# THE PRISM SPECTROMETER

OBJECTIVES:

1) Learn the theory of the prism spectrometer, and be able to explain the functions of its various components.

2) Observe the spectrum of a mercury discharge lamp and record the angle of deviation for the spectral lines.

3) Determine the index of refraction of a glass prism for various wavelengths.

4) Use the calibrated prism to measure unknown wavelengths.

5) Observe color sensation caused by light of particular wavelengths.

INTRODUCTION:

When a beam of light is transmitted from air to glass, the ray is bent according to Snell's law

$$\sin \theta_{air} = n \sin \theta_{glass} \tag{1}$$

where the angles are measured from the surface normal (the line perpendicular to the surface) and n is the index of refraction of the glass. The index of refraction is a dimension-less number and is a measure of how strongly the medium bends light. The greater n is, the more the light is bent. The index of refraction of air is 1. For glass, n varies from 1.3 to 1.8, depending on the type of glass and on the wavelength of the light.
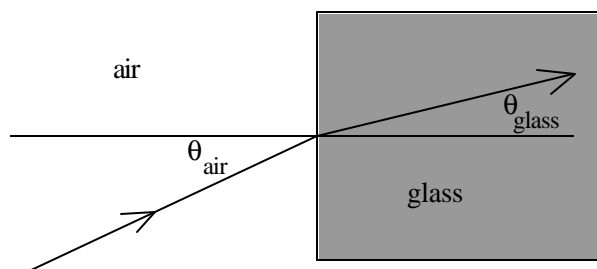
White light is made up of all the colors of the rainbow - red, yellow, green, blue, and violet. Different colors correspond to different wavelengths. Human eyes are sensitive to light with wavelengths in the range 390 nm (violet) to 750 nm (red) (1 nm = nanometer = 10^{-9} m).
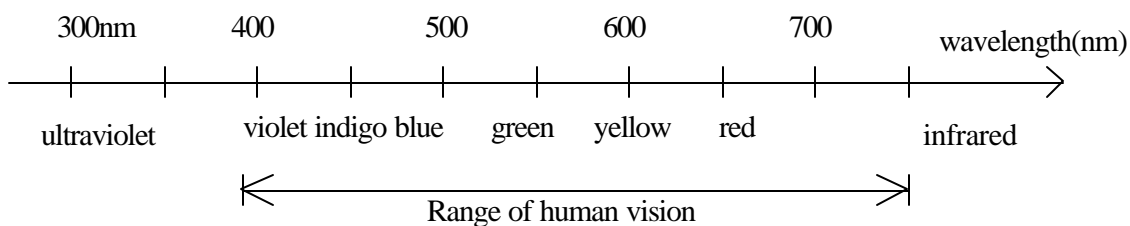
Glass has a greater index of refraction at shorter wavelengths, that is, it bends blue light more than red light. So a prism can be used to disperse white light into its component colors.
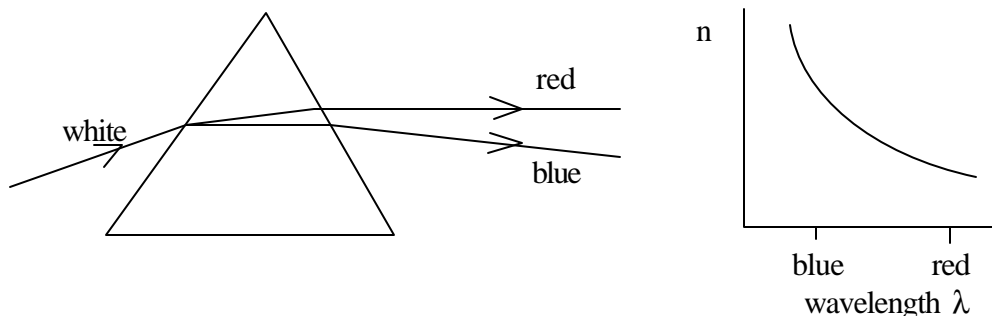
In this experiment, we will use a prism spectrometer to measure the dispersion angle of various wavelengths.   From the measurements, we will make a graph of the index of refraction vs. wavelength. The form of the curve of index of refraction as a function of wavelength, known as the Cauchy formula, is

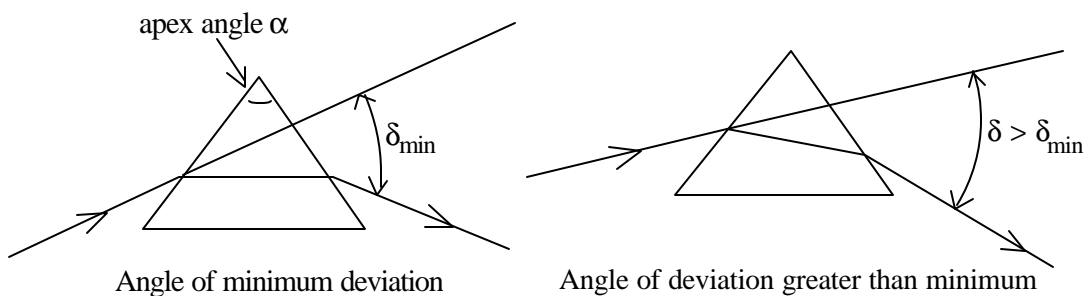$$n \,=\, A + B/\lambda^2 \quad \text{Or} \quad n \,=\, A + (b/\lambda)^2$$

In the introduction for your lab*, find B in terms of b, and solve the first equation for λ, given n, A, and B

As a light source, we will use a mercury lamp, which emits light at several discrete wavelengths. The device we are using is called a prism spectrometer because, once the prism is calibrated, it can be used to measure the wavelengths of the lines in the spectra produced by various atoms. The spectra contain bright lines at particular wavelengths, which correspond to light emitted during the transition between different energy states of the atoms. You see distinct lines because the atoms exist only in distinct, *quantized* energy states. Trying to explain the data from such experiments— the existence and pattern of sharp spectral lines—led to the development of quantum mechanics.

When a ray of light is refracted by a prism, the angle between the incoming and outgoing rays is called the angle of deviation (β). For a given prism and a given wavelength, the value of β depends on the angle between the incoming ray and the surface of the prism. β is minimum when the angles of the incoming and outgoing rays make equal angles with the prism surfaces.   In this special symmetric case, the prism's index of refraction (n) is related to β and the apex angle of the prism (α) by

$$n = \frac{\sin\left(\dfrac{a+b}{2}\right)}{\sin\left(\dfrac{a}{2}\right)} \qquad (2)$$

The prisms that we will use all have $\alpha = 60^\circ$ (exactly, we assume).

2

apex angle α

δ_{min}

$\delta > \delta_{min}$

Angle of minimum deviation   Angle of deviation greater than minimum

There exist extensive tables of the line spectra of many elements. In the first part of the experiment, you will be using the known spectrum of mercury to calibrate your prism spectrometer. As a result, you have measured the curve of index of refraction as a function of wavelength. So if you measure a new line of a spectrum, you can calculate the index of refraction and use your curve to look up the wavelength for the new line. This process is used in identifying the elements present in unknown samples, such as the atmospheres of distant stars. The element helium, used to inflate birthday balloons, was first discovered by observing the atmosphere of a nearby the star, the sun (*helios* is Greek for sun). In the last part of the experiment you will have the opportunity to measure the spectrum of a gas in this fashion.

The fine prism spectrometers used in this lab were purchased in 1970 for $700 each. Today (2002), inferior models are available for $1700. Handle them with respect! Never force any parts!
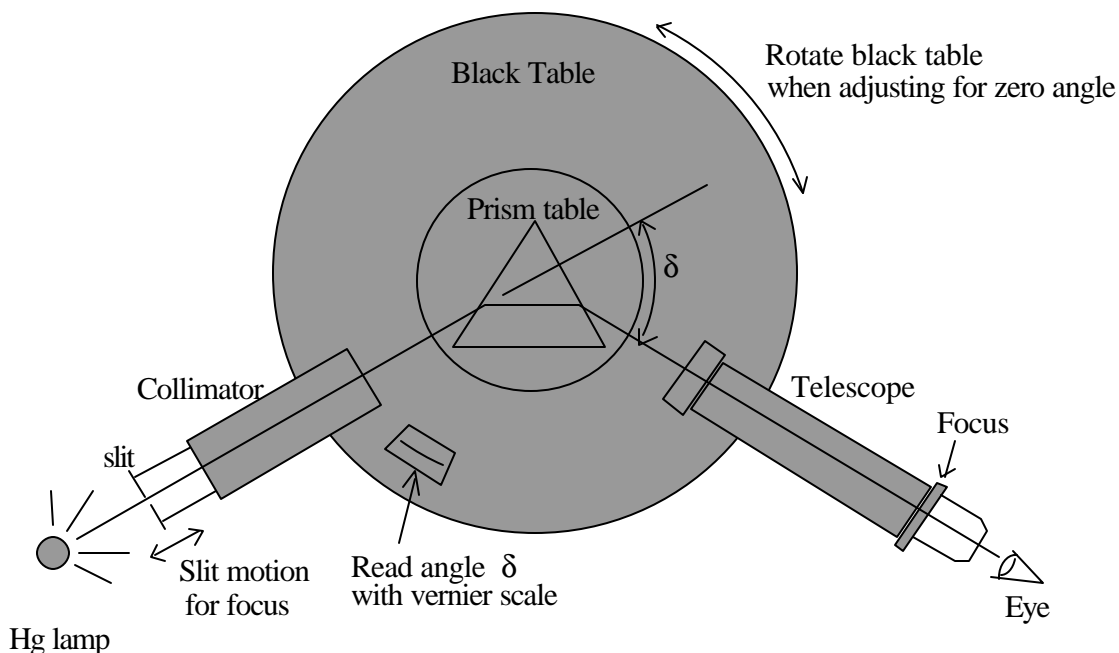
Partner _____   Name _____

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PROCEDURE

1. Become familiar with the spectrometer
    a) Identify each component: the black table, the prism table, the collimator, and the telescope (see figure above).
    b) Note the clamping screws and the fine adjustment screws for the telescope and the black table. Note the clamping screw for the prism table.
    c) Note how to adjust the telescope focus and the eyepiece.
    d) Note how to adjust the slit focusing in the collimator tube. Note how the slit width can be adjusted and how the slit orientation can be rotated.

2. Practice reading the angle from a precise protractor scale on the rim of the black table. Use the Vernier scale with the little magnifying glass to read the angle to the nearest arc minute. (1 arcmin = 1' = 1/ 60 degree.) **The following is an example**:
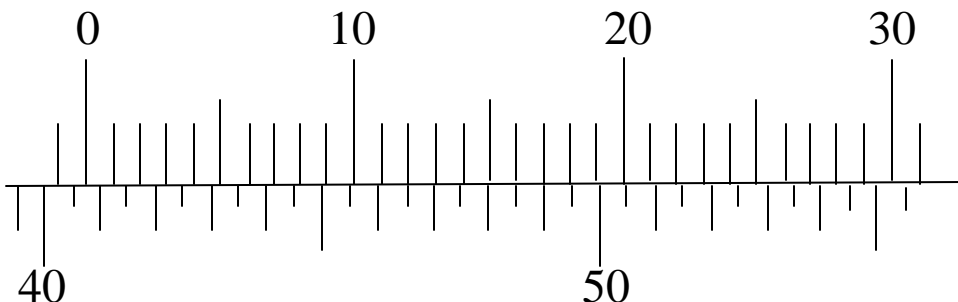
In this example, the zero line of the Vernier scale (the upper scale) is between 40.5° and 41°, so the angle is somewhere between 40° 30' and 41°. The Vernier scale tells exactly where in between. Look along the Vernier for the line that exactly lines up with the line below it. In this case, it's the 17' line. So the angle is 40° 47', which we get by adding 17' to 40° 30'. Before using this angle in equation (2), we must convert it to decimal degrees: 40 + (47/60) degrees = 40.78°.

3. Align the spectrometer
In order to correctly measure angles with the spectrometer, we must first align it. To do so, use the following steps:

a) **Telescope focus**: *Do not put the prism onto the silver table yet*. That will come later. Notice that there are two knobs associated with the telescope. They are located directly under the telescope barrel. One points along the barrel and one is perpendicular to it. The knob that is along the barrel will lock the telescope's position and will prevent it from rotating. When it is locked down in this way, you can use the other knob for a fine adjustment, to rotate it by very small amounts. If the telescope is not unlocked, turn the knob that is parallel to the barrel counterclockwise until you can freely rotate the telescope. Turn the telescope so that it is not pointing at the collimator but is instead aimed at something as far away from you in the room as possible. Now rotate the focus adjustment (**see diagram on page 5**) until you can see through the telescope clearly. You may notice that the image is upside down. This is normal. Just ensure that it is as clear and in focus as you can. **After this adjustment, you should not adjust the focus of the telescope again**.

b) **Telescope alignment**: Now place a white light (desk lamp) in front of the slit on the end of the collimator (**in the diagram on page 5**, the desk lamp goes where the "HG lamp" is pictured). Now rotate the telescope until it is pointed at the collimator. You should imagine

a straight line going from the lamp through the collimator, and through the telescope. By looking through the telescope, you should be able to line up the crosshair with the slit in the far end of the collimator. By locking down the telescope and using the fine adjustment (the knob perpendicular to the one that you used to lock down the telescope) you should be able to do this very accurately. If you are unable to see the slit, it may be closed too tightly. You can widen and narrow the slit by rotating the adjuster on the collimator (it is located on the far end of the collimator, much like the focus for the telescope). This will adjust the slit width, but will not focus the slit. If the slit does not have very crisp edges when you look through the telescope, move the end of the collimator near the lamp in and out to focus it. If your slit is not vertical in the telescope, you can also rotate it so that it is. Once you have a nice thin, well-focused slit, with your crosshairs centered on it **and your telescope locked down**, you are now ready to align the scales to read the angle.

c) **Angle adjustment**: If you look below the set of knobs that control the telescope, you will see another pair of knobs that look identical to the ones for the telescope. These knobs perform the same functions (locking down and fine adjustment) for the black table itself. If you unlock the black table, you can rotate it. Notice that there are two windows in which you can read an angle. We want to rotate the table until one of the windows has 0 (zero) lined up with 0 (zero) or 360 (since a circle is 360 degrees, 360 is the same as 180. If at all possible, we should try to use set it so that this window is to the left of the telescope (as we are looking over the barrel toward the lamp) because this will make reading our angle easiest. (please have a look at the diagram on page 5) On some scopes there is a small magnifier attached to the black table over one window, and this would also be advantageous to use. Once you have aligned them, you will **lock down the black table and will not rotate it again**. From now on, we will **only rotate the telescope**.

d) **Prism placement**: *Now you should place the prism* in the center of the silver table. Recall that light is bent toward the base of the prism, so it should be placed on the silver table so that the gray plastic part makes a "C" shape if you were to look at it from the telescope side of the apparatus. Now, without moving the telescope, move your head to the left (about to where the telescope is rotated to in the diagram on page 5) and look into the prism. You will have to put your head down at the height of the telescope/collimator. Now rotate the silver table clockwise until you can see a nice rainbow like spectrum "inside" the prism. (You should notice that the rainbow is inside of a black circle. You are seeing the light coming out of the collimator and bent through the prism.) If it does not look like a very nice, bright, well formed rainbow, you probably do not have your head in the right place; move further left and try to rotate the silver table back and forth. Once you have found it, unlock the telescope (**not the black table**) and rotate it **to the left** where you were looking. Now look through the telescope, and you should be able to find the rainbow. We are now in about the right place to find our spectrum with the mercury vapor lamp and to adjust for the minimum angle of deviation.

e) **Minimum angle of deviation**: *Now, remove the white light and replace it with the mercury vapor lamp*. You will want to move the lamp until it is aligned with the slit. To do this, look through the telescope and move the lamp back and forth until it is nice and bright in the telescope. **Instead of a complete rainbow, you should now see only certain bands of color**. If your bands do not look nice and sharp, you may have to adjust your slit focus or width. Some lines are better seen if you tighten the slit. (The lamp should be very close to the slit.) Move the telescope back and forth until you get the crosshair lined up on the **green band**. Now look back to the diagram on page 5. We want to make the angle β as small as possible. To do this, rotate the silver table back and forth just a little bit. You should be able to get the green line to move **to the right**. Now realign the crosshair on the green line and rotate the silver table a little bit again. Then realign the crosshair on the green line. You should repeat this process until no matter which way you rotate the silver table, the green line goes to the left, not the right. When this occurs, and the green line is as far as you can get it to go to the right, you are at the minimum angle of deviation. This angle should be around 51 or 52 degrees for the green line. If it is not, you may not have aligned the scales correctly, please repeat steps c, d, and e from above. (Record it below). Every time that you do a different color, you will have to repeat this process.

f) Record the prism number and read the deviation angle on the protractor.

   Prism # _____   β = _____ ° _____ ' = _____°

4. Measure the angle of deviation for each of the spectral lines of the Mercury lamp. The wavelengths and colors of the spectral lines are given in the table below. While making measurements, unclamp and rotate the prism table to check that the prism is oriented for minimum angle of deviation for the red, green, and blue lines.

   When measuring very closely spaced lines, like the double yellow lines, make the slit very narrow and check the focus. When measuring dim lines, make the slit wider.

5. To calculate the quantity of $1/\lambda^2$, **you should convert l from nm to mm first**, then do the calculation. That way, you are guaranteed to have the units correct. Calculate the index of refraction (n) for each spectral line using equation (2). **Keep four digits after the decimal point**. Write down the equation you will use for calculating the index of refraction.

Prism apex angle $\alpha = 60°$

color	wavelength λ (nm)	$1/\lambda^2$ $(\mu m)^{-2}$	angle of deviation β (deg,min)	(decimal deg)	Index of refraction
red	690.8				
yellow 1	579.1				
yellow 2	577.0				
green	546.1				
blue-green (dim)	491.6				
blue	435.8				
violet	404.7				

6. Make a graph of n vs. λ.

7. Make a graph of n vs. $1/\lambda^2$ and find a best straight line fit to the graph. Calculate the slope and the y-intercept.

8. Observe the spectral lines of another emission lamp. For any three bright lines in the spectrum, record the perceived color and intensity, measure the angle of deviation (β), and calculate the index of refraction (n). Now look back to your graph of n vs. $1/\lambda^2$. This graph told us how light of a certain wavelength was bent by our prism. Since we are using the same prism in this part of the experiment, this data can be used to help us. We can (and have) calculated a slope and a y-intercept from this graph. We know the equation of a straight line and we can compare that equation to the equation which reads: $n = A + B/\lambda^2$. Or, put another way:

$y = b + m * x$
$n = A + B * (1/\lambda^2)$

Using this, we can calculate $1/\lambda^2$ from the slope, y-intercept and the index of refraction (n).

Type of lamp: _____

color	intensity (dim, bright…)	angle of deviation β		Index n	$1/\lambda^2$ $(\mu m)^{-2}$	Wavelength λ (nm)
		(deg., min.)	(dec. deg.)			