Experiment #4: Optical Spectrometer and the Prism Deviation

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1 Purpose

In the first part of this lab you will set up and become familiar with an optical spectrometer. In the second part of the lab you will use a glass prism to determine the index of refraction at $\lambda = 590$ nm.

2 Safety/Protocol

Use the curtains to provide useful "black" backgrounds for the telescope. There are also screens to cut down on glare from the source.

3 Preparation/General Instructions

To prepare for this lab, you should read the corresponding section in your textbook (pages 60-67 in Pedrotti[3]). The most useful formula which will allow you to determine the refractive index is

$$n = \frac{\sin\left[(A+\delta)/2\right]}{\sin(A/2)} \tag{1}$$

where A is the angle of apex of the prism and δ is the angle of *minimum deviation*.

4 Procedure/Analysis

4.1 The spectrometer

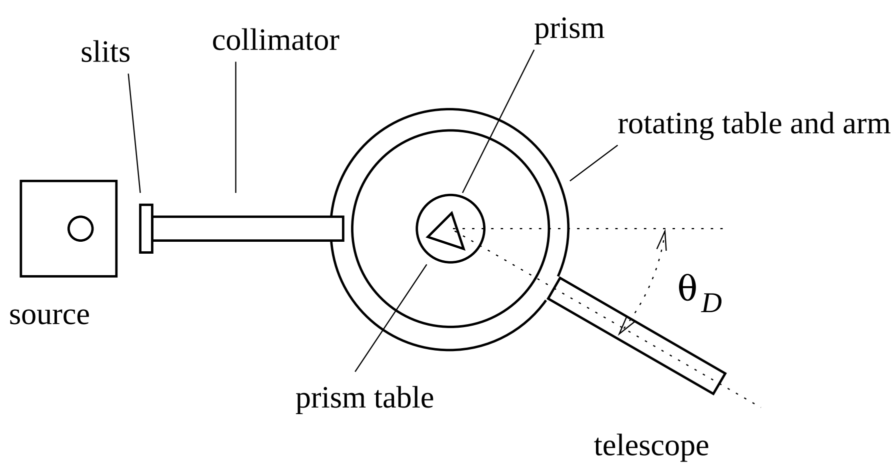

Figure 1: Schematic of the optical spectrometer using a prism..

4.1.1 Telescope

An astronomical (i.e. inverting) telescope with an achromatic objective and eyepiece is mounted on one arm of the spectrometer. The arm can be turned around a vertical axis passing through the center of the spectrometer. A graduated circular scale is attached to the telescope arm. This scale can be read by two Verniers 180 degrees apart. [1] The telescope stage can be clamped in any position by a screw and, in this position, a fine adjustment can be made by a tangent screw. Find these two adjustments and familiarize yourself with their operation. The telescope tube may be slightly tilted with the help of two screws attached to the arm of the spectrometer. The telescope has a $\times 7$ Ramsden eyepiece. The eyepiece can be slid in and out to focus the cross hairs. The cross hairs can be rotated to make them horizontal and vertical. (Try it.) Once the crosshairs are focussed a rack and pinion arrangement is attached to the telescope tube to focus the telescope.

4.1.2 Collimator and Slits

The purpose of the collimator is to produce a parallel beam of light i.e. an object at infinity. It consists of a tube mounted horizontally on another arm of the spectrometer. This arm is fixed to the spectrometer base. The end of the tube facing the prism table has an achromatic converging lens and the other end carries a sliding tube attached to an adjustable vertical slit. The distance between the slit and the lens can be varied by a a rack and pinion. The slit is composed of two sharp edges out of which one is kept fixed and the other can be moved by using the screw. There is also a slider to adjust the height of the slit. The entire "slit" can be rotated to either have it in horizontal or vertical position.

4.1.3 Prism table

The prism table consists of two circular plates of the same radius and separated by three springs. Each spring carries a leveling screw. Straight lines, parallel to a line that connects two of these screws are engraved on the upper plate and the prism is placed on the table so that a reflecting surface is perpendicular or parallel to these lines. The vertical axis of rotation of the spectrometer passes through the center of the prism table. The height of the prism table can be adjusted with a clamping screw that fixes the table to the circular Verniers. Thus the table can be moved around the vertical axis and its position (relative to the telescope arm scale) can be read by the Verniers. Like the telescope arm it can also be fixed at any desired angle by a clamping screw and rotated very slowly using a tangent screw. Familiarize yourself with these adjustments.

4.1.4 The Vernier scales

The optical spectrometer is a high precision instrument from a different era. Things like ergonomics or ease of use were secondary to precision and flexibility. Also they are pretty tough and have long lifetimes. Incidently, quite expensive to replace, which is one reason we are still using them after 40 years.

You will have used the Vernier before when doing the "Balmer Series" experiment from PHYS 201 but it is worthwhile to explain again just how it functions.

First, just how does a Vernier work to increase the precision of a scale. Have a look at Figure 2. Suppose that you have a primary scale that is marked in 0.5^{o}increments and that scale slides beside another secondary Vernier scale. You use the zero line on the seconday scale to make a

[1] You might think that the Verniers (and their "zeros") are attached to the spectrometer base but they are attached to the prism table.

Figure 2: A photograph of the Vernier from the optical spectrometers used in the lab. The lighting isn't perfect but I would say the "0" of the Vernier scale is somewhere between the 66°0' and 66°30' marks (maybe a quarter of the way). The Vernier scale marks definitely appear to the left of the primary scale below 7' and probably to the right for marks above 12' (and the slight flaking and corrosion on the primary scale opposite the 13', 14', and 15' mark don't help in this judgement. Best line up is probably at 9' or 10' with an error of 2'. Giving an answer of 66°9' or $66.15 \pm 0.03^{\circ}$.

measurement on the primary scale. Let's say for sake of argument that "0" is about one quarter of the way between 66.0 and 66.5°. You expect your answer to be somewhere between 66.1 and 66.2°.

Now the Vernier comes into play and as a "blast from the past" the Verniers on the spectrometer go up to 30 *minutes* (symbol '). There are 60' in 1°. The primary scale is in 0.5°(or 30') increments so a reading of the Vernier of between 6 and 12 minutes would correspond to the angles given above.[2]

The operation of the Vernier allows you to be much more precise about just how far "0" is past the primary scale. We want to try and somehow split this interval into 30 parts. The trick is make the secondary scale slightly more compressed so that 30 marks on the secondary occur in 29 marks on the primary. Whaa? Suppose that your "0" is in fact 1 minute of arc past 66°0'. Since the Vernier scale is compressed relative to the primary the first mark on the Vernier is only 29/30 of the smallest primary spacing (30') past "0". Excellent. Since "0" is 1' past 66°0' then the first mark on the Vernier will be $1' + (29/30)30' = 30'$ past 66°0' or exactly at 66°30'. Moving "0" by another minute of arc will move the first mark on the Vernier to 66°31' (not lined up) but should bring the second mark of the Vernier to $2' + 2(29/30)30' = 60'$ past 66°0'. It will line up with 67°0' and so on. All that matters is which mark on the secondary most closely corresponds to any primary scale mark. To test your understanding, suppose that "0" is right at 66°9' where would you expect the 9' mark on the secondary to be. Check your answer by looking at Fig. 2.

In principle you could make a Vernier as precise as you wanted by just adding more marks to the secondary but this makes it more of a judgement about which secondary mark to choose. Even with this 30 scale Vernier I find it a challenge to do any better than a range of 3'. The age of the scale, poor lighting, and lack of magnification can make it really tedious and mistake prone. If you are having trouble I'll explain my "headshake" method. Just remember that whatever you get should make sense versus the position of "0" between the marks on the primary.

The other annoying features. If you are in regions between 30' and 60' of the primary scale you will need to remember to add 30'. The scale reads backwards compared to most scales. The

[2] If you are using a computer for analysis I tend to keep these things as separate data columns and then use "Quick Transform" to make a new angle column with angle(°) + angle(minutes)/60.

important number on the primary scale is often covered up. Worst of all the angle isn't absolute. If you are trying to make measurements of telescope arm angle and the prism table moves because you forgot to clamp it... you have no idea what the angle is any more. You'll need to go back to a reference.

4.1.5 Alignment/ Setup

The key to aligning any instrument is to have a clear set of steps, making one adjustment at a time, and then never needing to adjust it again. Otherwise you go in circles. I am still working on the "best" procedure but let's try the following.

1. Put a spirit level on the base of the spectrometer (not the prism table) and use the adjusters on the base to make it level. The base of the spectrometer is normal to the axes of rotatation of the table and the telescope arm. **The axis of rotation now points along the vertical.** [3]

2. Now use a spirit level to level the collimator and the telescope. In principle **the collimator and telescope are now both in the plane normal to the vertical.** The incoming and scattered beam should stay in this plane.

3. You should be able to adjust the position of the eyepiece in and out relative to the crosshairs. You should also be able to rotate the cross hairs. First adjust the eyepiece to bring the cross hairs to the ffl. Now adjust the focus of the telescope to bring a distant object into focus. If possible set up a level object so that you can rotate your crosshairs (but just by hand is likely fine). Quickly check that that crosshairs to do not shift vertically relative to the level object. Also (as much as possible) make sure there is no parallax between the real image of the distant object and the cross hairs but very slightly adjusting the gaze of your eye. If one seems to be "hanging" in front of the other adjust to correct. **The telescope is now ready to accept a parallel beam of light, the angle of which can be determined from the scale once the crosshairs are in-line.**

4. Now illuminate the slit (a lamp is fine) and move the telescope so it is in-line with collimator. Adjust the collimator focus until you see a clear image of the slit. Again there should be no parallax. Can you tell which edge of the slit image is "fixed" and which can be adjusted by adjusting the slit width? You should make measurements from this fixed edge. **The collimator is now producing a parallel beam of light from the slit.**

5. *If* everything is sufficently level you should be able to rotate the slit to a horizontal orientation and its image will be right on the horizontal crosshair. If it isn't use your spirit level again to check to see if both tubes are level. Adjust which ever one is worst to bring the slit and crosshair into coincidence. If it is more than a slight adjustment there may be a bigger problem with the spectrometer and you should check with me or Jim. **Collimator and telescope are now fine adjusted for the same plane.**

6. The last step is to level the prism table. To make it easy on yourself use the spirit level to get it roughly correct. Now rotate the telescope to roughly 90°. Clamp it in place. Put a prism on the table with one of its polished sides normal to the engraved line mentioned earlier in Section 4.1.3. Rotate the table until the you can see the reflection of the slit in the telescope. Now adjust the table leveling screws along the engraved line to bring the horizontal crosshair

[3] There is nothing special about vertical; it just makes it easier to reference other things.

and slit into coincidence. Now rotate the prism on the table by 90°and then the prism table 90 the other way to bring the reflection back again. Now adjust the leveling screw that is not on the line. Rotate the prism table to the other polished side to verify that everything is level.

7. Remove the prism and go back to the 0°position for the telescope and bring the slit back to vertical.

Great. You are now ready to go!

4.1.6 The actual experiment Part I

Refer to diagrams in Pedrotti[3] such as Figure 3-9. You don't have a single ray but instead a collection of parallel rays. Start with a sodium source (essentially only $\lambda = 590$ nm) and verify the behaviour of Figure 3-10. Doing this is challenging because it involves moving both the prism table and telescope which are referenced to each other through the Vernier scale. Try the following procedure. Jim and I can help.

1. Change to the sodium source.
2. With no prism in place, clamp the prism table.
3. Bring the telescope to the zero deviation location using a combination of clamping and fine adjustment. Record the angle.
4. With the prism table still clamped, bring the telescope to 60°0'. Clamp the telescope.
5. Install the prism so its apex roughly points to the collimator. You rotate the table however you wish. The apex angle of the prism is should be 60°.
6. Now rotate/clamp/fine adjust the table to bring the slit in-line with the crosshair. Record the Vernier reading. You now know where the normal of the prism is. Question: what is the angle of incidence?
7. Now to get something like Fig. 3-9 you will need to rotate the prism table. Try and adjust for a zero degree incident angle. Record the Vernier angle.
8. Now move the telescope to find the deviated ray. You should be able to determine θ_D by reading the Vernier and making all of the appropriate subtraction.
9. Continue to adjust the incident angle θ_i and find the θ_D taking care to keep track of your angles. Plot the angles by hand in your lab book.
10. Once you have a good idea of the θ_i and θ_D that correspond to δ return the spectrometer to that position. While looking through the telescope slowly rotate the prism table and you should be able to see θ_D go to a minimum (it will be the other way because of the inversion; hey that is probably why the scale is backward). Clamp the table at the θ_D position and record the value to give you θ_i. Now move your telescope to actually measure δ. Calculate n with an error.