Experiment 8

DIFFRACTION GRATINGS AND SPECTROSCOPY

Objectives

• To introduce and calibrate a diffraction grating, and use it to examine several types of spectra.
• To learn how to use a Vernier scale.
• To learn to use a grating spectrometer.
• To measure the wavelength of spectral lines of Na and H.

Diffraction Gratings:
In the previous lab you found that light shining through a double slit produced a central bright spot with alternating dark and bright spots on either side. The angle \( \theta \) between the central bright spot and the center of the bright spots of light on either side of the central spot is given by \( d \sin \theta = m \lambda \). \( d \) is the distance between slits, \( m \) is an integer that identifies the \( m \)th intensity maximum on either side of the central maximum, and \( \lambda \) is the wavelength of the light. If you have more slits, all spaced \( d \) apart, the angles to principal maxima will remain the same regardless of the number of slits as long as \( d \) remains the same. What will change is the shape of the intensity pattern; see figure at right. With more slits, the bright spots get narrower and secondary maxima in between the bright spots get more numerous and fainter. Eventually only the bright, sharp principal maxima can be seen. A diffraction grating has a large number of slits, often 10,000 or more, that are very close together. Each intensity maximum or “order” is very narrow and intense. Diffraction gratings rely on both interference and diffraction: diffraction to bend the light away from the straight-line path, and interference to make very bright spots where the path length from each neighboring slit differs by exactly \( m \) wavelengths, so the individual wave disturbances add constructively.

IN WHAT FOLLOWS, MAKE SURE LASERS ARE TURNED OFF EXCEPT WHEN IN USE. NEVER POINT LASERS AT ANYONE, AND NEVER LOOK DIRECTLY INTO LASER BEAMS.
Set up the optical bench, laser, diffraction grating and large white board as shown in Fig. 8.1. The component carrier with the diffraction grating should be located so that the locating edge is 25.0 cm from the end of the bench. Tape a piece of paper to the wood screen, and then place the base of the screen in contact with the end of the optical bench. The surface of the screen should be perpendicular to the bench.

**Note:** If the laser, grating, and screen are not oriented correctly, there can be a significant error in your measurement of the angle from the central maximum to the higher order maxima. You can eliminate almost all of this error by taking the average of the distances from the central maximum to the maxima on the left and on the right.

1. Measure the distance $D$ from the diffraction rulings to the screen surface and record it below.

   $D = \pm \quad \text{mm}$

2. Mark on the paper the location of the central maximum and the location of the first two maxima (orders $m = 1$ and 2) to the right and left of the central one. Measure the distance between the two first-order maxima $2x_1$ and the distance between the two second-order maxima $2x_2$. Use these measurements, the measurement of $D$ and the wavelength of the laser, 632.8 nm, to calculate the sine of the diffraction angles for the two maxima and the slit separation $d$ for the diffraction grating. Compare your values to the one derived from the nominal slit linear density of 300 lines/mm. Show your work.

   $2x_1 = \pm \quad \text{mm} \quad \quad 2x_2 = \pm \quad \text{mm}$

   $\sin \theta_1 = \pm \quad \quad \quad \quad \sin \theta_2 = \pm \quad \quad \quad \quad$

   $d = \pm \quad \quad \quad \quad \quad d = \pm \quad \quad \quad \quad \quad$

   Average $d = \pm \quad \quad \quad \quad \quad$
Remove the laser. Set the white light source on the end of the optical bench as shown in Fig. 8.2. Center the light source in the opening at the end of the source enclosure and place the SLIT PLATE directly on the end of the light source. Center the SLIT PLATE so that a beam of light travels down the center of the optical bench. Remove the diffraction grating and center the PARALLEL RAY LENS on the bench. Move the PARALLEL RAY LENS along the bench until the central beam is focused on the screen. Reposition the diffraction grating 25.0 cm from the end of the bench as you had it in 1.

3. Describe the pattern you see on the screen. Include the order of the colors in your description.

4. **Measure** the distance \(2x_1(\text{red})\) between the extreme outer edges of the spectrum in first order. **Measure** the distance \(2x_1(\text{violet})\) between the extreme inner edge of the spectrum in first order. Use your value of \(d\) from 2 to calculate the wavelength \(\lambda_{\text{red}}\) of the extreme red edge of the spectrum and the wavelength \(\lambda_{\text{violet}}\) of the extreme violet edge of the spectrum. **Show** your work. **Comment** on the consistency of these wavelengths with the usually quoted extent of the visible spectrum, 400nm to 750nm.

\[
\text{distance from the grating to the screen } D = \quad \pm \quad \text{mm}
\]

\[
2x_1(\text{red}) = \quad \pm \quad \text{mm} \quad 2x_1(\text{violet}) = \quad \pm \quad \text{mm}
\]

\[
\lambda_1(\text{red}) = \quad \pm \quad \text{nm} \quad \lambda_1(\text{violet}) = \quad \pm \quad \text{nm}
\]

TA initials

AT THIS POINT TURN ON THE SODIUM LAMP. IT WILL TAKE 10 MINUTES OR LONGER TO REACH A BRIGHT YELLOW COLOR.
**Spectroscopy:**

In part 3 you saw that, since diffraction gratings bend light of different wavelengths at different angles, they can be used to separate white light into a spectrum of different colors. So far you have looked at laser light, which contains just one wavelength, and visible white light, which contains a range of wavelengths. The pattern produced by shining a beam of white light through a diffraction grating is called a continuous spectrum. You can see other kinds of spectra by looking at the light emitted or absorbed by atoms. If you look at the spectrum of light emitted by a heated gas of atoms, you will see an emission spectrum. This often consists of a few bright lines at specific wavelengths and no light at other wavelengths. These bright lines are produced by electrons in the atoms radiating quanta with energies that correspond to the lines. Isolated atoms cannot store internal energy in arbitrary amounts, but only in discrete, quantized amounts. An absorption spectrum is a continuous spectrum with a few dark lines where quanta corresponding to the dark lines have been absorbed by the same atoms responsible for the bright lines.

5. Use your diffraction grating to look at the emission spectra produced by the sodium lamp and the hydrogen lamp. Then look at the fluorescent light inside a box with a slit, which should contain some combination of the three kinds of spectra discussed above, i.e. emission line, emission continuum, and absorption line. Which kinds do you see?

**Optical Spectrometer**

We will use the Model P67000 Intermediate Spectrometer to measure the yellow wavelengths emitted by a sodium (Na) lamp and three wavelengths emitted by a hydrogen (H) lamp. Please put away the optical benches and all the components before using the spectrometer.

The principal parts of the spectrometer are: 1) an adjustable-width slit that is illuminated with the light for which a spectrum is to be measured, 2) a "collimator" that focuses the light from the slit so that it becomes parallel (the slit is at the focal point of the collimator), 3) a diffraction grating, 4) a viewing telescope that focuses the parallel light from the grating onto a reticle (a glass disk on which a pattern of lines has been inscribed) and 5) an eyepiece with which to view the image of the slit focused on the reticle.

**Please do not turn the slit screw with any force! It is very easy to break! Be gentle with it!**

**ALIGNING THE SPECTROMETER**

The major part of the alignment of the spectrometer should have been done before you came to the lab. If something seems out of alignment, consult your TA. The spectrometer is provided with a large number of adjustments. Leave these as you find them or risk a lengthy alignment procedure. Four of the adjustments you will need to use are color-coded and the two others are easily described. Locate the red, yellow, green and blue color-coded screws first.

**Setting the divided circle, the vernier and the telescope.**

A. Loosen the four color-coded screws. Rotate the telescope until it is approximately at zero degrees on the outer divided circle, and then tighten the green screw. This will lock the telescope to the divided circle.

B. Rotate the inner platform with the vernier scales until one of the vernier scales is at about 50°. Tighten the blue screw. This locks the position of the verniers relative to the divided circle. This position is chosen to facilitate reading the diffraction angles. It can be changed if you like, but do not change it once measurements are started. You should now be able to rotate the telescope by hand to any desired angle and read the angle with the outer divided circle and the vernier scale.
C. Later, when you have the telescope in a position such that a line is near the vertical crosshair, tighten the red screw and use the yellow screw to make fine angle adjustments.

Setting the light source, slit width and eyepiece focus
D. With no grating in place, set the spectrometer close to the edge of the table with the slit end away from the edge. Cover the round opening in the Na lamp with a diffuser glass and a vertical rectangular metal slit. Move the Na lamp and/or the spectrometer so it is close to and aligned with the slit of the spectrometer and axis of the collimator tube.
E. Adjust the slit width with the knurled knob near the slit until the slit is several times its smallest width. Turn the large knurled knob at the end of the telescope until the slit image is in sharp focus. The crosshairs should also be in sharp focus. If not, consult your TA.

Installing the diffraction grating and reading the telescope angle.
F. Put the 300 line/mm grating in the slotted base and place base and grating on the grating table. Adjust the grating to be as perpendicular to the incoming collimated light as you can. The grating assembly is free to move on the table. Take care not to disturb it during the course of measurements on a spectrum or you will have to start over!

6. Read the telescope angle with the slit image centered in the eyepiece and record it in the Table below. Move the telescope until the line is nearly in the center of the field of view, and then tighten the red screw. Use the fine adjustment yellow screw to center the crosshairs on the line.

How to read a Vernier Scale.

Your spectrometer is capable of very precise angle readings. It includes a clever method for making it easier to read the angle setting precisely, called the Vernier scale.

a. The divided-circle scale is calibrated in degrees, with numbers every 10 degrees. The smallest marked interval is half a degree.

b. There are 60 “minutes of arc” in a degree, so half a degree is 30 minutes. (Astronomers even subdivide the minute into 60 “seconds of arc”).

c. The movable Vernier scale is placed alongside the circle scale, but its markings are slightly closer together than the circle scale. 31 marks on the Vernier scale fit in the same space as 30 marks on the circle scale. This trick provides a way to subdivide, or interpolate, the circle scale marks to an accuracy of 1/30 of the smallest circle scale interval! So, each mark on the Vernier scale is 1 minute. (If you don’t quite see how it works, it is ok just to learn the rule for reading it.)

d. Make a rough reading of the angle setting, using the index marked “0” on the Vernier scale. In the figure it rests between 120° 30’ and 121°. If you have a good eye, you can see it is actually about halfway between those marks, so you would add another 30/2 = 15’ to the reading and estimate 120° 45’.

e. Now look at the Vernier scale. The eleventh or perhaps twelfth mark lines up with a mark on the circle scale. That tells us the exact number of extra minutes to add to the 30 we got from the rough reading, and gives us the final answer, 120° 41’. This is more accurate than the estimate from the index mark alone.

f. To do calculations, you need to convert to decimal fractions of degrees: 120° 41’ = 120° + 41/60 = 120.68 degrees.
Measuring the Sodium Line

8. Adjust the slits until a narrow line is obtained and move the telescope to the right and center the first order yellow line in the field of view. You may be able to see that the “line” is actually two lines very close together (this will be easier to see in 2nd order). The longer wavelength \( \lambda(D_1) = 589.592 \text{ nm} \) line (it has the larger diffraction angle) is commonly called the D_1 line of the Na doublet. The other line is called D_2 \( \lambda(D_2) = 588.995 \text{ nm} \). Record the angle for the D_1 member of the doublet in the row labeled 1st order, D_1 – right in the Table below.

9. Move the telescope to the left and record the angle for the D_1-left line in first order.

10. Repeat the right and left measurements for 2nd and 3rd orders for D_1 and record them in the table. You may need to refocus the eyepiece in the higher orders if the slit image is not sharp.

11. Complete the table by first calculating 1/2 the angular separation of D_1 in three orders. Use these values in the expression \( d \sin \theta = n \lambda \) to calculate 1/d, the number of lines per millimeter in the grating. Estimate the uncertainty in 1/d from the uncertainty \( \delta(1/2 \text{ angular separation}) \).

\[
\begin{align*}
1^{st} \text{ order} & \quad 1/d = \phantom{-} \pm \phantom{a} \text{lines/mm} \\
2^{nd} \text{ order} & \quad 1/d = \phantom{-} \pm \phantom{a} \text{lines/mm} \\
3^{rd} \text{ order} & \quad 1/d = \phantom{-} \pm \phantom{a} \text{lines/mm}
\end{align*}
\]
12. Calculate the mean of the three values of 1/d and the uncertainty in the mean. Comment on the consistency of your values. Are they as equal as you might expect them to be? If not, what experimental problems may have led to the inconsistency?

\[(1/d)_\text{mean} = \text{_________} \pm \text{_________} \text{ lines/mm}\]

Comment:

13. Compare \((1/d)_\text{mean}\) to the value you obtain from 2.
14. Devise a method for measuring the wavelength separation $\Delta \lambda$ of the two D lines. Record your data below and use it to determine $\Delta \lambda$ and its uncertainty. Compare your value to the accepted value.

$$\Delta \lambda = \boxed{\text{nm}} \pm \boxed{\text{nm}}$$

15. Replace the Na lamp with a hydrogen lamp (H-lamp, black vertical narrow box). Take care not to move the spectrometer or the grating. Use blocks of wood to raise the lamp, if necessary. Turn on the lamp and measure the zero angle (alignment angle) and the angles at which the three easiest-to-see spectral lines are found in first order. You will have to adjust the position of the hydrogen lamp very carefully and you may have to open the slit a bit to see the lines.

$$\theta (^\circ) = \boxed{\text{}}$$

1st order

- red line $\theta = \boxed{}$
- blue-green line $\theta = \boxed{}$
- violet line $\theta = \boxed{}$

16. How many orders can you see for each color? Is there a case where you see the short wavelengths of a higher order before you see the long wavelengths of a lower order? Describe your observations.

17. By the same technique you used to measure the Na lines, measure the positions of the three H lines in first or second order (say which you use) and calculate their wavelengths using your measured value of $(1/d)_{\text{mean}}$.

<table>
<thead>
<tr>
<th>Order</th>
<th>line</th>
<th>Left/Right</th>
<th>$\theta$</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>red</td>
<td>L</td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>blue-green</td>
<td>L</td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>violet</td>
<td>L</td>
<td>R</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
18. Find the best values for the wavelengths of the three lines and record them below with their uncertainties. Compare (7.1) them to the values listed below.

\[ \lambda(\text{red}) = 656.279 \text{ nm} \quad \lambda(\text{blue-green}) = 486.133 \text{ nm} \quad \lambda(\text{violet}) = 434.047 \text{ nm} \]

red \quad \lambda = _______ \pm _______ \text{ nm}
blue-green \quad \lambda = _______ \pm _______ \text{ nm}
violet \quad \lambda = _______ \pm _______ \text{ nm}

These spectral lines belong to the famous Balmer series, in which electrons decay to the first excited electronic level of the H-atom from higher excited states. Decays to the lowest level (ground state) give the Lyman series. All the Lyman series wavelengths are in the ultraviolet range of wavelengths (the longest wavelength in the series is called Lyman \( \alpha \) and has a wavelength of \( \lambda = 121.568 \text{ nm} \)). Radiation of such short wavelengths does not penetrate the glass envelope of the lamp. Decays to the third excited state give rise to the Paschen series. All the wavelengths in this series are in the infrared (the shortest wavelength is \( \lambda = 1093.8 \text{ nm} \)) and are not visible.