of polarisation clockwise, when back looking towards the source. Such materials are called **dextrorotatory** or d-rotatory. This is how dextrose has got its name. Materials that rotate the direction of polarisation counter-clockwise are called **levorotatory** (sometimes laevorotatory) or l-rotatory.

The sketch below tries to show what is happening for a long sample. A measure of the optically active of a sample is the rotation produced for a 1 mm slab for a solid, or a 100 mm path length for a liquid. This measure is called the **specific rotation**.



If you make sugar by chemical reaction, then you'll find it is not optically active. In fact it contains equal amounts of dextro- and levo-rotatory molecules. Biologically produced sugar is always dextro-rotatory. One application of optical activity is simply to measure the effect in a natural sugar solution and take the activity as a measure of the sugar concentration (e.g. in differently concentrated fruit juices). This is much quicker than detailed chemical analysis of each solution. Another example of using the effect is to measure sugar concentrations in urine, to test for diabetes.

Aims

- To appreciate the phenomenon of *optical activity*
- To observe the effect of optical activity on the direction of polarisation
- To measure the specific rotation of a solution containing natural sugar by plotting the rotation produced for different lengths of liquid column.

Safety and Practical Points

- As you'll see, the column is quite tall – take care not to knock it.
- The juice is both wet and sticky. Please try not to spill any. If you do, wipe it up immediately.

The experiment

To make the experiment easier in practice, we've put the rotatable polariser at the foot of the tube. There is a scale on the holder with which you can measure the angle that the polariser is set to. With no liquid in the tube, make sure the polariser at the foot of the tube is set so that when you look into the top with the help of the top mirror, down through the centre of the filling funnel, you see the centre of the tube as dark as it will go. The juice you're going to add will twist the direction of polarisation, brightening the light coming out of the top. What you will do is turn the polariser at the foot to compensate for this twist so that the top goes dark again. The angle you have turned the Polaroid will be the angle the juice has twisted the direction of polarisation.

What you do is fill the column up in about four stages. At each stage determine at what angle the polariser needs to be set to so that the light emerging from the top is extinguished. Record the result. Finally, plot a graph of analyser setting verses depth of sugar solution (the juice) and find the slope in degrees per 100 mm. This is the *specific rotation of the solution* that you are looking for.

- Start with an empty column. Make sure you can see in the top mirror right down the tube to the light underneath the column. You may also see light reflected off the inner walls of the tube but that doesn't matter. Set the Polaroid below to extinguish the light. Actually, this can't be done completely since Polaroid doesn't work fully over all wavelengths of light. You will be left with a residual purple colour. Record the polariser setting in the adjacent table.

Juice column length (mm)	polariser setting (degrees)
0	

- Carefully pour in the solution to about a quarter full (180 mm). You don't need to get it to exactly this value. Allow time for the funnel to drain. Rotate the polariser until the light coming up the tube is as extinguished as possible, appearing a dull purple. Measure the angle and record it in the table, along with

the corresponding length of the liquid column as determined by reading on the metre-stick.

- Repeat the above, filling the tube approximately half-full, three-quarters full and almost full in 3 more stages.

- On accompanying graph paper, plot your results. Draw the best straight line through your data and record the slope as degrees per 100 mm.

Specific rotation of the juice:	

- Write your answer on the Whyte board.
- Is the solution dextro-rotatory or laevo-rotatory?

THE END

JSR

Polarisation at Brewster's Angle

Background

David Brewster was a Scottish Natural Philosopher with an international reputation in optical science. He was active in the first half of the nineteenth century and was one of the pioneers who made experiments on the then newly discovered phenomenon of the polarisation of light. At Brewster's angle of incidence, i_{pol}, light polarised in the plane of incidence is not reflected. The reflected light is 100% polarised perpendicular to the plane of incidence. [Old textbooks talk about the 'plane of polarisation' of light. Nowadays the term used is *direction of polarisation*, with the **direction of polarisation being the direction of the electric field** associated with the light. Light is said to be *linearly polarised*, not plane polarised.] It can be shown that i_{pol} is given in terms of the refractive index ratio (n_2/n_1) at the reflecting surface by

$$i_{pol} = \tan^{-1}(n_2/n_1) \quad .$$

For a sample of Perspex with $n_2 = 1.45$ and $n_1 = 1.0$ (a suitable value for air in the whole of this experiment),

$$\begin{aligned} i_{pol} &= \tan^{-1}(n_2/n_1) \\ &= \tan^{-1}(1.45) \\ &= 55.4° \quad . \end{aligned}$$

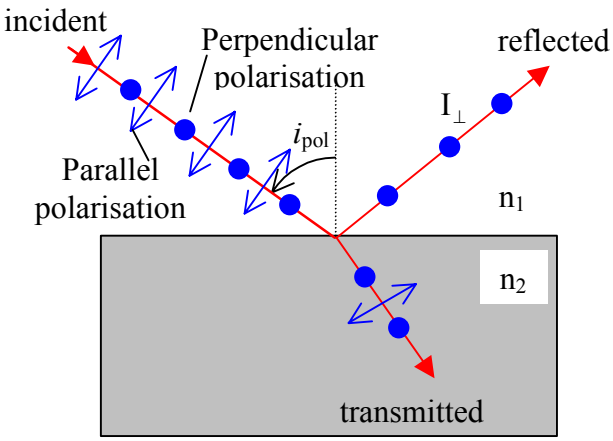


Diagram drawn in the 'plane of incidence'

You can deduce the formula for the Brewster angle if you know that the reflected and transmitted rays are at 90° to each other when the angle of incidence is the Brewster angle.

Aim

This is more an experiment of exploration than of precise measurement. You will:

- measure the Brewster angle for Perspex, and one or two glass samples
- set up a glass plate to act as a reflection polariser
- explore how well a 'pile-of-plates' polariser works.

Laser Safety

There are strict Health & Safety at Work rules for anyone using a laser. Our lasers are Class II, the safest of all likely to be met with in a general laboratory. If you were to accidentally get the laser beam or a direct reflection in your eye then your natural blink reflex would protect you. Nonetheless, take great care, for the source is as bright as the sun and better collimated. Your eye could focus a laser beam onto a very small spot of high energy density on your retina. Observe the following safety requirements:

☠ **Never look straight into the laser light, either into the direct beam or into the beam after it has been refracted or reflected.**

- Never lift up the source and wave it around.
- Take care when putting objects into the laser beam that stray reflections are kept at bench height.
- In so far as you can, direct reflections in towards the backboard of the bench, or the wall.
- Always look down on the laser beam; never put you head at bench level.
- If relevant, keep a backstop that prevents the beam going into the space of a neighbouring experimenter.
- Switch off the laser when you have stopped using it and use the beam-stop lever to suppress the beam when you are pausing in your use.

Our lasers produce unpolarised light. Note the off/on switch at the rear and the beam-stop lever at the top front.

Experiment

Picture showing the front of the laser, the Polaroid in its holder in front of the laser, the semi-circular Perspex prism reflecting the laser beam to the back board.

- Switch on the laser and let it shine directly on to the side wall.

- Take up one of the squares of Polaroid and look through it at a reflection of room lighting coming from a bench-top further down the lab. Twist the Polaroid around until the most reflected light is seen. Circle the correct answer to the following question.

  In which direction is the electric field of the light transmitted by your Polaroid?

Horizontal

Vertical

In a vertical plane but perpendicular to the direction of the light beam reaching your eye.

If you don't know the answer, you should be able to work it out from the diagram on the first page of this topic.

- Place this piece of Polaroid in the holder in front of the laser beam, keeping it in the same orientation as you found above. The intensity of the emerging laser beam is reduced a bit but the emerging beam is now horizontally polarised.

Normal incidence →	Protractor (º) :
Angle at which reflection disappears →	Protractor (º) :
i_{pol}:	
Refractive index n:	

- You will measure the Brewster angle from a Perspex sample. Place the Perspex baseplate with the semi-circular Perspex block onto the black wooden platform so that the laser beam shines onto the block approximately above the rotation pin. Use the flat side of the block as the incident side. Look for the weak reflection coming back onto the front of the laser. Twist the block so that this reflection goes back towards the hole from which the laser beam comes. You have now set the flat face at right angles to the beam, giving an angle of incidence of 0º. You ought to know that this arrangement is called *normal incidence*. Record the protractor reading in the first row of the table, measuring against the line inscribed on the Perspex base.

- Twist the prism so that the reflection goes towards the bench backboard. Once the reflection is passed being at right-angles to the incident beam it will conspicuously fade out. Use a sheet of white paper secured to the backboard to make the reflection more visible in the dark. Determine the protractor reading when the reflection disappears, or reduces to a minimum, and record this in the following line of the table. [If your reflection doesn't fade out, you have put the Polaroid in front of the laser at right angles to the direction it should have been in]. Calculate the angle of incidence i_{pol} as the difference between the two angles you have just recorded. Calculate a value for the refractive index n and put your result in the final line of the table.

- Now tilt the Polaroid in front of the laser and see how sensitive the minimum in reflected intensity is to the tilt. Finally, remove the Polaroid from in front of the laser and answer the following question:

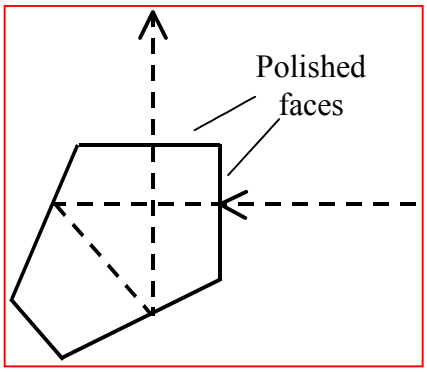
  In which direction is the polarisation of the reflected beam?

A) Horizontal
B) Vertical
C) At about 55° to the horizontal

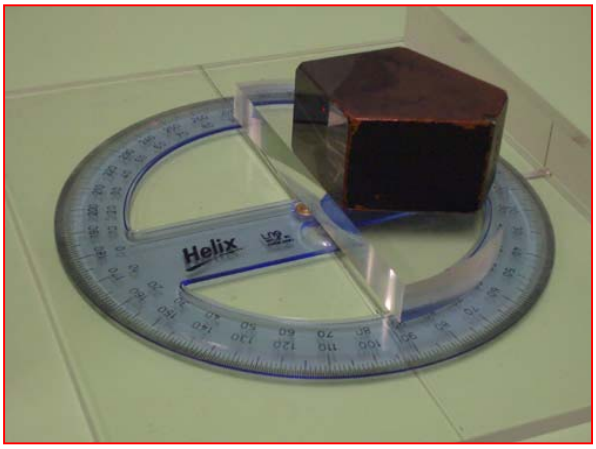
- Slide the Polaroid round to intercept the reflected ray. What direction of polarisation does this Polaroid extinguish?

Put the Polaroid back in front of the laser.

- Now use the technique to investigate whether the glass from which our pentagonal prism is made has a similar refractive index. As a slight digression, look at the pentagonal prism. It has two polished faces at right-angles and the rest coated black. Hold one of the polished faces horizontal and the other away from you, look down closely into the horizontal face and you will see part of the lab. Notice that any writing you can see is legible, unlike the situation of holding a mirror at 45° so you can see through a right-angle. How is this achieved? Some pentagonal prisms can be used as 'optical squares', giving a surveyor an exact right angle. These squares are even more popular now with the widespread use of lasers in surveying and they can even be bought in DIY shops with the advent of lasers for levelling and other jobs about the house.



- The 'pentag' is a useful device. Is its refractive index special? The Brewster's angle test gives you a quick estimate of its refractive index. Remove the black wooden table and put the Perspex base directly on the bench. Sit the pentag on top of the semi-circular prism so that the middle of one polished face intercepts the laser beam and the other polished face is away from you. Set the incident face perpendicular to the laser beam as you did with the semi-circular prism, record the protractor reading and again find when the reflected beam vanishes. Fill in the table as before. Does the refractive index match what you might have expected?



Normal incidence →	Protractor (°) :
Angle at which reflection disappears →	Protractor (°) :
i_{pol}:	
Refractive index n:	

- Now you've seen that the method is very quick. Try it on the block of special glass we

have provided, filling your results into our final table here, on the next page. The nominal refractive index of the glass is 1.76. There are a few reasons why the reflected spot may not disappear completely. One is that the Polaroid or laser beam is tilted from the horizontal; a second is that the divergence of the beam means that the Brewster angle condition isn't exactly satisfied for all the beam.

Normal incidence →	Protractor (º) :
Angle at which reflection disappears →	Protractor (º) :
i_{pol}:	
Refractive index n:	

THE END

Experiments on Interference by Division of Wavefront

Aims

1) To re-inforce the textbook concept of interference of light by division of wavefront by choosing one of the phenomena of Newton's rings **or** Fizeau's wedge fringes, setting up a practical example and making measurements using the phenomenon.

2) For those who have time, to observe another examples of such fringes without making measurements.

Choose either Newton's rings

3) To determine the radius of curvature of one surface of a lens using a graph drawn from measurements of a set of ring diameters.

If you have time

4) To take further measurements of an altered set of rings where water fills the gap between lens and optical flat and hence deduce the refractive index of the water.

or choose Fizeau's wedge fringes

5) To set up wedge fringes using one or more suitable spacers and observe the result

6) plot a graph of the fringe position against fringe number and hence deduce the spacer thickness in microns

7) To make a rough estimate of the separation of the yellow doublet lines in the sodium spectrum

Haidinger's fringes and other qualitative observations

8) To observe Haidinger's fringes from one or two optical flats and comment on your observations. To make other qualitative observations.

Summary

You should do *either* activity 3 *or* activities 5 and 6. The choice is up to the accompanying teacher. The other activities are optional for those who get on quickly with their chosen activity and have time left. Read the next section and then go to section 3 or 6 according to the experiment you are going to do.

Health, Safety & Good Lab Practice

- Take normal laboratory precautions.

- Broken glass is a hazard you want to avoid. We do, too, because we have provided high quality optical components that are expensive to replace. Please take care when handling all apparatus, especially glass components.
- This practical uses PRECISION OPTICAL FLATS AND OTHER HIGH QUALITY COMPONENTS. Please don't put your fingers on the important optical surfaces but hold components by their edge. Keep the important surfaces away from anything that might scratch them.

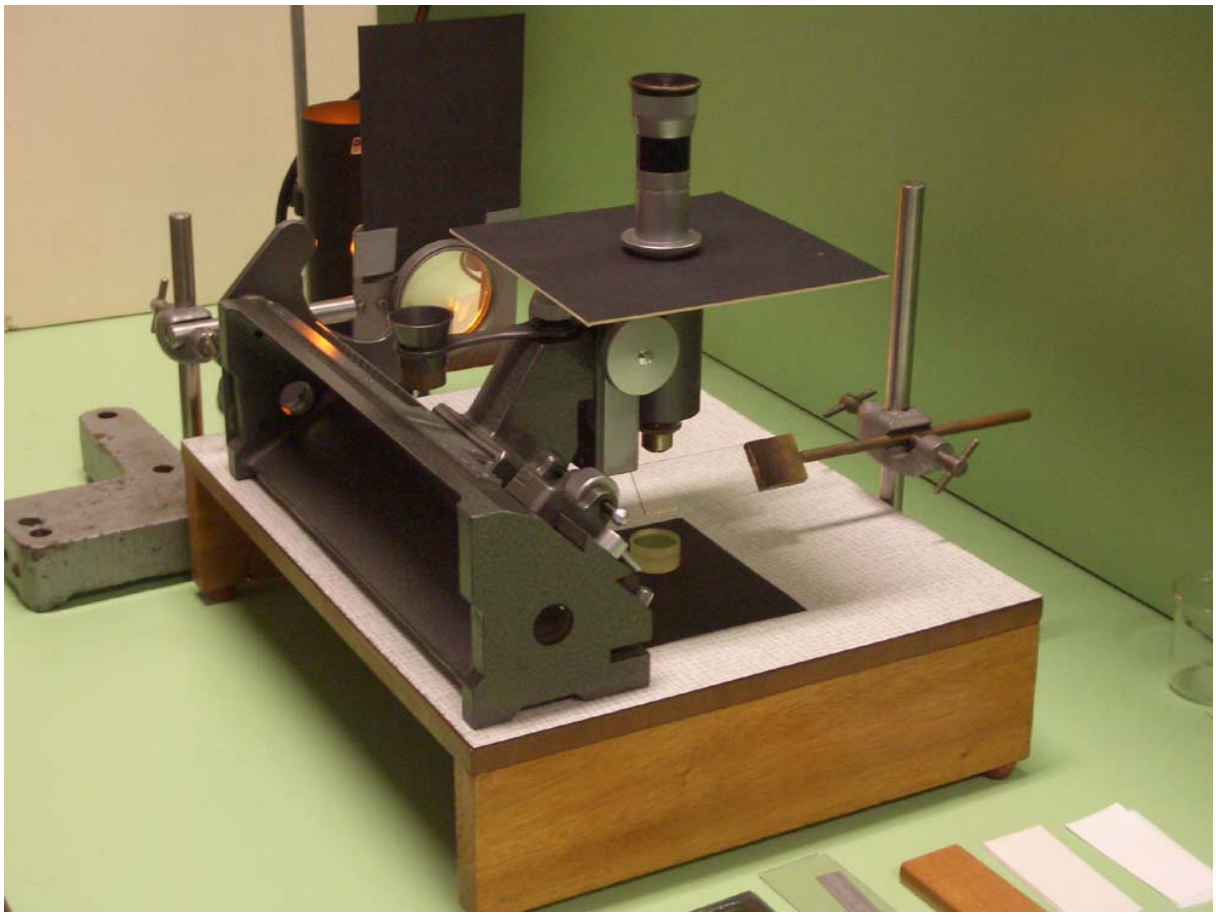
- The sodium lamp ballast resistors on the bench tops get quite hot. There should be no need to touch them once the sodium lamps have been switched on.

- Take care not to pull down the supplementary white lights from the top of the bench. They can also get quite hot to touch.

Theory

You are expected to be familiar with the underlying theory for the type of fringes you will measure but a summary of the ideas, with a schematic diagram of the equipment, is contained in the accompanying *notes*.

Experimental arrangement



Sitting on the black card just below the centre of the picture is an optical flat with small lens on top. An inclined glass sheet reflects sodium light from a source at the back onto the flat.

The fringes are observed through the optics of a travelling microscope that also carries the scale for measuring the fringe diameters.

Activities

3) If the space between the lens and the optical flat has refractive index n, then the radius y of the mth dark ring is given by

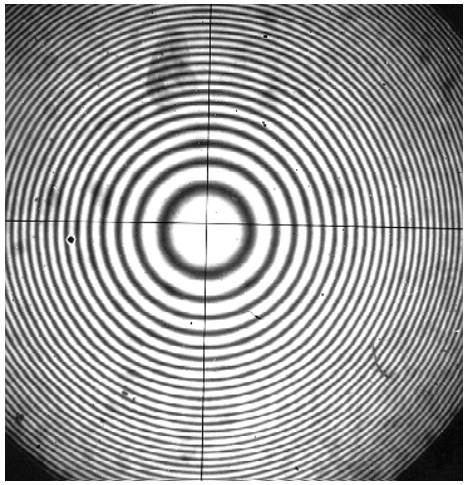
$$y^2 = mR\lambda/n \quad , \qquad (1)$$

where R is the radius of the curvature of the underside of the lens and λ is the wavelength of the light. For sodium yellow light, λ = 589.3 nm. For air, n = 1 to the accuracy required. If the lens is not in exact contact with the glass plate, m will differ from an integer by a small amount.

What the experiment is about is to observe the rings and measure a set of diameters. From the relationship between ring radius, y, and lens radius of curvature, R, that is given above then you can deduce the radius of curvature of the underside of the lens. Our lenses have the top surface nominally planar (i.e. infinite radius of curvature).

Procedure

See the notes for a general description of the optical arrangement. The apparatus is in front of you, more or less already set up.



Direct measurement

Both illumination and viewing the rings have to be arranged perpendicular to the plate. This is achieved with the help of a glass slide held at 45º. Illumination needs to be uniform over only a few mm at the centre of the lens but it also needs to be directed, after reflections, into the microscope objective lens. You don't need an auxiliary condensing lens to see Newton's rings but it helps.

A ring pattern roughly like that shown here should fill the field of view of the microscope. The fringes are *localised* at the underside of the lens and hence you have to focus the microscope there. You may have to adjust the microscope focus a little. If you do, DON'T RACK DOWN THE MICROSCOPE TOWARDS THE 45º GLASS PLATE WHILE LOOKING THROUGH THE EYEPIECE. The technique is to take your eye away from the eyepiece, move the microscope towards the angled plate so you can see clearly that you aren't hitting it, then look through the eyepiece and slowly **rack the microscope up** until you see the image clearly in focus.

The microscopes all have cross-wires that you can focus on by twisting the knurled eyepiece ring around. Adjust this focus so the cross-wires are sharp and clear. Set the cross-wires across the diameter of the ring system, which makes one cross-wire parallel to the travel direction of the microscope. Before you start, compare the picture shown above with your effort. The picture shown was taken by a student. It looks OK but there are two ways you

can do a bit better. First, the centre should be black. If it's not, it means that a tiny piece of grease or dirt is preventing the lens making a clean contact with the optical flat below. If this happens to you, take up the lens and flat and wipe them gently with a piece of lens tissue. Secondly, the eyepiece cross-wires are not exactly across the centre of the pattern.

You are now almost ready to start measurements. Check that you know how to move the travelling microscope by small amounts and how to read the vernier scale. There is an appendix sheet on reading a vernier in these notes but if you are not sure about any aspect of the microscope ask a demonstrator for help. The microscope measures in cm, which is not a standard unit of the SI system. Count the centre fringe as number zero.

Measure the locations of the dark rings from one side of the pattern to the other, recording ring position against ring number in the table below. You will get a more accurate answer if you measure the **diameter** of your chosen rings, recording the mid-point of the width of each of the rings on either side of the centre. Hence determine the diameter, $2y$, of every second ring out to number 20 or so.

Ring number	Left-hand side (cm)	Right-hand side (cm)	Diameter ($2y$ in cm)
2			
4			
6			
8			
10			
12			
14			
16			
18			
20			

- Plot $(2y)^2$ against ring number on the accompanying graph sheet.
- Draw in the best straight line that represents the relationship.
- Measure the slope of this line (you can use a calculator with regression facilities if you know how to). Call this slope s in units of cm^2 per fringe. Record the result here:

Slope, s, of graph of diameter^2 against fringe number (in cm^2 per fringe):	cm^2 per fringe

- Hence determine the radius, R, of the underside of the lens from eq. (1). [$R = s/4\lambda$]. Work out what units you have used for the various quantities and convert the result to mm. You are on the right lines if you get a result in the region of 600 mm.
- Can you estimate the accuracy of your result?

Write your results on the Whyte board in the lab and record your result here:

Experimenter's names	Lens radius of curvature in mm

4) In this part of the experiment you put a tiny drop of liquid between the lens and the flat so that it fills the gap between the two at the centre. If you look at equation (1) you'll see that the diameters of the rings will shrink in proportion to $\sqrt{n}$, where n is the refractive index of the liquid. The mathematically inclined can work out (at home!) how much liquid you need to fill the gap for the distance out of the fringes. It's only a fraction of a cubic mm and hence this is a method of measuring the refractive index when you have only a small drop of liquid available. Today we have unlimited water, which is what we'll use.

Pick up a drop of water with the short wooden stick and transfer it onto the flat. Put back the lens and look again at the fringes. You'll notice that they have shrunk and are not as clear as before. The lack of clarity is simply because the refractive index difference between the glass and the water is less than that between glass and air. As a result, the fraction of light reflected at the key surfaces is less and hence the fringes are less visible against stray light in the system.

To measure the refractive index accurately, you really want to plot a similar graph to the last one and take the ratio of the slope of the previous graph to that of the new one. This will give directly the refractive index n of the water. Since there's not much time today, try the experiment quickly by measuring the diameter of just 2 rings, the second and the twentieth. Assume you've done this well and draw or calculate the line between just these two results. Obtain a new figure for the slope of the graph and hence deduce n.

Ring number	Left-hand side (cm)	Right-hand side (cm)	Diameter ($2y$ in cm)
2			
20			

The new slope, s_n, is estimated as $s_n = \left((2y)_{20}^2\right) - (2y)_2^2\big)/18$.

Hence $n = s/s_n$. Record your result on the Whyte board and write it here:

Experimenter's names	Measured refractive index of water

It's actually easier to estimate the accuracy of your result if you have obtained the slope from fitting a range of measurements. Estimating the accuracy properly is a distraction from the day's concentration on the optics so we suggest here that all you do is compare the result with that obtained by other groups and with the tabulated result for water of $n = 1.333$.

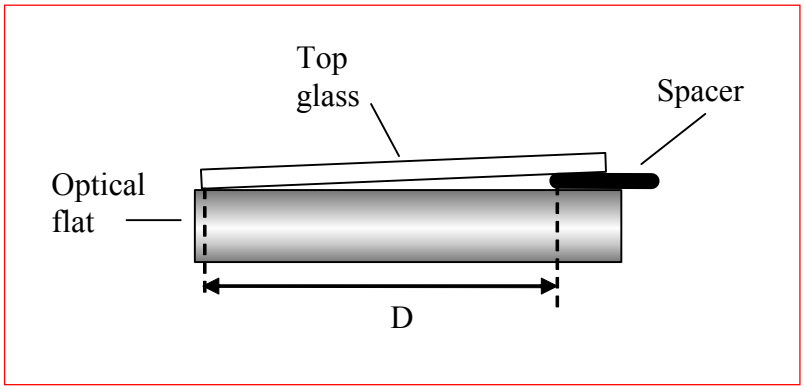
A few quick questions

Write your answer to each question in a phrase alongside the question.

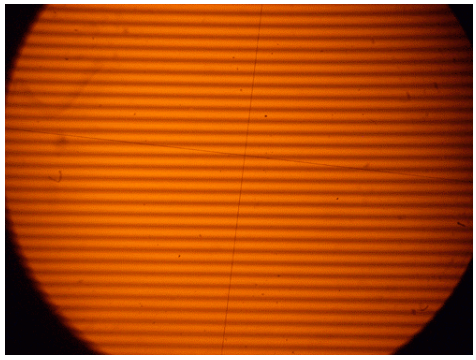
- What would you see if the liquid had the same refractive index as the glass?
- At what wavelength have you measured your refractive index?
- Could the experiment be done by photographing the ring pattern through the microscope and measuring the photograph?
- Over what distance from the centre of the lens have you actually measured the radius of curvature of the lens surface?
- How would the fringes differ if you had used green light?
- What would the pattern look like if the lens wasn't truly circular?

5) Fizeau's wedge fringes are formed between two flat pieces of glass inclined to one another. Your experiment uses rectangles of float glass for both sides of the wedge. Both illumination and viewing the rings have to be arranged perpendicular to the plate. This is achieved with the help of a glass slide held at 45º. The experimental arrangement for viewing these fringes is very similar to that used for Newton's rings excepting the lens and optical flat in Newton's rings is replaced by the wedge between two the flats. See the accompanying notes if you are not familiar with the layout of the components.

You have to make up the wedge, observe the fringes, measure the fringe separation and deduce the thickness of the spacer used. Actually, you will measure the thickness of two objects: first the thin piece of yellow paper we supply and secondly a hair from your partner's head.



Check that you understand how the fringes are formed and why you expect equi-space straight-line fringes. We have provided a shorter piece of glass with a yellow paper strip attached to one end. Use this as the top portion of the wedge, as in this sketch. Wipe both the underside of the slide and the top surface of the optical flat with a piece of lens tissue to clean off minor dust and grease.



The optical flat and the glass plate act together to produce the wedge. Place them on the black paper square in the illuminated region beneath the 45º reflector and look for the fringes through the microscope. The fringes are *localised* at the underside of the lens and hence you have to focus the microscope there. You may have to adjust the microscope focus a little If you do, DON'T RACK DOWN THE MICROSCOPE TOWARDS THE 45º GLASS PLATE WHILE LOOKING THROUGH THE EYEPIECE. The technique is to take your eye away from the eyepiece, move the microscope towards the

angled plate so you can see clearly that you aren't hitting it, then look through the eyepiece and slowly **rack the microscope up** until you see the image in clear focus.

Move the wedge around until the fringes lie parallel to the microscope travel. Notice that the fringes are particularly clear close to the line of contact of the upper and lower glass surfaces. The microscopes all have cross-wires that you can focus on by twisting the knurled eyepiece ring around. Focus on the cross-wires. Set the microscope eyepiece cross-wires so that one is parallel to the microscope travel and the other parallel to the fringes.

6) You are now almost ready to start measurements. Check that you know how to move the travelling microscope by small amounts and how to read the vernier scale. There is an appendix on reading a vernier in these notes but if you are not sure about any aspect of the microscope ask a demonstrator for help. The microscope measures in cm, which is not a standard unit of the SI system. Arbitrarily choose one fringe as the zero fringe.

You'll have noticed that the fringes are close together, so close in fact that the microscope doesn't move much between successive fringes. To get better accuracy from the experiment you need to measure a reasonable number of fringes. We'll choose to measure every third fringe. This will test your concentration. Count the fringes out loud to your partner who can write down the numbers for you. Record the fringe positions y in the adjacent table.

Fringe number	Microscope position (y in cm)
0	
3	
6	
9	
12	
15	
18	
21	
24	
27	
30	

- Now plot a graph of microscope position, y, against fringe number. If you've a conspicuous kink in the graph, you have probably made a mistake in counting the fringes. Re-check your questionable readings.
- Draw the best straight line through your results. The line should be pretty good.

- Obtain the slope of this best line; call it s (in cm per fringe). This slope is $\lambda/2\alpha$, as shown by the theory, where α is the wedge angle (in radians). Record it here:

Slope of graph in cm per fringe

Distance D in cm:	

- Finally, extract the wedge from under the microscope and measure the distance D between the line of contact and the spacer, using a small steel ruler. Use units of cm to match the travelling microscope units.

- Calculate the thickness of the paper spacer ($t = D\lambda/2s$) converting the result to microns. Record the result on the Whyte board in the lab and in the following table.

Names of experimenters	Thickness of paper space in microns

How accurate is your result? This is an optics day and not one to spend a long time considering experimental errors. Estimate the % accuracy in the measurement of D and the percentage accuracy in the measurement of the slope of your graph. In the worst case, the % accuracy of your result is the sum of these two figures. This is a very rough and ready approach that somewhat over estimates the error you might have made. Write the result as a ± figure in the above table.

Having now seen how to use these fringes you are in a position to use them quite quickly to measure something new. Ask your partner for a short piece of hair from their head. (At least one of you needs to volunteer a sample!). Remove the paper spacer and use this hair as the spacer, taking care to make it lie more or less straight. This is a bit tricky, since hairs tend to curl.

Reset up the fringes. Since this is intended to be a quick experiment, we'll just make two measurements of the fringe positions, one at your chosen zero fringe (any fringe will do) and one 20 fringes later. Complete the accompanying table.

Fringe number	Position (y in cm)
0	
20	

Now measure the new value for D.

Distance D in cm:	

Finally, in this section, calculate the hair thickness, *t*, in microns. Use the previous method, namely $t = D\alpha = D\times\lambda\times10/(y_{20} - y_0)$. If D and *y* are in the same units, you will need to express the wavelength in microns to get the thickness in microns, as you probably noticed.

Record your results here and on the Whyte board in the lab.

Names of experimenters	Thickness of hair in microns

7) Did you notice with the spacers used that the fringes became less distinct as you looked close to the spacer itself? This is because the sodium light is not strictly monochromatic but contains two bright yellow lines close to each other in the spectrum. These lines each independently produce their own set of fringes that gradually become out of step as the path difference lengthens. Hence the bright fringes of one wavelength start to fill in the dark fringes of the other wavelength, washing out the appearance of the pattern. The two lines are so close together in the spectrum that they aren't seen as separate colours by our eyes.

Suppose the shorter wavelength is λ and the longer wavelength is $\lambda+\Delta\lambda$. The shorter wavelength produces fringes that are slightly closer together. After N fringes of wavelength

$\lambda+\Delta\lambda$ we find that there are N+½ fringes of wavelength λ and the pattern appears washed out for the reason given above. When this happens $(N+½)\lambda = N(\lambda+\Delta\lambda)$ and hence:

$$\Delta\lambda/\lambda = 1/2N \quad . \qquad (2)$$

- Look at a set of wedge fringes you have set up. Looking through the microscope at the fringes, slide the wedge from the line of contact to where the fringe pattern seems pretty washed out, perhaps close to the spacer. Measure the distance on the wedge with a steel ruler and using the distance per fringe found above, convert this distance to a number of fringes N.
- Use equation (2) above, with λ = 589.3 nm, to estimate the separation $\Delta\lambda$ of the two unseen sodium wavelengths and record your reading and results:

Distance from space to where fringes seem washed out (cm)	Equivalent no. of fringes N	$\Delta\lambda$ (nm)

How does your answer compare with the accepted answer of about 0.7 nm?

Notice that we have found out something about the spectral content of the source by examining the visibility of the fringe pattern that the source produces. This general idea is the basis of a very powerful spectral analysis technique called Fourier Transform Spectrometry. Such spectrometers use no prisms and no diffraction gratings, 'just' a device for producing interference fringes and a powerful computer. Such a spectrometer is flying in ESA's Mars Express space probe that is returning high precision spectral data from Mars at this moment.

A few quick questions

Write your answer to each question in a phrase alongside the question.

- What would be the effect on the fringe pattern if one or both reflecting surfaces were not properly flat?
- What would be the effect on the fringe pattern if the glass plate sagged under its own weight?
- How would the appearance of the fringes change if you filled up the air wedge with liquid?
- How would they change if you used green light instead of yellow light?
- Why do the fringes sometimes seem to run sideways?
- Could the spacer thickness be measured by photographing the fringes and measuring the photographs?

8) This activity is here for those who have made good progress in the quite short time available.

- What appearance have the kind of fringes you measured when you use a white light source?

- Assuming you are familiar with the fringes that you DID NOT MEASURE, locate the central optical pieces needed to show these fringes, put them in place and observe the fringes. You may need to read the beginning of the section you didn't follow to complete the set-up successfully.
- Haidinger's fringes are a different kind of fringe in that they are *fringes of constant inclination* and not fringes of constant optical thickness. They are very easy to see with any good two-sided optical flat to hand. Take the circular optical flat used for Newton's rings and put it on the black card so it is illuminated by the sodium lamp. Carefully lift the microscope aside and look straight down into the flat. With your eyes relaxed so as to focus at infinity, you should see the Haidinger's fringe pattern very easily.
- What change would you expect in Haidinger's fringes if the bottom of the optical flat were not parallel to the top of the flat?
- For a given width of optical flat, do you expect more fringes or fewer fringes across the flat if you could make the flat thicker?

You can't do much with the Haidinger's fringes you have here because there is nothing much you can vary. Haidinger's fringes come into their own when you can vary the distance between the two reflecting surfaces. This is the case in a Michelson interferometer which is the kind of interference arrangement used to measure the spectral content of a light source, as mentioned briefly at the end of section 6.

If you have reached the end of this section in the two hours available and obtained good results along the way, you have done very well. We expect most people will not have got this far. Nevertheless, we hope you have experienced what optical fringe systems can deliver and have seen why they are the basis of some of the most precision measurement available.

THE END

An appendix on the theoretical background follows

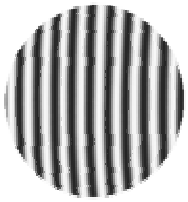
JSR

Appendix Notes on Interference by Division of Amplitude

These notes consist of

- A revision of the phenomenon of interference
- The outline arrangement for observing Newton's rings
- A derivation of the radius of the *m*th dark ring in the Newton's ring pattern
- Similar discussion for Fizeau's wedge fringes
- A brief discussion of Haidinger's fringes of constant inclination

A quick revision of background ideas



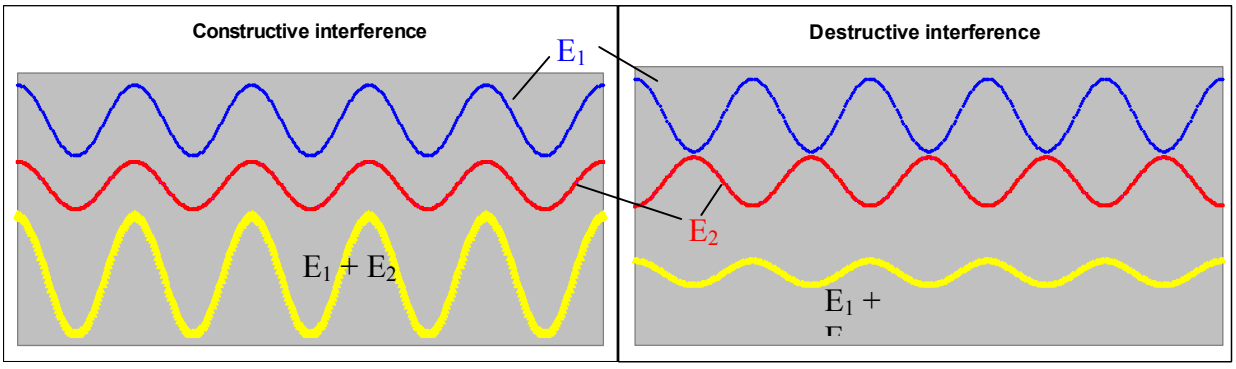
Interference usually shows itself as regular **fringe patterns**, a series of light and dark areas of illumination. Sometimes these are straight-line fringes, sometimes circular, sometimes wiggly. Sometimes the neighbouring lines are equi-spaced, sometimes not.

In the interference in these experiments, **two** coherent light waves will come together at each point in the detector used to see the fringes, usually your eye. How two light waves behave when added together depends on the relative phase of the waves. The two extreme circumstances are:

1) the light waves have just the same phase, which leads to **constructive interference**
2) the light waves are 180° (π radians) out-of-phase, which leads to **destructive interference**

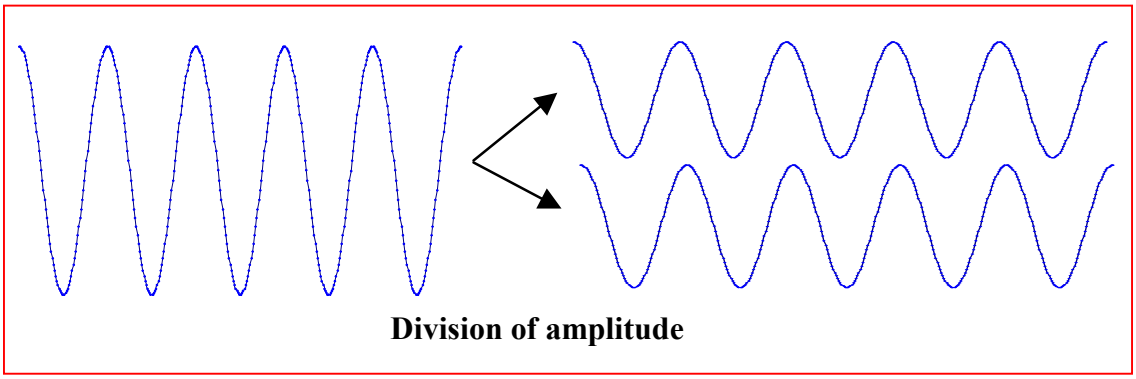
Of course, there can be any phase difference in between these extremes.

The accompanying diagrams show what happens. The top wave (E1) has amplitude 3 units and the lower wave (E_2) has amplitude 2 units. The constructive interference has an amplitude of 5 units and the destructive interference an amplitude of 1 unit.



For interference to be visible, the two waves must keep a constant phase difference in time at any point. The only way to make this happen is to derive the two waves from the same initial wave by a suitable technique (OK, a trick, if you like!). Our experiments use the technique of **division of amplitude**. In this technique a single wave is divided into two by partial reflection at a transparent surface. This is shown schematically in the next diagram. The two waves are made to travel through different paths and then finally come together at the

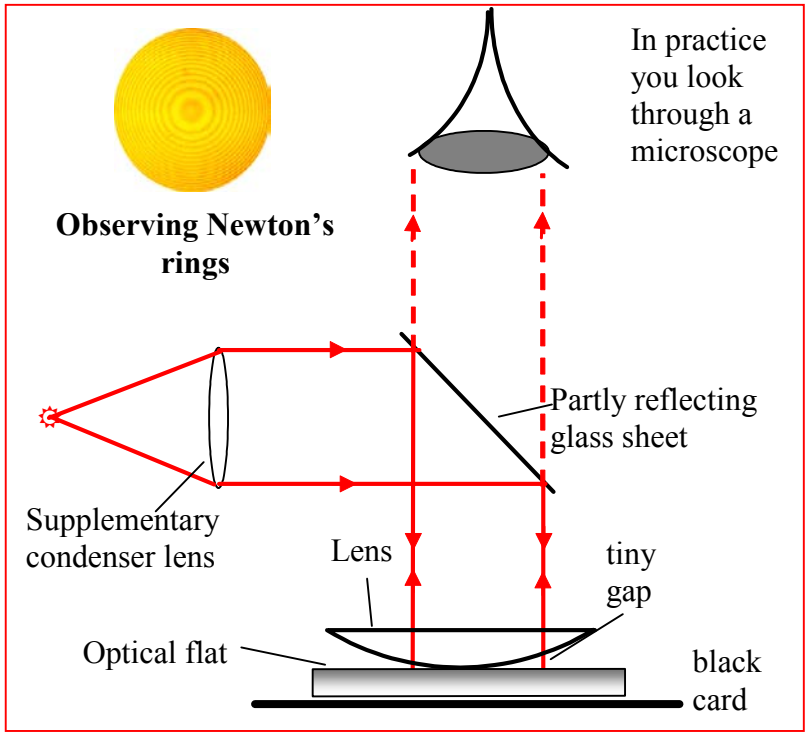
detector. There they add together and the result depends on their phase difference, as above. This is the phenomenon of 'interference'.



The fringes you see are clearest if the two waves interfering have the same amplitude. The arrangements in the lab try to make this so.

Fringes of constant optical thickness

The essential components for observing Newton's rings are a convex lens sitting on an optically flat piece of glass. These are illuminated normally (i.e. at right angles) by a fairly parallel beam of light. Newton's rings are interference fringes formed by light reflected from the **bottom surface of the lens** and the **top surface of the optical flat**. Fringes occur because the *amplitude of each single light wave from the source is divided* by the reflections so that part of the wave travels by one path to the eye and part by a longer path across the (tiny) gap between the lens and flat and back again. When the waves recombine in your eye (or in a camera that can replace your eye) the interference takes place. The spacing between the two reflecting surfaces, and hence the extra distance taken by part of the light, gradually increases as you look away from the point of contact of lens and flat in the middle. The simple geometry of the situation ensures that the fringes are circular (if the lens is truly circular). They are described as **fringes of constant optical thickness**.



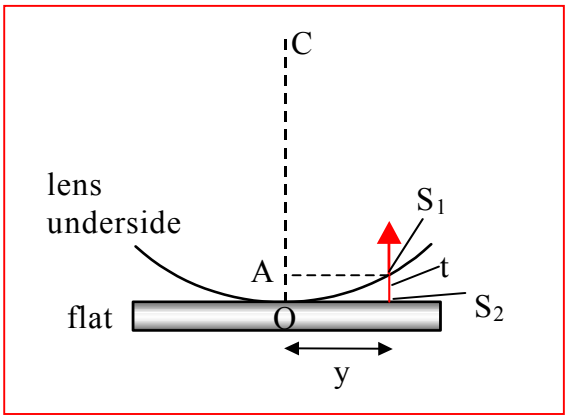
The figure shows the arrangement for observing the fringes used in the lab. Light from an almost monochromatic source, a sodium lamp, is shone down via a glass plate onto the air

wedge between the lens and the flat. The fringes are observed vertically, through the glass sheet. In practice they are usually so close together that you use a low power microscope to see them. The microscope has to be focused on the underside of the lens because the fringes appear to be *localized* there.

The theory giving the distance out from the centre of the '*m*th' fringe is given in the next section. The experiment involves measuring this distance for a range of '*m*' and deducing from the results the radius of curvature of the lens and, later on, the refractive index of the medium that you will put in place of the air.

Relation between dark ring radius 'y' and ring number 'm'

In the adjacent diagram:



O point of contact of lens and flat
C centre of curvature of lens surface
S_1 point of reflection of light from lens
S_2 point of reflection of light from flat
y distance of S_1 and S_2 from the line OC, i.e. ring radius
t physical separation of S_1 and S_2
R = OC = CS_1, radius of curvature of lens lower surface
n refractive index of medium in gap between lens and flat
λ wavelength of the light (in vacuum or, near enough, in air)

Facts:

1) there will be destructive interference leading to a **dark fringe** at a distance y if the extra light reflected at S_2 is an *odd number of half wavelengths* out-of-phase with the light reflected at S_1. An odd number is given by (2m +1), where m is an integer.

2) The number of wavelengths in a light path of length 2t in a medium of refractive index *n* is $2nt/\lambda$. $2nt$ is called the *optical path length*.

3) If *n* is less than the refractive index of the lens and flat, then light reflected at the flat undergoes a phase shift of π radians (equivalent to an extra path length of half a wavelength), whereas light reflected at the lens rear surface does not.

Putting these facts together gives:

$$(2m+1) = 2.\frac{2nt}{\lambda} + 1 \quad ,$$

i.e.

$$t = \frac{m\lambda}{2n} \quad . \qquad (1)$$

If the lens surface were plane rather than curved, then the distance y of the dark fringe from the centre would just be proportional to the integer m. Because the lens surface is spherically curved then t is not proportional to y but to y^2. This follows from the figure because:

$$y^2 = R^2 - CA^2 \quad \text{(triangle } CAS_1\text{)}$$
$$= R^2 - (R - t)^2$$
$$= 2Rt - t^2$$
$$\approx 2Rt \quad \text{(because } t << 2R\text{)} \quad . \qquad (2)$$

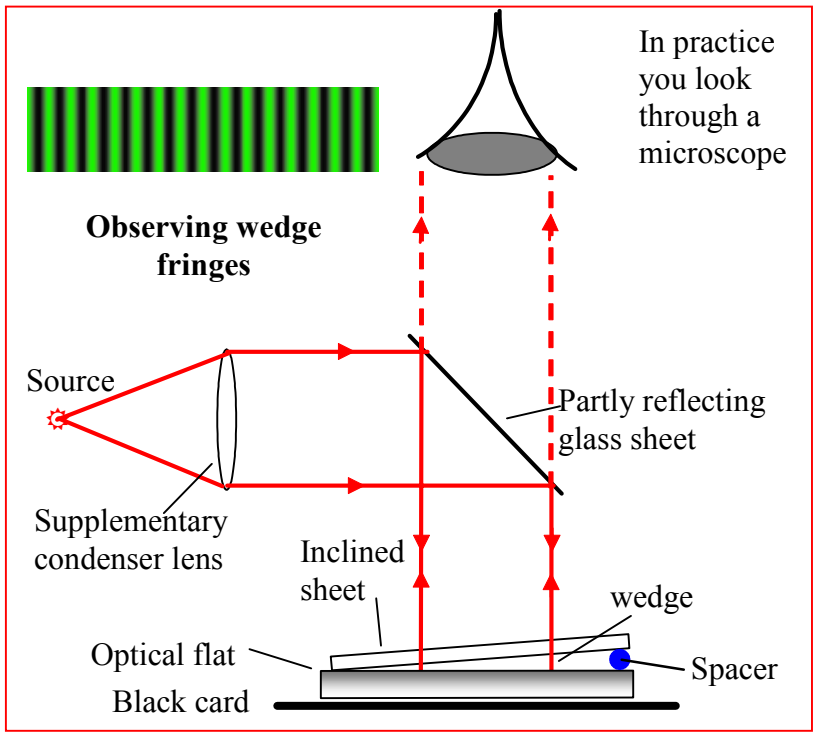
Putting (1) and (2) together gives:

$$\boxed{y^2 = \frac{mR\lambda}{n}} \quad .$$

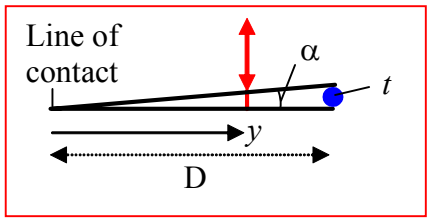
This relationship underlies the practical use of Newton's rings.

Wedge fringes (alternatively known as Fizeau's fringes)

Wedge fringes are formed in the very same way as Newton's rings, except that the gap is created by a wedge formed between two flat pieces of glass. The fringes are now straight lines parallel to the line of contact between the two flat pieces of glass (or they would be completely straight if both pieces of glass were completely flat).



You can use the wobbles in these fringes to look at how the surface of the glass differs from ideal flatness. You can use the method to measure very simply the thickness of the spacer holding the plates apart.



Let the spacer have thickness t. The wedge angle α is given by

$$\alpha = t/D \quad .$$

In Fizeau's wedge fringes, the optical path increases linearly with distance y from the line of contact. The extra path difference between the light reflected from the top surface and that reflected from the bottom surface is clearly $2\alpha y$. This path difference increases by one wavelength for each successive fringe. The fringe spacing is therefore given by

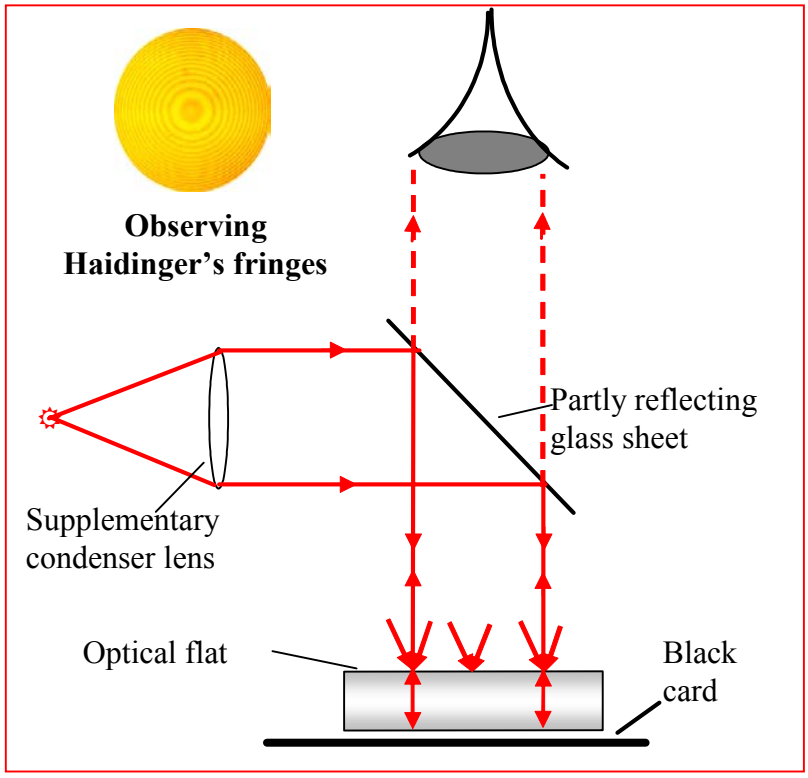
$$\Delta y = \lambda / 2\alpha,$$

where λ is the wavelength of the light in the wedge. If you measure Δx then you can quickly find α and hence adding a measurement of D will give you the spacer thickness *t*, since t = αD.

In practice the angle has to be pretty small for the fringes to be visible to the naked eye. E.g. if the distance between neighbouring fringes is Δy = 0.1 mm for λ = 500 nm, then the angle $2\alpha = 5\times10^{-3}$ radians and hence α<0.2°. If the spacer is a hair of thickness 75 μm, then D, the length of the glass plates, needs to be at least 30 mm long.

Haidinger's fringes

Haidinger's fringes are seen without a microscope. They are **fringes of constant inclination** formed by interference between the top surface of the optical flat and the bottom surface of the optical flat. What is happening is this.



The broad source of light illuminates the flat not only with perpendicular rays but with rays coming in at a range of angles, as hinted at in the diagram. The extra path length between light reflected from the top of the flat and the bottom depends on both the thickness of the flat and the inclination of the rays. The more you look away from the centre of the flat the more inclined are the rays that you see. At a given distance from the centre line to the flat, all rays around a circle are inclined at the same angle and hence you get a fringe pattern that is circular, superficially just like Newton's rings.

There are 3 differences between these fringes and Newton's rings. First, they are spread out over the whole flat. Secondly, they are formed by interference between parallel wavefronts and are localised at infinity, meaning you have to focus your eyes or a camera at infinity to see them. Finally, of course, the reflecting surfaces dividing the amplitude of the light waves are different from those that form Newton's rings, being the front and back surface of the flat.

JSR

The Spectrometer

Introduction

The spectrometer you have before you is an accurate instrument. The component that generates the spectrum from the incident beam is called the *dispersive element*. You have a choice of *prism* or *diffraction grating*. Both of these components create outgoing light at different angles for different wavelengths. This outgoing light is observed by a *telescope* that swivels about the centre of the spectrometer and whose angle can be measured to half a minute of arc on a *precision scale with vernier*. Because the wavelength of light and the telescope angle are related, this angular measurement is the crucial one that lets you determine the wavelength of a chosen feature in the spectrum. The other projecting part to the spectrometer is a fixed *collimator*, whose purpose is to create a parallel beam out of the light from an illuminated *slit*, so that the dispersive element is illuminated by *parallel light*. Under these conditions, the telescope will form an image of the slit at each wavelength and it is this image that constitutes the *spectral lines* seen. That is the principle of the spectrometer. Important practical details can be left until later.

Aims

- To appreciate the purpose and function of the parts of an optical spectrometer.
- To set up a prism correctly on the spectrometer table and know how to adjust the prism so that any spectral line is seen in the **minimum deviation** position
- To observe the spectra of different light sources with the spectrometer and appreciate the variation in the spectra.
- To calibrate the prism spectrometer using a helium discharge tube.
- To measure the wavelength of the brightest line in the mercury spectrum and the wavelength limits of your own vision.

EITHER

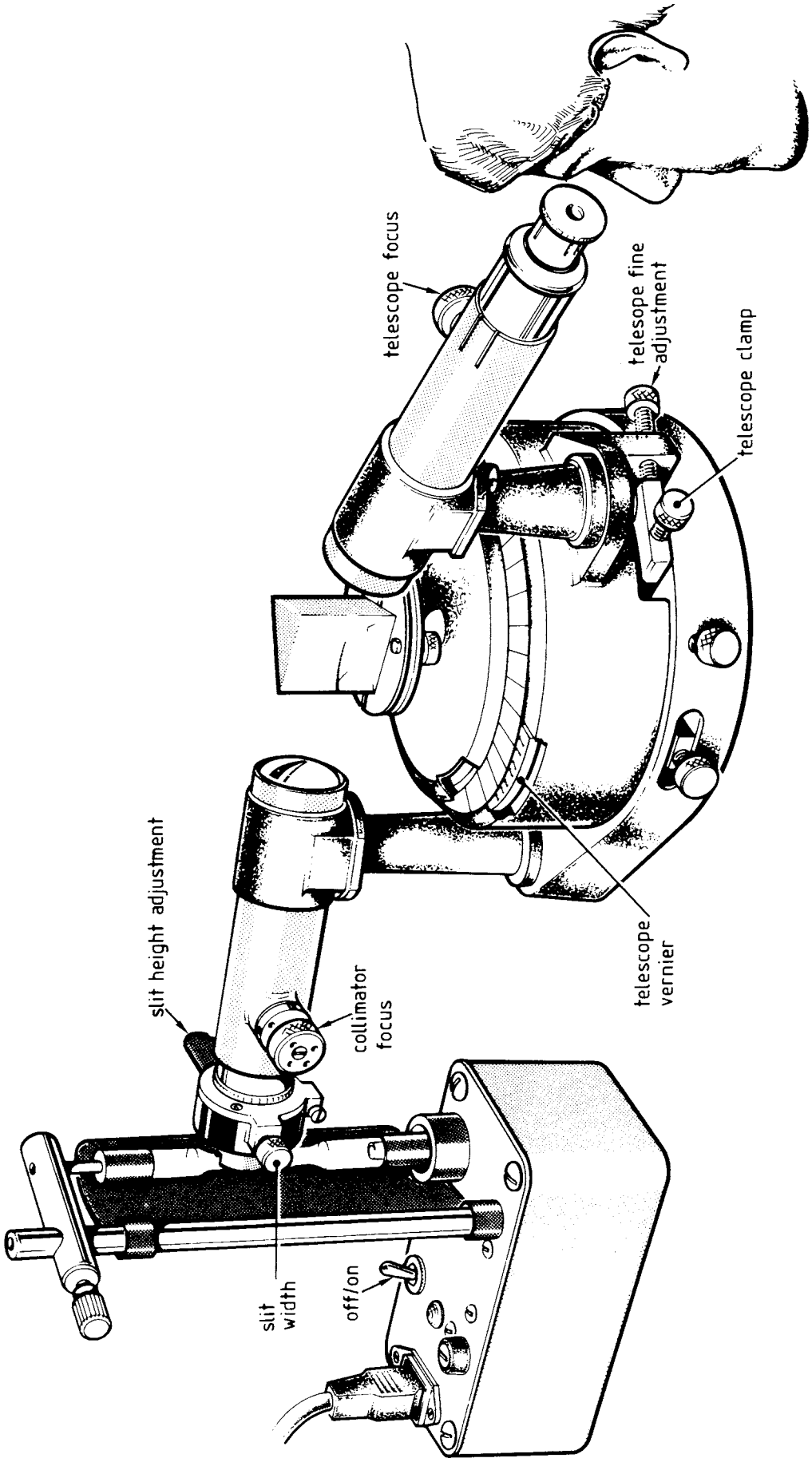
- To measure the dispersion of refractive index shown by a glass prism.

OR

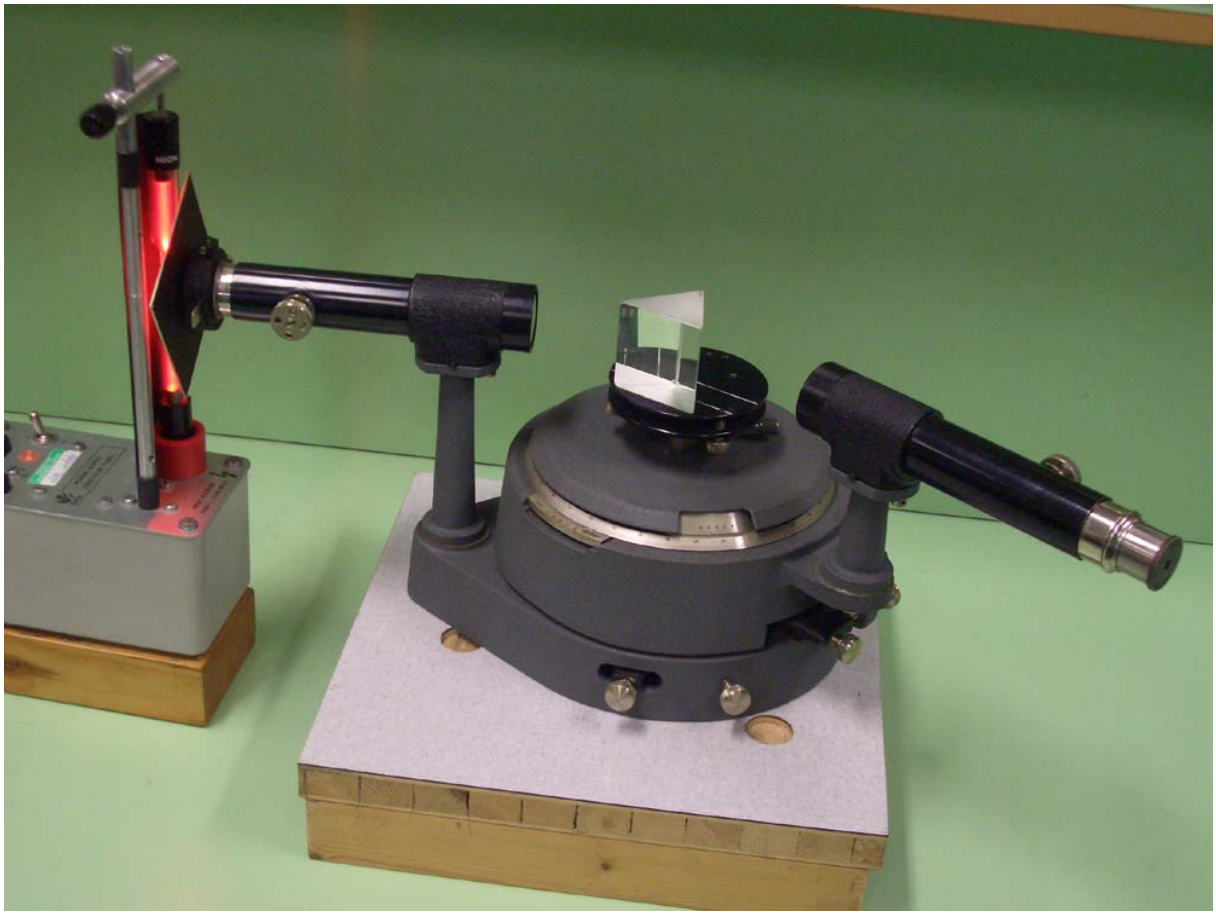
- To observe the spectrum given by a diffraction grating, note the difference between it and the prism spectrum and to calibrate the diffraction grating.

Activities

The activities in this practical are highlighted by bullet points in the following notes. Between the bullet points there is background information.


telescope focus
telesope fine adjustment
telescope clamp
telescope vernier
slit height adjustment
collimator focus
slit width
off/on

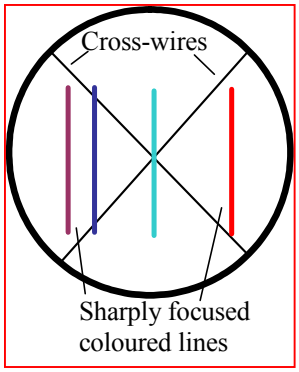
Adjusting the Prism Spectrometer



It helps if you start by taking time to relate the parts named on first diagram to the instrument itself. You will then know what the various adjustments do. However, you should find the spectrometer already adjusted optically so that spectral lines are sharply in focus, fairly narrow and in the middle of the field of view. If they aren't, consult a demonstrator. There is an appendix describing how to focus the instrument correctly, for those who would like to know. The spectrometer is an accurate and quite expensive instrument and you can get good results from it by reading the scales carefully.

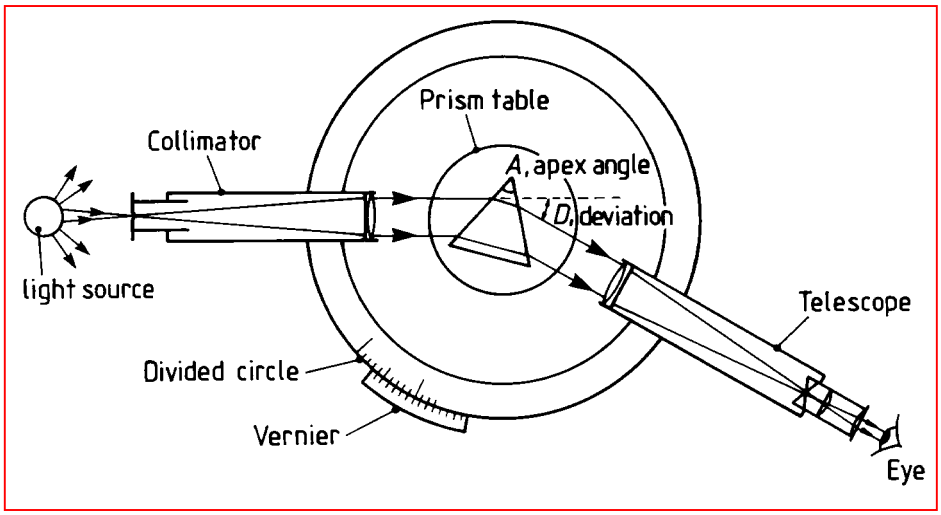
- Check that you have a power supply with a **neon tube** (Ne) mounted on it. Switch it on and move it up so that it is just in front of the open spectrometer slit. The lamp sits on a wooden block. Look straight into the collimator lens *without the prism on the table* and check that a narrow vertical slit of bright red light can be seen.

- Place the prism on the table so that it is in the position shown in the schematic diagram on the next page. The prism is not placed centrally, but slid back so that its left face intercepts all the light coming out of the collimator.



- Move the telescope out of the way, squint down with your head at the same level as the prism and move your head around to look through the prism for the emerging light in more or less the position shown in the diagram. You should see a row of red and

yellow lines quite close together, within the dark outline of the end of the collimator. They are very pretty. Make sure the cross-wires are focused by pulling the eyepiece in or out as needed.



Now we come to a crucial part in the use of the spectrometer that takes longer to describe than to do. For reproducible results the prism can't be placed at any angle to the incident light, because the telescope angle and hence the calibration would be altered by any slight rotation of the prism. Moreover, there is one special position of the prism that produces bright, clear, reproducible lines. This position is the one that produces the *minimum deviation* of the light by the prism. In terms of the diagram above, at minimum deviation the *telescope is at the furthest anti-clockwise position at which you can still see a spectrum*. Clearly, at this position the deviation, angle D in the diagram above, is at its smallest. **When you use the prism spectrometer for measuring, every line being measured must be in its minimum deviation position**.

- Move the telescope round so you can see the lines through the eyepiece. Twist around the prism table via the plate below, unclamping the plate if need be, so that the lines move to your right. You will find that there is a limit to how far the lines can be moved in this direction, no matter how you turn the prism table. This limit is the *minimum deviation position*. The setting of the prism necessary to achieve this differs very slightly for different lines.

Observation of Gas Discharge Spectra

- Move the telescope and prism so that the lines can be re-observed each in their **minimum deviation position**. Notice the number and brightness of the lines, and that there are lines in the green and blue part of the spectrum, though the light looks "neon red".

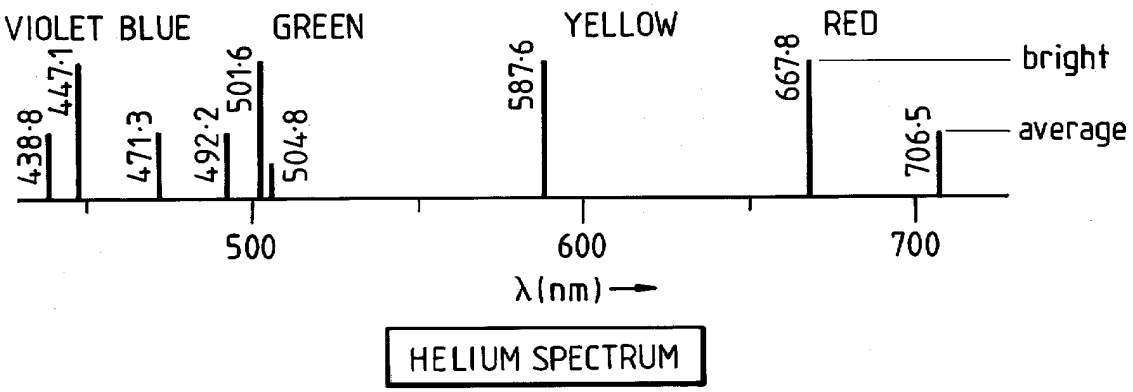
- **Switch off the power supply to the light**. Change the tube to a **helium** tube (He). These discharge tubes, which are expensive, need only be laid into the holder and the top clamp, the earth connection, gently tightened. **PLEASE DON'T FORCE THE TUBE INTO ITS SOCKET.** If someone has pushed your tube too far into the holder, remove it with a

modest grip **near the bottom**, or ask the demonstrator. Look at the helium spectrum and notice its qualitative difference. Write a sentence or two below describing this difference:

Calibration of the Spectrometer

The spectrometer will let you measure the wavelength of a spectral feature. You will also be able to get some quantitative idea of whether a spectral line is strong or weak. Wavelengths of light are specified in units of nanometers (1 nm ≡ 1×10^{-9} m) or, less commonly nowadays, in Ångströms (1 Å ≡ 1×10^{-10}m, a recognised supplementary unit in the SI system). We shall follow the modern practice of using nanometers.

The calibration of the spectrometer is a graph of the telescope position against the wavelength of the spectral line. This graph is most simply obtained by taking a known set of spectral lines and finding the telescope position for each line. Plot a graph of the result and draw the smooth curve that best fits the results. The result is the calibration curve for the spectrometer. Our known set of lines will be that given by the helium discharge lamp. It doesn't matter whether your telescope positions differ from those of your neighbour. It is only the relative position, or the separation, of the lines that matters.



HELIUM SPECTRUM

The diagram above gives the wavelengths of spectral lines and some indication of their intensity. In the diagram, less intense lines are shown smaller rather than fainter. There are two scales on the spectrometer for measuring telescope angle, these scales being 180º apart. For really accurate work, the average of both scales is used but in this experiment where time is short, use only one scale. A hand lens is available to help you read the vernier scale. This scale is calibrated every half-minute of arc and covers 20 arc minutes. The main scale is calibrated every third of a degree (or 20 arc minutes). If you are not sure about vernier scales, see the appendix **Reading Vernier Scales**, where there is a worked example relevant to our scale here. Everyone finds that reading this vernier is a bit tricky but remember that you are reading very small

telescope angle (degrees, minutes)	λ (nm)

angles. Half-a-minute of arc, the smallest calibration division, is the angle across the width of your hand as seen by someone 1 km away. The spectrometer is indeed an accurate instrument.

- Measure the position of the clearly visible lines in the spectrum, **making sure you record the position of each line at its minimum deviation**. Plot the calibration points and draw a smooth line (slightly curved) that will represent the calibration at all visible wavelengths. Choose a scale for plotting the wavelength that will allow you to extend your line at either end beyond the largest and smallest wavelengths measured by about 50 nm. If you are unsure which spectral line is which, make a trial identification and subsequently change it if needed.

Food for thought: how could you determine a good, smooth calibration line through your data? One way is to use the method of least-squares to fit the curve $\theta = \theta_0 + k/\lambda^2$, where θ_0 and k are constants that you calculate from your data. Once you have found these two constants, the telescope angle θ can then be accurately plotted. Unless you have a calculator that can do such a calculation for you on the spot, there isn't time to pursue this now.

Measuring with the Spectrometer

In this short section you will measure the wavelength of a spectral line from the mercury spectrum and then estimate the range of wavelengths visible to your own eyes.

- Replace the He tube with the **mercury** tube (Hg). As before, take care with the tubes. Allow a minute for the new tube to warm up. Determine the wavelength of the brightest line in the mercury spectrum. It is green.

telescope position of brightest line =

wavelength of brightest line = nm

- Move the mercury source out of the way and replace it by the white-light source in the grey box. This source has been 'borrowed' from another experiment. Place the external hole over the end of the spectrometer. Measure the wavelength limits of your vision.

	telescope angle	wavelength
red limit:		
violet limit:		

You have a set of seven mounted coloured filters: *red, green, blue, magenta, yellow*, *cyan* and *purple*. Each filter has a fairly broad spectral transmission.

- Hold the filters in turn in the light path and see their effect on the spectrum. The transmission can be made more specific by putting two filters together. For example, try yellow and blue together and observe the residual transmission in the green. Look through the pair! Try magenta and cyan. Does it make any difference where in the light path the filter is placed?

A good human eye can distinguish only some 300 hues across the visible spectrum. They are not equally spaced in wavelength. Some 7.5 million different colour sensations can be produced by also varying the purity of the colour (i.e. the amount of white) and the luminance of the source (the intensity per unit area coming from the source). Colour vision is a large and commercially important subject intimately related to spectroscopy.

CHOICE:

Either tackle the next section on calculating quite accurately how the refractive index of a prism varies across the spectrum (**prismatic dispersion**)

or

if you would like to explore the **diffraction grating**, go to the final section.

Measuring the Dispersion of the Prism

Using a spectrometer to measure the refractive index of a piece of material in the shape of a triangular prism is pretty quick and gives an answer that is far more accurate than most other methods. In fact with our spectrometer it is easy to measure the modest change in refractive index with wavelength.

A prism bends light because of the *refraction* that occurs at the faces of the prism. A spectrum is formed because the refractive index (n) of the glass depends on the wavelength (λ) of light. This last phenomenon is called *dispersion*. Since the *deviation of the light* by the prism depends on its refractive index, dispersion will therefore spread out the emerging light into a spectrum. You can measure the phenomenon at the heart of the spectrometer simply by finding the deviation (D) for each of the calibration spectral lines and using the relation between deviation (D) and refractive index (n) that is valid at minimum deviation.

$$n = \frac{\sin((A + D)/2)}{\sin(A/2)} \quad , \qquad (1)$$

where A is the apex angle of the prism. It is given as 60^0. [You could measure it, for example, by reflecting light off one face of the prism into the telescope and seeing by what angle you need to turn the prism table to get the other face to reflect light to the same position. For now, you can take this angle as given]. The deviation is simply found by

Deviation (D) = *telescope* position - *straight-through* position . (2)

You have already measured the *telescope* position for all the calibration lines in the helium spectrum, and identified their wavelengths.

- Determine the *straight-through* position by removing the prism and looking directly into the collimator through the telescope. This can be done with the white light source in place.

straight-through position = degrees and minutes.

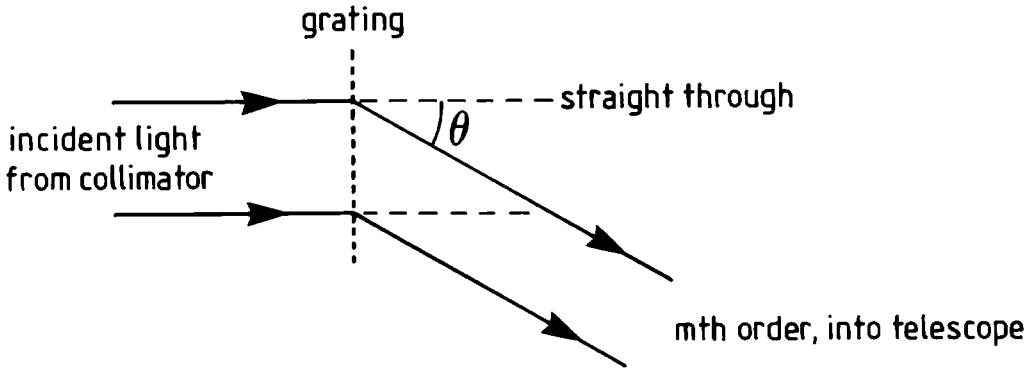
- Calculate the refractive index for the prism at the wavelength of five well spread calibration lines, using equation (2) with the telescope positions you have already measured to find the deviation D and then (1) to calculate *n*. Keep three decimal places and record your answers in the table here. Plot the dispersion curve of *n* against λ for the prism. Notice that the refractive index is larger for violet light than red light and therefore the bending of violet light is greater than of red light.

λ (nm)	*n*

- On your calculator, *change* one value of the deviation by 2 minutes of arc, representing the *angular accuracy* of the spectrometer. Re-calculate the refractive index *n* and hence find out how much *n* changes. This is the refractive index accuracy of your result.

refractive index accuracy is ±

Diffraction Grating Spectrum



A diffraction grating is a sheet with a large number of very fine regularly spaced slits marked out on it. A sheet 20 mm wide with 200 lines (i.e. slits) per mm would have 4000 lines. You could not see the individual slits with your naked eye. The process of *diffraction* of the light through each slit can be likened to the spreading out of a wave on a pool when you throw in a stone. The light potentially travels out in a wide range of directions from each narrow slit but the process of *interference* in the light waves produced by the whole line of slits means that in most directions the disturbance comes to nothing. Only in a very few directions, described as the *orders of the diffraction grating*, do we get a lot of light. This happens when the path difference between light emerging from neighbouring slits is a multiple of the wavelength of the incident light.

If light is incident straight on to a diffraction grating, you will find from any optics textbook dealing with diffraction that the m^{th} order of diffraction (*m* is an integer) occurs out to the side at an angle θ given by

$$m\lambda = d \sin\theta \quad . \qquad (3)$$

'*d*' is the *grating spacing*, defined as the distance between neighbouring slits of the grating. Notice that to calibrate a diffraction grating you need only find *one* quantity, namely *d*.

- Place the diffraction grating centrally on the spectrometer table and orient it by eye broadside on to the beam from the collimator. Put the **mercury** source in front of the slit and look by eye for the first-order spectrum. [The diffraction grating produces a fainter spectrum than the prism. It may be helpful to shield off any spurious light reaching your grating from a neighbour's apparatus]. Now locate a line in the telescope, which should be in good focus from your previous work with the prism. Notice how the spectrum is more spread out than the prism spectrum. Hence you would expect the *resolution* of the diffraction grating, the ability to separate neighbouring lines, to be better. However, the lines are fainter.

- Measure the telescope positions of 3 lines in the mercury spectrum, as in the following table.

line	telescope position	θ	λ(nm)
longest wavelength:			
brightest green:			546.1
deepest violet:			

- From the previous diagram, you will see that the deviation of the light has now been called θ, for consistency with textbooks. You have already measured the straight-through position, hence can calculate θ for each line. Use equation (3) on the brightest line with $m = 1$ for the first-order and λ **expressed in mm**. Calculate the *grating spacing*, in mm.

grating spacing d = mm .

Hence

no. of lines/mm = $1/d$ = ± mm^{-1} .

To find the accuracy, change the angle used in the formula by 2 minutes of arc, representing the angular setting accuracy, re-calculate $1/d$ and hence from the difference in value, find the appropriate "±" figure. Use the grating spacing found to determine the wavelengths of the other two lines and hence complete the previous table. If you have been able to see the red line these limits should not be far away from the limits of the visible spectrum that you found earlier.

THE END (but see the two appendices that follow)

Appendix on focusing the spectrometer

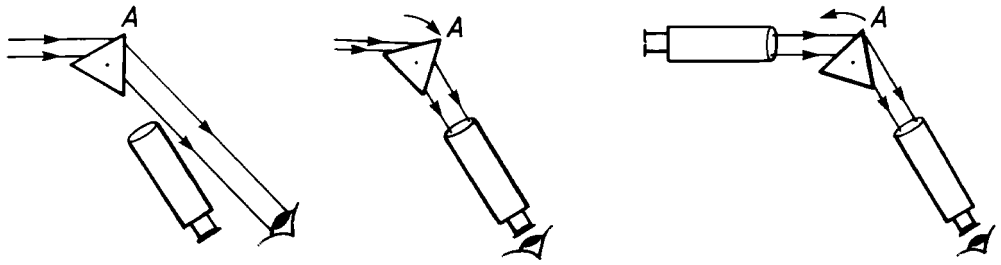
- Begin by sliding the eyepiece in or out until the cross wires appear sharp.

Proper focusing, i.e. adjustment for parallel light, is best carried out according to an intriguing recipe discovered by the notable experimentalist Sir Arthur Schuster. It is used by professional spectroscopists. The recipe is easy to follow but takes a little time to describe. The important point about the method is that the telescope focus is adjusted when the telescope is **not** in the minimum deviation position.

- First, turn the prism table clockwise while looking through the telescope, so that the lines are definitely **not** in a minimum deviation position.

- The lines will most likely be out of focus. Refocus **only the telescope** to make the lines sharp.
- **Now rotate the prism table anticlockwise so that the apex of the prism moves towards the collimator**. Keep doing this while simultaneously watching through the telescope. The lines move off to the right and then re-appear centrally again. They are likely to be wide and blurred. **Refocus only the collimator now**.
- Using the table again, move the prism apex back towards the telescope until the lines are re-centred again. Refocus only the telescope.
- Rotate the prism back towards the collimator and check the collimator focus.
- Repeat these last two steps, as needed. The method is one of successive approximation that will soon converge, leaving a properly adjusted spectrometer with both collimator and telescope focused for parallel light. The whole thing can be done in a minute when you see what you're doing. The spectrometer is, at last, ready to use.

The following diagram summarises Schuster's method of focusing a spectrometer.



Appendix on Reading Vernier Scales

The vernier is a short supplementary scale alongside the main scale. It enables you to determine what fraction of main scale divisions the reading should be.

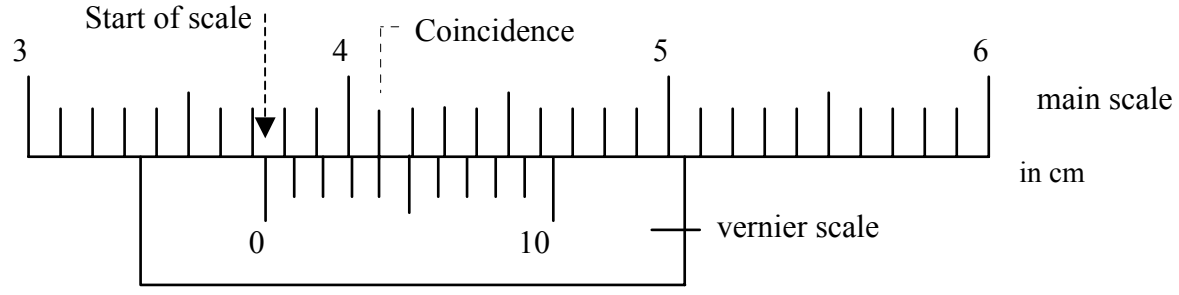
The beginning of the vernier scale is its origin mark. It is this position on the main scale you are trying to read.

The fraction of the smallest main scale division intervals read by the vernier is given by the number of division intervals on the vernier. Typically there will be 10 vernier divisions and therefore the vernier will read to $1/10^{th}$ of a main scale division. There may be more divisions. For example, with 20 vernier divisions, a reading is given to $1/20^{th}$ of a main scale division. **If there are n vernier divisions, the vernier gives a reading to $1/n^{th}$ of a main scale division.**

To read a vernier, notice that the vernier division lines next to the origin usually fall between a main scale division. Further along the vernier they come into coincidence with the main scale division lines and finally they go past them. See the following diagrams. **To read the vernier, find the vernier division line that coincides exactly with a main scale division line. That vernier line gives the fraction of the main scale division you are looking for.**

Once you have learnt the secret, reading a vernier scale is easy but time-consuming. It helps greatly when you are looking at finer scales to have a small magnifying glass available. The larger the number of vernier divisions, the harder it is to judge the coincidence between scale lines.

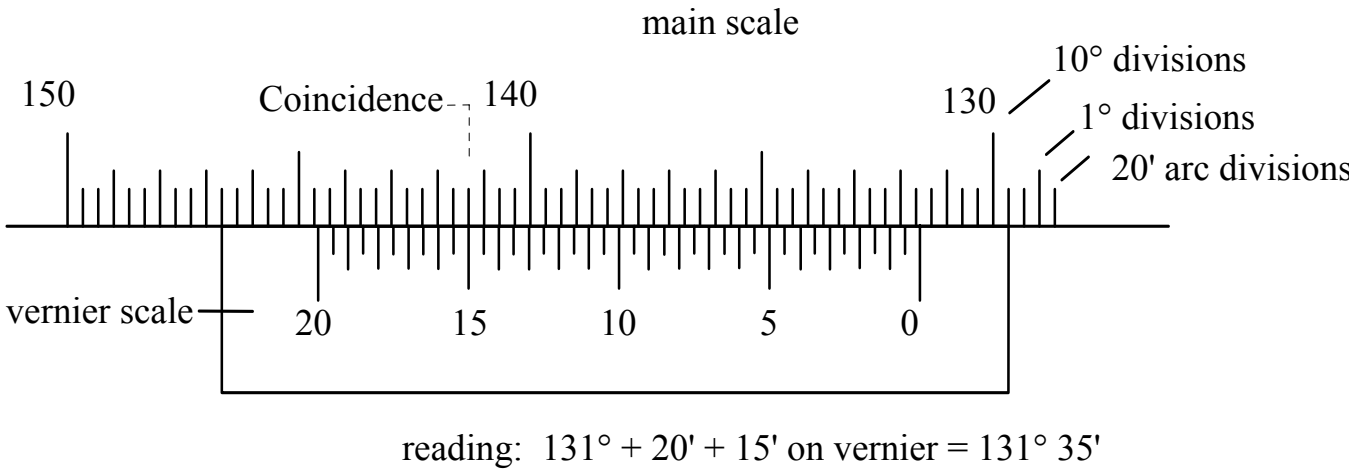
The vernier scale works because each vernier scale division is shorter than a main scale division by one vernier division unit. For example, a vernier designed to read to $1/10^{th}$ of a mm has divisions that are $1/10^{th}$ mm shorter than the main scale divisions of 1 mm. If, in one case, the origin of the vernier scale starts 0.4 mm from a main scale division, it will take 4 vernier divisions before the vernier scale marks have dropped into exact coincidence with a main scale mark. Hence the recipe for reading the vernier will produce the correct answer of 0.4 mm. Think about it.



reading: 3.74 cm = 37.4 mm

Example 1: Vernier calipers scale, with vernier reading 1/10 th of a mm.

over/



reading: 131° + 20' + 15' on vernier = 131° 35'

Example 2: Spectrometer angular scale, with vernier reading to 1/40th of a main scale division, i.e. 1/40 of 20′ arc or 0.5′ arc.

Remember the simple sequence:

1. record the main part of the reading from the main scale
2. move your attention to the vernier scale divisions and read the fraction from this scale.

JSR