

Introduction

In principle, a spectrometer is the simplest of scientific instruments. Bend a beam of light with a prism or diffraction grating. If the beam is composed of more than one color of light, a spectrum is formed, since the various colors are refracted or diffracted to different angles. Carefully measure the angle to which each color of light is bent. The result is a spectral "fingerprint," which carries a wealth of information about the substance from which the light emanates.

In most cases, substances must be hot if they are to emit light. But a spectrometer can also be used to investigate cold substances. Pass white light, which contains all the colors of the visible spectrum, through a cool gas. The result is an absorption spectrum. All the colors of the visible spectrum are seen, except for certain colors that are absorbed by the gas.

The importance of the spectrometer as a scientific instrument is based on a simple but crucial fact. Light is emitted or absorbed when an electron changes its orbit within an individual atom. Because of this, the spectrometer is a powerful tool for investigating the structure of atoms. It's also a powerful tool for determining which atoms are present in a substance. Chemists use it to determine the constituents of molecules, and astronomers use it to determine the constituents of stars that are millions of light years away.

In its simplest form, a spectrometer is nothing more than a prism and a protractor. However, because of the need for very sensitive detection and precise measurement, a real spectrometer is a bit more complicated. As shown in Figure 1, a spectrometer consists of three basic components; a collimator, a diffracting element, and a telescope.

The light to be analyzed enters the collimator through a narrow slit positioned at the focal point of the collimator lens. The light leaving the collimator is therefore a thin, parallel beam, which ensures that all the light from the slit strikes the diffracting element at the same angle of incidence. This is necessary if a sharp image is to be formed.

The diffracting element bends the beam of light. If the beam is composed of many different colors, each color is diffracted to a different angle.

The telescope can be rotated to collect the diffracted light at very precisely measured angles. With the telescope focused at infinity and positioned at an angle to collect the light of a particular color, a precise image of the collimator slit can be seen. For example, when the telescope is at one angle of rotation, the viewer might see a red image of the slit, at another angle a green image, and so on. By rotating the telescope, the slit images corresponding to each constituent color can be viewed and the angle of diffraction for each image can be measured. If the characteristics of the diffracting element are known, these measured angles can be used to determine the wavelengths that are present in the light.

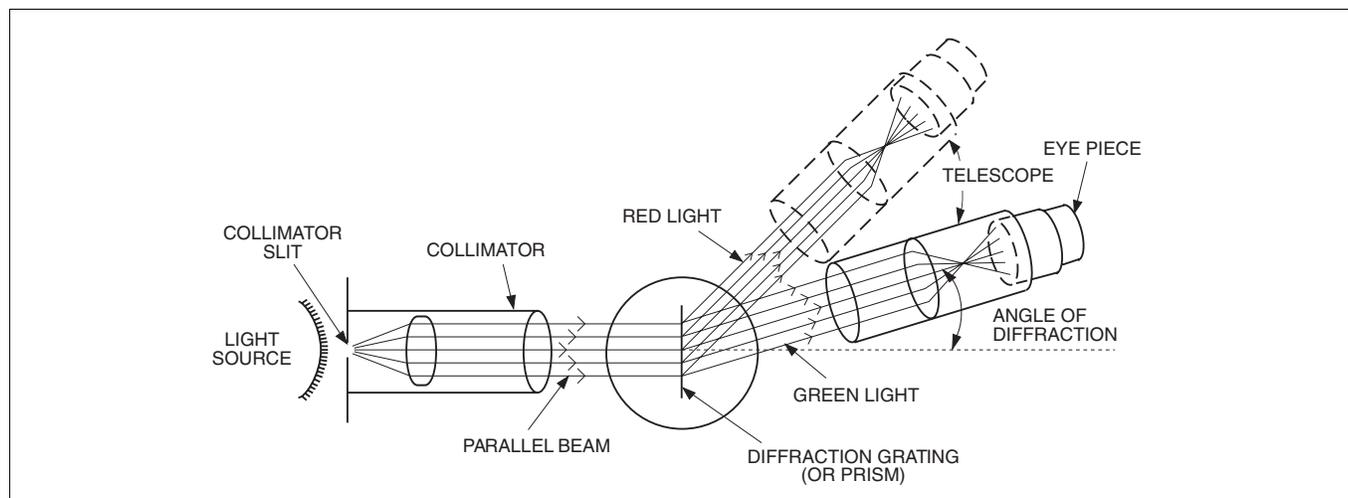


Figure 1 Spectrometer Diagram

Equipment

The PASCO scientific Model SP-9268A Student Spectrometer provides precise spectroscopic measurements using either a prism or a diffraction grating as the diffracting element. The spectrometer includes the following equipment (see Fig 2).

Collimator and Telescope

Both the collimator and the telescope have 178 mm focal length, achromatic objectives, and clear apertures with 32 mm diameters. The telescope has a 15X Ramsden eyepiece with a glass, cross-hair graticule. The collimator is fitted with a 6 mm long slit of adjustable width. Both the collimator and the telescope can be leveled. They can also be realigned (though this is rarely necessary) so that their optical axes are square to the axis of rotation.

Rotating Bases

The telescope and the spectrometer table are mounted on independently rotating bases. Vernier scales provide measurements of the relative positions of these bases to within one minute of arc. The rotation of each base is controlled with a lock-screw and fine adjust knob. With the lock-screw released, the base is easily rotated by hand. With the lock-screw tight, the fine adjust knob can be used for more precise positioning.

Spectrometer Table

The spectrometer table is fixed to its rotating base with a thumbscrew, so table height is adjustable. Three leveling screws on the underside of the table are used to adjust the optical alignment. (The table must be level with respect to the optical axes of the collimator and telescope if the diffracting element is to retain its alignment for all positions of the telescope.) Thumbscrews are used to attach the prism clamp and the grating mount to the table, and reference lines are etched in the table for easy alignment.

Accessories

Accessories for the spectrometer include a dense flint prism and two mounting clamps; a 300 line/mm diffraction grating and mounting clamp; two thumbscrews for attaching the mounting clamps to the spectrometer table; a magnifying glass for reading the vernier; three Allen keys for leveling the telescope and collimator; and a polished hardwood case.

NOTE: A 600 line/mm diffraction grating is available from PASCO as an optional accessory.

Optional Equipment: Gaussian Eyepiece

The Gaussian eyepiece (SP-9285) is an optional component that simplifies the task of focusing and aligning the spectrometer and aligning the diffraction grating. Its use is described in the Appendix.

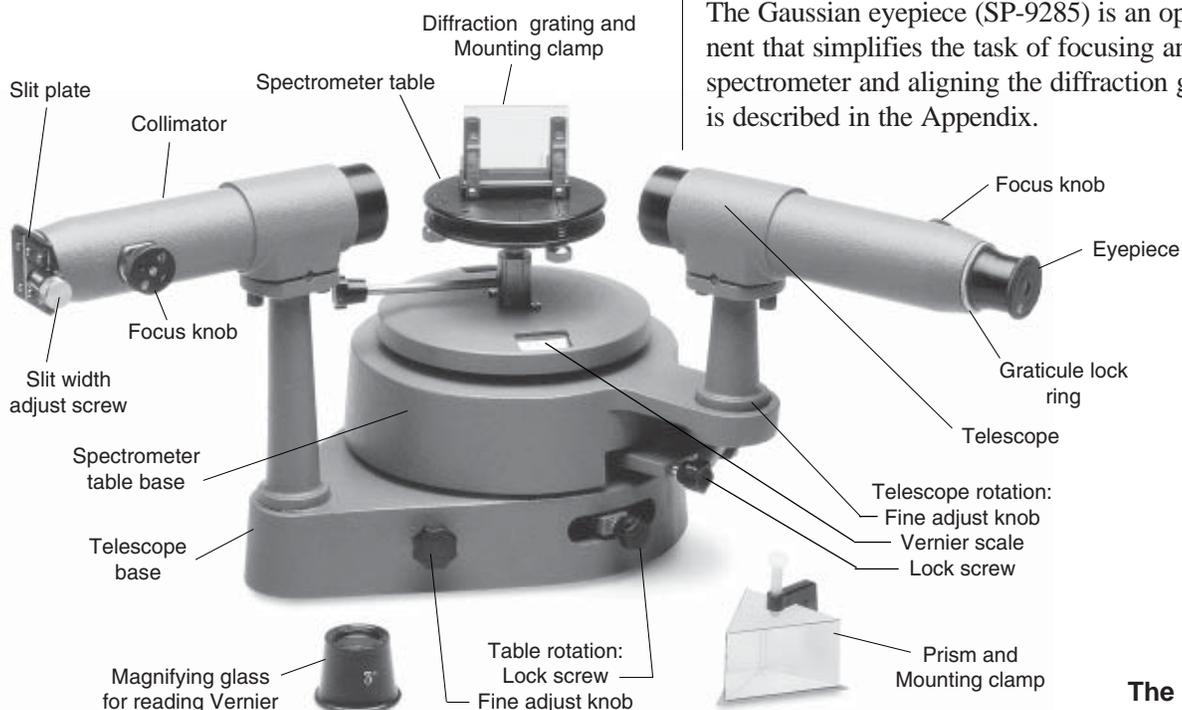


Figure 2
The Spectrometer

Equipment Setup

NOTE: If you are using the optional Gaussian Eyepiece (SP-9285), equipment setup is somewhat simpler than described below. See the Appendix for instructions.

Leveling the Spectrometer

For accurate results, the diffracting element must be properly aligned with the optical axes of the telescope and collimator. This requires that both the spectrometer and the spectrometer table be level.

1. Place the spectrometer on a flat surface. If necessary use paper or 3 X 5 cards to shim beneath the wood base until the fixed-base of the spectrometer is level.
2. Level the spectrometer table by adjusting the three thumbscrews on the underside of the table.

Focusing the Spectrometer

1. While looking through the telescope, slide the eyepiece in and out until the cross-hairs come into sharp focus. Loosen the graticule lock ring, and rotate the graticule until one of the cross-hairs is vertical. Retighten the lock ring and then refocus if necessary.
2. Focus the telescope at infinity. This is best accomplished by focusing on a distant object (e.g.; out the window).
3. Check that the collimator slit is partially open (use the slit width adjust screw).
4. Align the telescope directly opposite the collimator as shown in Figure 3.

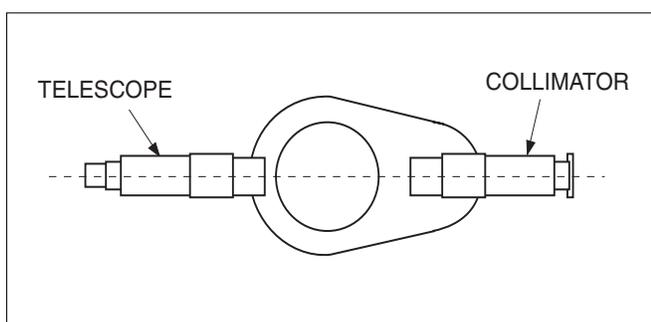


Figure 3 Align the Telescope directly opposite the Collimator

5. Looking through the telescope, adjust the focus of the collimator and, if necessary, the rotation of the telescope until the slit comes into sharp focus. **Do not change the focus of the telescope.**
6. Tighten the telescope rotation lock-screw, then use the fine adjust knob to align the vertical line of the graticule with the fixed edge of the slit. If the slit is not vertical, loosen the slit lock ring, realign the slit, and retighten the lock ring. Adjust the slit width for a clear, bright image. Measurements of the diffraction angle are always made with the graticule line aligned along the fixed edge of the slit, so a very narrow slit is not necessarily advantageous.

NOTE: When the telescope and collimator are properly aligned and focused, the slit should be sharply focused in the center of the field of view of the telescope, and one cross-hair should be perpendicular and aligned with the fixed edge of the slit. If proper alignment cannot be achieved with the adjustments just described, you will need to realign the spectrometer as follows.

Realigning the Spectrometer

Under normal circumstances, the spectrometer will maintain its alignment indefinitely. However, if the spectrometer can not be properly focused, as described above, it may be necessary to adjust the optical axes of the collimator and telescope, as follows:

1. The telescope and collimator pivot about a fulcrum on their respective mounting pillars (See Fig 4). Use the aluminum rod provided with the accessory equipment to adjust the leveling screws. Loosen one as the other is tightened until the unit is level and secure.

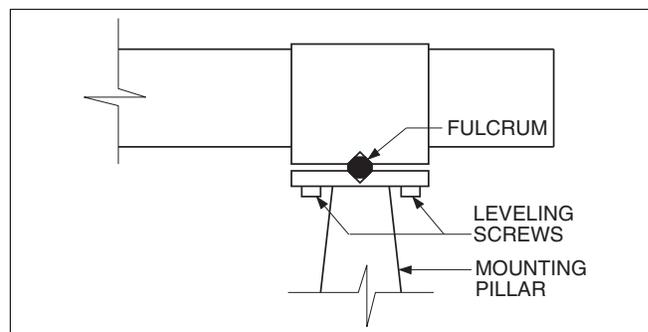


Figure 4 Leveling the Telescope and Collimator

- The mounting pillars of the telescope and collimator can be rotated by using an Allen wrench to loosen the screws that attach the pillars to their respective bases. To loosen the screw for the collimator, the spectrometer must be removed from the wood base.
- To be sure both optical units are square to the axis of rotation, follow the focusing procedure described above, adjusting the mounting pillars as necessary so the slit image is well centered in the viewing field of the telescope.

Measuring Angles of Diffraction

When analyzing a light source, angles of diffraction are measured using the vernier scales. However, the scales only measure the relative rotational positions of the telescope and the spectrometer table base. Therefore, before making a measurement, it's important to establish a vernier reading for the undeflected beam. All angles of diffraction are then made with respect to that initial reading (see Fig 5).

To obtain a vernier reading for the undeflected beam, first align the vertical cross-hair with the fixed edge of the slit image for the undeflected beam. Then read the vernier scale. This is the zero point reading (θ_0).

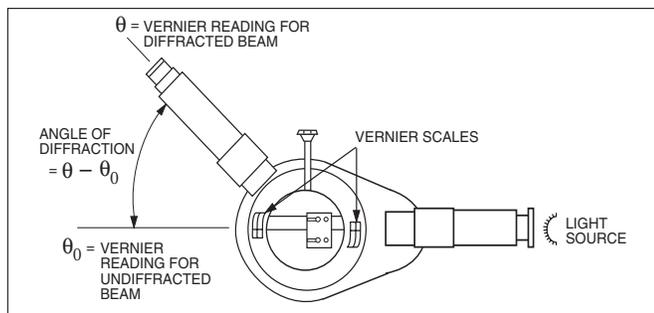


Figure 5 Measuring an Angle of Diffraction

Now rotate the telescope to align the vertical cross-hair with the fixed edge of a deflected image. Read the vernier scale again. If this second reading is θ , then the actual angle of diffraction is $\theta - \theta_0$. If the table base is rotated for some reason, the zero point changes, and must be remeasured.

Reading the Vernier Scales

To read the angle, first find where the zero point of the vernier scale aligns with the degree plate and record the value. If the zero point is between two lines, use the smaller value. In Figure 6, below, the zero



point on the vernier scale is between the 155° and $155^\circ 30'$ marks on the degree plate, so the recorded value is 155° .

Now use the magnifying glass to find the line on the vernier scale that aligns most closely with any line on the degree scale. In the figure, this is the line corresponding to a measurement of 15 minutes of arc. Add this value to the reading recorded above to get the correct measurement to within 1 minute of arc: that is, $155^\circ + 15' = 155^\circ 15'$.

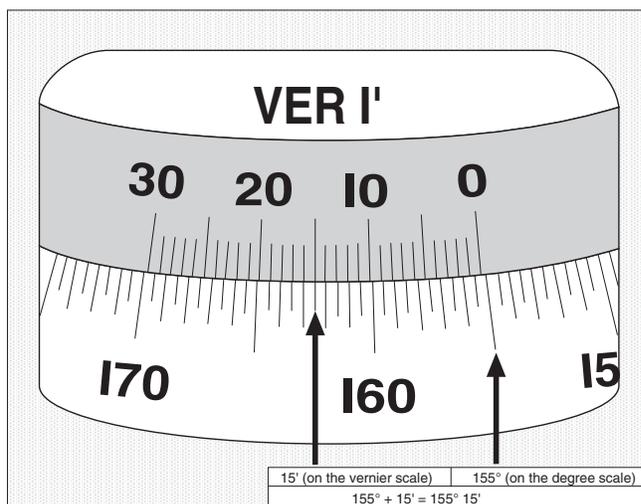


Figure 6 Reading the Vernier Scales

Using the Diffraction Grating

IMPORTANT: The Diffraction Grating is a delicate component. Be careful not to scratch the surface and always replace it in the protective foam wrapping when it is not being used.

Aligning the Grating

To accurately calculate wavelengths on the basis of diffraction angles, the grating must be perpendicular to the beam of light from the collimator.

1. Align and focus the spectrometer as described earlier. The telescope must be directly opposite the collimator with the slit in sharp focus and aligned with the vertical cross-hair.

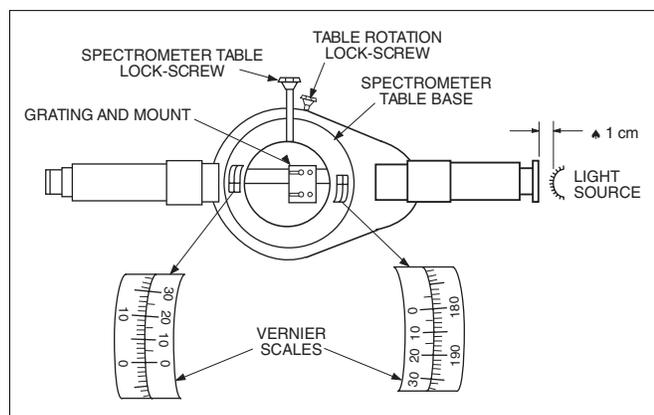


Figure 7

Perform steps 2-5 with reference to Figure 7.

2. Loosen the spectrometer table lock-screw. Align the engraved line on the spectrometer table so that it is, as nearly as possible, colinear with the optical axes of the telescope and the collimator. Tighten the lock-screw.
3. Using the thumbscrews, attach the grating mount so it is perpendicular to the engraved lines.
4. Insert the diffraction grating into the clips of the mount. To check the orientation of the grating, look through the grating at a light source and notice how the grating disperses the light into its various color components. When placed in the grating mount, the grating should spread the colors of the incident light horizontally, so rotation of the telescope will allow you to see the different colored images of the slit.

5. Place a light source (preferably one with a discrete spectrum, such as a mercury or sodium lamp) approximately one centimeter from the slit. Adjust the slit width so the slit image is bright and sharp. If necessary, adjust the height of the spectrometer table so the slit image is centered in the field of view of the telescope.

IMPORTANT: Stray light can obscure the images. Use the spectrometer in a semi-darkened room or drape a sheet of opaque material over the spectrometer.

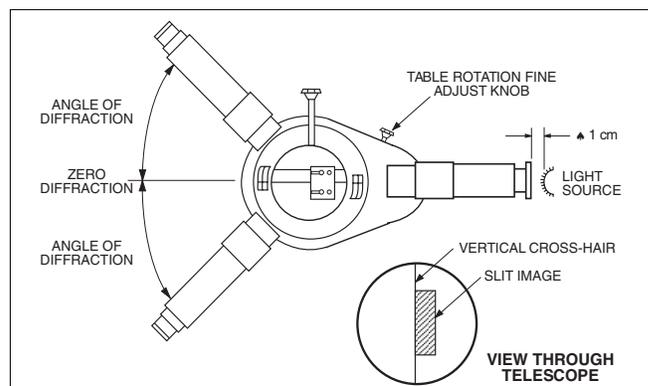


Figure 8

Perform steps 6-9 with reference to Figure 8.

6. Rotate the telescope to find a bright slit image. Align the vertical cross-hair with the fixed edge of the image and carefully measure the angle of diffraction. (See the previous section, *Measuring Angles of Diffraction*.)
7. The diffraction grating diffracts the incident light into identical spectra on either side of the line of the undiffracted beam. Rotate the telescope back, past the zero diffraction angle, to find the corresponding slit image. Measure the angle of diffraction for this image.
8. If the grating is perfectly aligned, the diffraction angles for corresponding slit images will be identical. If not, use the table rotation fine adjust knob to compensate for the difference (i.e.; to align the grating perpendicular to the collimator beam so the two angles will be equal).

9. Repeat steps 6-8 until the angles for the corresponding slit images are the same to within one minute of arc.

Making the Reading

Once the grating is aligned, do not rotate the rotating table or its base again. Diffraction angles are measured as described in the previous section, *Measuring Angles of Diffraction*. (Since the vernier scales were moved when the spectrometer table was adjusted, the point of zero diffraction must be remeasured).

Wavelengths are determined according to the formula:

$$\lambda = \frac{a \sin \theta}{n}$$

where λ is the wavelength; a is the distance between lines on the diffraction grating

($a = 3.3 \times 10^{-3}$ mm for the 300 line/mm grating or 1.66×10^{-3} mm for the optional 600 line/mm grating);

θ is the angle of diffraction; and n is the order of the diffraction spectrum under observation.

Using the Prism

Advantages and Disadvantages

A prism can also be used as the diffracting element in a spectrometer since the index of refraction of the prism (and therefore the angle of refraction of the light) varies slightly depending on the wavelength of the light.

A prism refracts the light into a single spectrum, whereas the grating divides the available light into several spectra. Because of this, slit images formed using a prism are generally brighter than those formed using a grating. Spectral lines that are too dim to be seen with a grating can often be seen using a prism.

Unfortunately, the increased brightness of the spectral lines is offset by a decreased resolution, since the prism doesn't separate the different lines as effectively as the grating. However, the brighter lines allow a narrow slit width to be used, which partially compensates for the reduced resolution.

With a prism, the angle of refraction is not directly proportional to the wavelength of the light. Therefore, to measure wavelengths using a prism, a graph of wavelength versus angle of refraction must be constructed using a light source with a known spectrum. The wavelength of unknown spectral lines can then be interpolated from the graph.

Once a calibration graph is created for the prism, future wavelength determinations are valid only if they are made with the prism aligned precisely as it was when the graph was produced. To ensure that this alignment can be reproduced, all measurements are made with the prism aligned so that the light is refracted at the angle of minimum deviation.

The Angle of Minimum Deviation

The angle of deviation for light traversing a prism is shown in Figure 9. For a given wavelength of light traversing a given prism, there is a characteristic angle of incidence for which the angle of deviation is a minimum. This angle depends only on the index of refraction of the prism and the angle (labeled A in Figure 8) between the two sides of the prism traversed by the light. The relationship between these variables is given by the equation:

$$n = \frac{\sin \left\{ \frac{A+D}{2} \right\}}{\sin \frac{A}{2}}$$

where n is the index of refraction of the prism; A is the angle between the sides of the prism traversed by the light; and D is the angle of minimum deviation. Since n varies with wavelength, the angle of minimum deviation also varies, but it is constant for any particular wavelength.

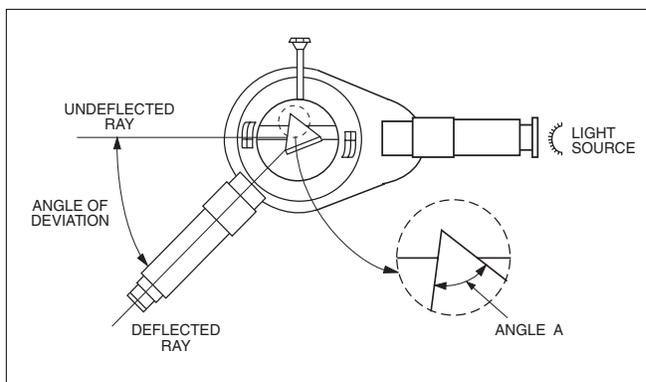


Figure 9 Angle of Deviation

To Measure the Angle of Minimum Deviation:

1. Align and focus the spectrometer as described earlier.
2. Use the two thumbscrews to attach the prism clamp to the spectrometer table and clamp the prism in place as shown in Figure 10.
3. Place the light source a few centimeters behind the slit of the collimator. (It may be helpful to partially darken the room, but when using the prism this is often not necessary.)

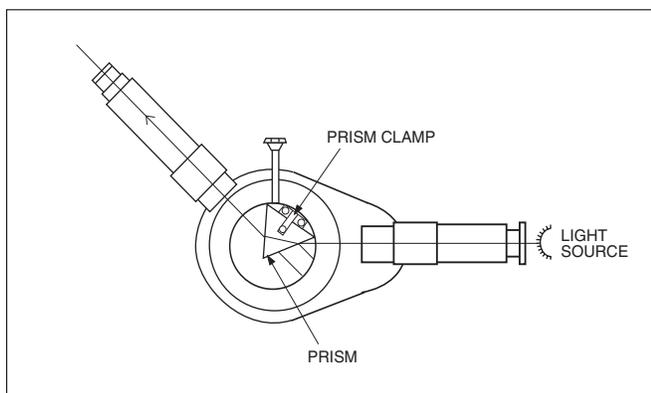


Figure 10 Mounting the Prism

4. With the prism, it is generally possible to see the refracted light with the naked eye. Locate the general direction to which the light is refracted, then align the telescope and spectrometer table base so the slit image can be viewed through the telescope.
5. While looking through the telescope, rotate the spectrometer table slightly back and forth. Notice that the angle of refraction for the spectral line under observation changes. Rotate the spectrometer table until this angle is a minimum, then rotate the telescope to align the vertical cross-hair with the fixed edge of the slit image. Use the fine adjust knobs to make these adjustments as precisely as possible, then measure the telescope angle using the vernier scale.
6. Without changing the rotation of the spectrometer table, remove the prism and rotate the telescope to align the cross-hair with the fixed edge of the undiffracted beam. Measure the angle on the vernier scale. The difference between this angle and that recorded for the diffracted spectral line in step 5, is the angle of minimum deviation. Notice that, since the determination of the angle of minimum deviation for each spectral line requires rotational adjustments of the spectrometer table, the angle of the undeflected beam must be remeasured for each line.