

# Spectroscopy

## Experiment Three

Physics 192  
Michigan State University

### Before Lab

- Carefully read the entire lab guide
- Attempt the theory questions

### Experiment Overview

This is a two-week lab expanding on concepts from both geometric and wave optics. You will study the spectra of atomic gases in a process called spectroscopy.

- Use two different dispersion mechanisms to separate light into its component wavelengths
- Make accurate measurements with an optical spectrometer
- Practice instrument calibration
- Produce comprehensive and understandable lab report: always provide context for your work, show all relevant calculations, explain your thought process, and interpret your results

## 1 Atomic Physics

The properties of refraction and diffraction studied in the previous labs can be used to probe the internal structure of matter. Experiments examining light emitted by chemical elements in the early 1800s were instrumental in developing our modern atomic theory. The phrase *atomic physics* primarily refers to the study of atoms, ions, and molecules as systems of electrons and nuclei interacting via the electromagnetic force. This is differentiated from *nuclear physics*, which deals with radioactivity and the forces mediating nuclear reactions. In this lab, you will study phenomena that established the framework of quantum theory.

### 1.1 Dispersion

Light emitted by most sources is a combination (superposition) of multiple wavelengths. White light emitted by natural sources<sup>1</sup> consists of a continuous spectrum of color, an observation demonstrated by Isaac Newton. By passing sunlight through a prism, Newton separated the white light into its colored components. The process by which light is decomposed into its component wavelengths is called **dispersion**. Dispersion occurs in materials whenever the velocity of an electromagnetic wave depends on the wavelength. Both prisms and diffraction gratings are capable of dispersing light, but they do so by different mechanisms.

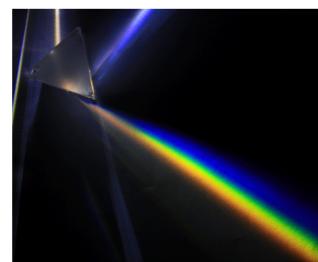


Figure 1: A prism dispersing sunlight into spectrum of color.

<sup>1</sup>Electronic displays produce white light using a combination of only three colors in equal proportions: red, green, and blue.

### 1.1.1 Dispersion by a Prism

Recall that light travels at different speeds in different optically transparent media. A light wave passing from air in to glass experiences a reduction in speed as it interacts with electrons in the glass. The reduced speed is related to the speed in vacuum by the index of refraction (IOR), defined as

$$n = \frac{c}{v}, \quad (1)$$

where  $c$  is the speed of light in vacuum and  $v$  is the speed in the material. The IOR is a material property that generally depends on the wavelength of light. In 1837, French mathematician Augustin-Louis Cauchy defined an empirical relationship between the IOR of a material and the wavelength of light. The most general form of **Cauchy's equation** is an infinite sum, but most cases can be sufficiently described by the first two terms:

$$n(\lambda) = A + \frac{B}{\lambda^2}, \quad (2)$$

where the coefficients  $A$  and  $B$  are determined by fitting a curve to experimental data (this equation was introduced in the theory questions in the geometric optics lab).

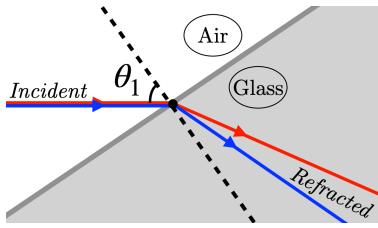


Figure 2

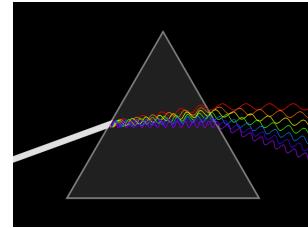


Figure 3

Figure 2 shows a beam of mixed red and blue light refracting into glass. The incident and refracted angles are related by Snell's law,

$$\sin \theta_1 = n(\lambda) \sin \theta_2, \quad (3)$$

where  $n(\lambda)$  is the IOR of glass for a wavelength  $\lambda$  and the approximation  $n_1 = n_{air} \approx 1$  has been used for air<sup>2</sup>. The refracted angles are different for each wavelength. This can be understood by solving Equation 3 for the refracted angle,

$$\theta_2 = \sin^{-1} \left( \frac{1}{n(\lambda)} \sin \theta_1 \right). \quad (4)$$

The result shows that the refracted angle depends on both the incident angle *and* the wavelength. Figure 3 shows white light refracting through a triangular prism. The light is dispersed into its component wavelengths because each refracts at a different angle upon entering and exiting the prism.

The geometry of a prism is an important aspect of its dispersive properties. Figure 4 shows a prism with an apex angle labeled as  $\alpha$ . The **apex angle** is the angle between the refracting surfaces of the prism. Prisms with large apex angles produce the most dispersion, maximizing the separation of wavelengths.

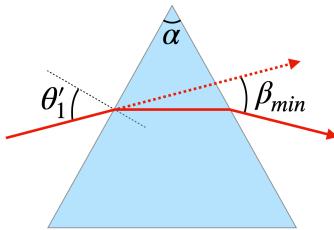


Figure 4: Minimum Deviation

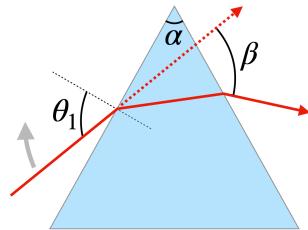


Figure 5: Not minimum deviation

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<sup>2</sup>This is a safe approximation. The IOR of air is 1.00029 for light with wavelength  $\lambda = 589$  nm, differing from the vacuum value by less than 0.03%.

In Figure 5, a ray at incident angle  $\theta_1$  refracts into a prism. The dashed red arrow indicates the path of the undeviated ray (as if the prism were not there). The angle  $\beta$  is called the **deviation angle**, as it measures the deviation of the transmitted ray from the undeviated path.

If the incident angle is reduced, a special situation can be reached in which the incident angle is equal to the refracted angle. In this orientation, the deviation angle takes its minimum value, labeled as  $\beta_{min}$  in Figure 4. The **minimum deviation angle** has two special properties:

1. It produces the sharpest spectrum with the most uniform separation of colors
2. It can be used to calculate the IOR of the prism geometrically

Figure 6 shows the deviation angle,  $\beta$ , as a function of the incident angle for a typical prism. Starting with an incident angle  $\theta_1 = 0$ , the deviation angle decreases until it reaches a minimum value at  $\theta'_1 = 23^\circ$  (red dot). This corresponds to the orientation in Figure 4. Beyond this point, the deviation angle increases monotonically with the incident angle. The blue dot on the graph corresponds to the orientation in Figure 5.

It is important to recognize that the deviation angle depends on the wavelength of light: this is what causes dispersion. If the rays in Figures 4 and 5 consisted of multiple wavelengths, the refracted rays would disperse and exit the prism at different angles. By measuring the deviation angle for a known wavelength of light, the IOR of a prism calculated using

$$n(\beta_{min}) = \frac{\sin\left(\frac{\alpha+\beta_{min}}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)} \quad (5)$$

where  $\alpha$  is the apex angle and  $\beta_{min}$  is the minimum deviation angle.

### 1.1.2 Dispersion by a Diffraction Grating

The wavelength dependance of interference effects was discussed extensively in the diffraction lab. Recall that **diffraction gratings** consist of very small repetitive structures, such as narrow slits. The incident light diffracts and produces bright, widely-spaced *interference maxima*. The **grating equation** relates the angular locations of the maxima and the wavelength of light:

$$d \sin \theta_m = m\lambda, \quad (6)$$

where  $d$  is the grating spacing,  $\lambda$  is the wavelength,  $m$  is the order number, and  $\theta_m$  is the angular location of a bright spot from the central diffraction maximum. The dispersive behavior of a diffraction grating is baked into Equation 6: different colors are dispersed at different angles. Note that the separation of colors is *not* due refraction here, but instead results from the interference of light waves passing through the grating.

## 1.2 Line Spectra

Figure 1 on the first page shows a prism dispersing sunlight into a rainbow, appearing as a smooth gradient of colors. Because of its immensely high temperature ( $\sim 6000$  K), the sun emits high-intensity thermal radiation across the visible spectrum. At lower temperatures, something interesting happens when light from an excited gas is viewed through a prism or diffraction grating. The right side of Figure 7 shows a neon lamp with its characteristic orange glow. When passed through a prism, the neon light is dispersed, producing a pattern of discrete lines known as a **line spectrum**. The lines are the individual wavelengths of light that combine to produce the familiar orange color.

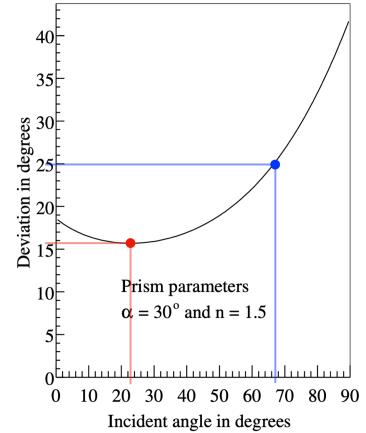


Figure 6: The deviation angle as a function of incident angle with the minimum labeled in red (Kenyon, 2008)

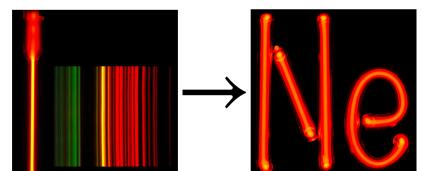


Figure 7: (Image source: [Neon](#))

By the mid 1800s, it was well established that different chemical elements have unique emission and absorption characteristics. In the 1860s, Gustav Kirchhoff and Robert Bunsen established a method for identifying chemical compositions by studying line spectra, forming the basis of **spectroscopy**.

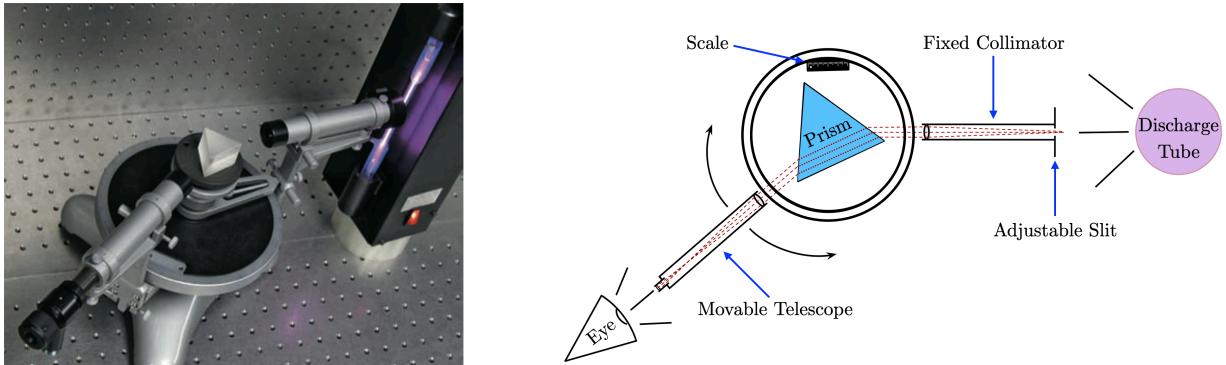


Figure 8: An optical spectrometer using a prism for dispersion of light from a gas vapor lamp.

A simple optical **spectrometer** is shown in Figure 8. A central rotating table holds the dispersive element, which can be a prism or diffraction grating. A **discharge lamp** is a gas-filled glass tube with electrodes at each end. A voltage is applied across the tube, generating an electric field that ionizes the gas. The ionized gas conducts an electric current between the electrodes, causing the gas to emit characteristic light<sup>3</sup>. A spectrometer can be used to analyze the emitted light as follows:

- i. The gas emits specific wavelengths of light that combine to produce a single color.
- ii. A fixed arm holding a collimator is positioned near the lamp. The collimator focuses a beam of light with a diameter controlled by an adjustable slit.
- iii. The beam passes through a prism or diffraction grating at the center of the circular table. The light is decomposed into its component wavelengths which propagate at different angles.
- iv. The light is observed through a movable telescope containing a focusing eyepiece. By aligning the telescope with each emission line, the angular location can be measured using a high-precision scale.

Pay close attention to *what* is measured with the spectrometer. If a prism is used, the minimum deviation angle,  $\beta_{min}$ , is measured. The prism can be replaced by a diffraction grating, in which case the diffraction angles,  $\theta_m$ , are measured. Each color is displaced by a unique angle as described in the section on dispersion.

The top picture in Figure 9 shows a hydrogen discharge lamp emitting light. The purple-pink hue results from a combination of four distinct wavelengths of light. The violet, deep-blue, teal-blue, and red lines shown in the bottom picture comprise the visible hydrogen line spectrum.

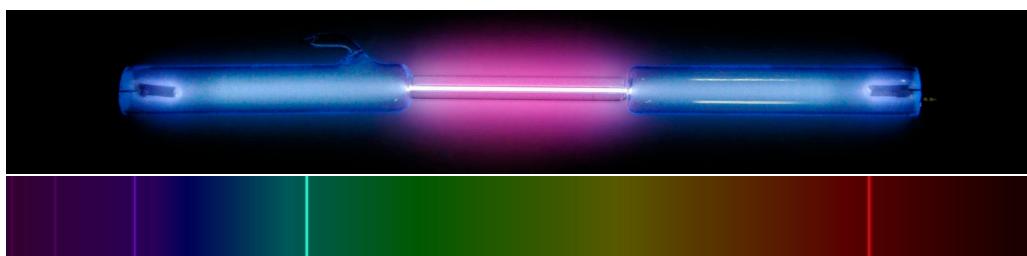


Figure 9: (Top): a hydrogen discharge lamp. (Bottom): the emitted light decomposed using a diffraction grating with 600 lines/mm. Image source: [Discharge Lamps](#).

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<sup>3</sup>More than just *visible* light can be emitted by a discharge lamp. The range of emitted electromagnetic radiation extends beyond the visible spectrum.

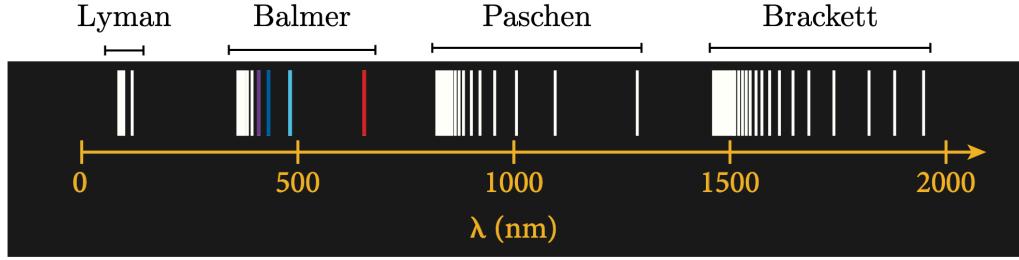


Figure 10: The hydrogen emission spectrum including ultraviolet through far infrared wavelengths.

The spectrum of hydrogen is not limited to visible light. Figure 10 shows a more complete picture of the hydrogen spectrum. The four colored lines represent the visible wavelengths from Figure 9. The remaining white lines correspond to invisible wavelengths of electromagnetic radiation. Pay close attention to the significance of this observation: excited gases do not emit a smooth distribution of wavelengths; instead, the emission is discrete and well-defined.

The pattern in Figure 10 shows the allowed wavelengths for hydrogen, consisting of four distinct domains named after their discoverers. Interpretation of this pattern played a significant role in the development of quantum theory. In 1888, Johannes Rydberg published an empirical formula that successfully predicts the wavelengths of the full hydrogen spectrum. The **Rydberg formula** for hydrogen is

$$\frac{1}{\lambda} = R_H \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right), \quad \text{with } n_f < n_i \quad (7)$$

where  $n_f$  and  $n_i$  are natural numbers;  $R_H$  is a number called the *hydrogen Rydberg constant*, with a value of

$$R_H = 1.09678 \times 10^7 \text{ m}^{-1}. \quad (8)$$

The value of  $R_H$  was determined as a fitting parameter before any theoretical explanation for the discrete nature of line spectra.

Line Series	Wavelength	$n_f$
Lyman	Ultraviolet	1
Balmer	Ultraviolet & Visible	2
Paschen	Infrared	3
Brackets	Infrared	4

Table 1: The hydrogen series of spectral lines.

### 1.3 The Bohr Model

The wave theory of light studied in previous labs cannot fully account for the discrete nature of line spectra, which instead predicts a continuous range of wavelengths. While studying thermal emission of electromagnetic radiation, Max Planck proposed that electromagnetic energy could only be emitted or absorbed in discrete packets called "quanta." Shortly after, Albert Einstein extended the quantization concept to a range of electromagnetic phenomena. Einstein proposed that the energy of a light wave consists of a finite number of indivisible units called **photons**, each of which carrying a discrete energy of

$$E = hf$$

where  $f$  is the frequency of the wave and  $h$  is a number called **Planck's constant**, with a value of  $h = 6.62607 \times 10^{-34} \text{ J} \cdot \text{s}$ . Einstein's key observation was that a complete description of light requires both wave and particle characteristics. This contradictory perspective is called the **wave-particle duality**, marking

a significant departure from classical theories. Using the speed of light,  $c = \lambda f$ , the photon energy can be expressed in terms of the wavelength as

$$E = \frac{hc}{\lambda}. \quad (9)$$

Motivated by high-precision measurements of the hydrogen spectrum, Neils Bohr began a pursuit to find an atomic theory which could produce the empirically-determined Rydberg formula. It was thought that atoms consist of a small, massive nucleus surrounded by negatively-charged electrons moving in circular orbits. This classical interpretation was appealing for its similarity to planetary motion, but it failed to explain why electrons do not lose energy and spiral into the nucleus.

Bohr reconciled this shortcoming by assuming that an electron's angular momentum can only exist in discrete, quantized states. The Bohr model is based on three fundamental postulates:

1. Electrons can only orbit the nucleus in specific *stationary states* which have a fixed total energies
2. The angular momentum of an electron in orbit can take only discrete values in multiples of Planck's constant:  $L = n\hbar$  where  $\hbar = h/2\pi$  is the reduced Planck constant and  $n$  is an integer called the **principle quantum number**, which increments the allowed states
3. Electrons can gain or loose energy by jumping between allowed orbits through the absorption or emission of a photon

With these assumptions, Bohr formulated a model of the hydrogen atom which successfully reproduced the hydrogen Rydberg equation. Quantization of angular momentum imposes restrictions on the allowed orbital radii, confining the electron to a series of shells. Each shell has a distinct energy state that depends on the principle quantum number as

$$E_n = -\frac{E_0}{n^2} = -\frac{13.6 \text{ eV}}{n^2}, \quad \text{where } n = 1, 2, 3, \dots \quad (10)$$

The "ground state" corresponds to  $n = 1$  and has the lowest energy,  $E_1 = -13.6 \text{ eV}$  (eV is an energy unit called the **electronvolt**). The electron energy is negative to reflect that it is in a *bound* state, in which energy is required to remove the electron (i.e. *ionize* the atom).

Figure 11 shows a diagram of Bohr's interpretation of the hydrogen atom, in which an electron in an "excited"  $n = 3$  state transitions to the lower-energy  $n = 2$  state. The transition requires the emission of a photon carrying the energy difference between the two states,  $\Delta E = E_3 - E_2$ . In this context, it is worth revisiting the Rydberg formula for hydrogen:

$$\frac{1}{\lambda} = R_H \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right).$$

The integers  $n_f$  and  $n_i$  can now be interpreted as the quantum numbers of the final and initial energy states. The unique wavelengths observed in line spectra correspond to photons with energies dictated by allowed transitions between energy levels.

The Bohr model was an important step in the development of quantum theory, but it is an incomplete description of atomic structure. It does not describe atoms with more than one electron and it fails to account for the wave-like properties of matter<sup>4</sup>. Nevertheless, it was an important link between classical and quantum mechanics and it provides a basic interpretation of line spectra.

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<sup>4</sup>See [Matter Waves](#) for more information.

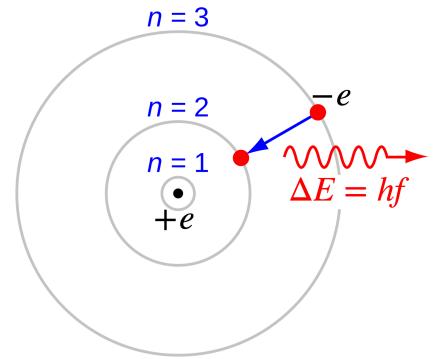


Figure 11: A Bohr diagram showing photon emission resulting from a transition between the  $n = 3$  and  $n = 2$  states.

## 2 The Vernier Scale

A Vernier scale is an analog tool for making high-precision measurements of linear or angular quantities. In this lab, you will be using a Vernier scale to measure the angles  $\beta_{min}$  and  $\theta_m$  using the prism and diffraction grating, respectively, for dispersion. The scale on the spectrometer consists of a full  $360^\circ$  with minimum increments of  $0.5^\circ$ . Precision beyond this level is necessary for accurately determining wavelengths of light from spectral lines.

One degree is subdivided into 60 smaller units called arcminutes, notated as  $1^\circ = 60 \text{ arcmin} = 60'$ . In the same way that a length can be expressed as ( $a$  feet +  $b$  inches), an angle can be described as ( $x$  degrees +  $y$  arcmin). Splitting units in this way avoids the need for decimals and is common in American standard measurement units. Consider the following examples:

- Time:  $2 \text{ hours} + 39 \text{ minutes} = 2 \text{ hours} + (39/60) \text{ hours} = 2.5 \text{ hours} + (9/60) \text{ hours} = 2.65 \text{ hours}$
- Weight:  $5 \text{ lbs} + 9 \text{ oz} = 5 \text{ lbs} + (9/16) \text{ lbs} = 5.5 \text{ lbs} + (1/16) \text{ lbs} = 5.563 \text{ lbs}$
- Length:  $3 \text{ ft} + 2 \text{ in} = 3 \text{ ft} + (2/12) \text{ ft} = 3.167 \text{ ft}$
- Angle:  $12^\circ 33' = 12 \text{ degrees} + 33 \text{ arcmin} = 12.5 \text{ degrees} + (3/60) \text{ arcmin} = 12.55 \text{ degrees}$

**Important:** calculators do not recognize subdivided units. You must convert all measurements to degrees or radians, depending on your calculator, before doing any calculations.

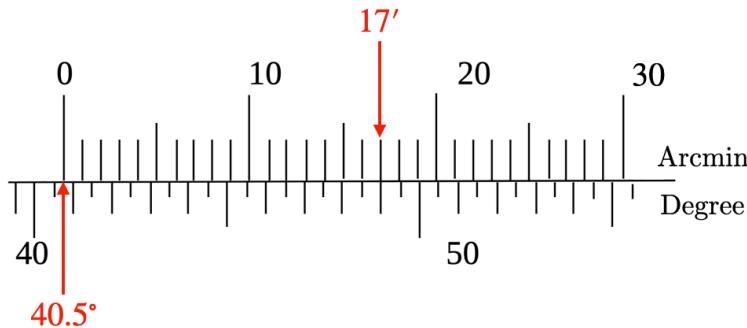


Figure 12: The Vernier scale (top) is split into 30 divisions of size 1 arcmin

The example in Figure 12 shows a reading of an angle on a scale identical to that on the spectrometer. The divisions on the bottom are in degrees. The top portion is called the Vernier scale, with subdivisions of 1 arcmin. The Vernier scale is fixed in place, while the degree scale moves to the left or right. The spacing on the top scale is slightly larger than that on the bottom, so all lines cannot be simultaneously aligned. Instead, only one top and bottom line can be perfectly aligned. Interpret this reading as follows:

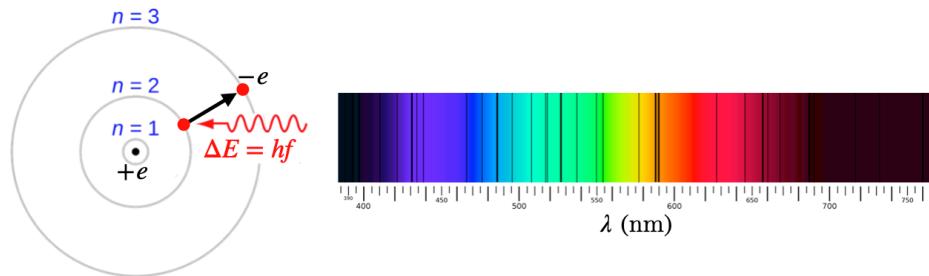
1. The "coarse" measurement is determined by locating the 0 on the top scale with respect to the bottom as indicated by the arrow on the left. The reading is between  $40.5^\circ$  and  $41^\circ$ , so the angle will be  $40.5^\circ + (\text{a small amount})$ .
2. The "fine" measurement is made by looking along the Vernier for the line that aligns perfectly with a line on the bottom. In this example, alignment occurs at 17 arcmin.
3. The total measurement is  $40.5^\circ 17' = 40.5^\circ + (17/60)^\circ = 40.783^\circ$

## 3 Theory Questions

1. (1 pt) In your own words, describe the difference between dispersion by a prism and diffraction grating.
2. (1 pt) What happens when a beam of monochromatic light from a laser refracts through a prism at the minimum deviation angle?

3. Recall your experience with a diffraction grating in the previous lab. Consider a beam consisting of a combination of light with  $\lambda_{red} = 630$  nm and  $\lambda_{blue} = 470$  nm passing through a diffraction grating with grating constant  $G = 600$  lines/mm.
- (1 pt) What is observed on the graph paper?
  - (1 pt) Use the grating equation (6) to calculate the first order ( $m = 1$ ) deviation angles for each wavelength. Recall that the grating spacing is related to the grating constant by  $G = 1/d$ . Pay attention to the length units, and give your answers in degrees. Please show your work.
4. (2 pt) Use the Rydberg formula (7) to calculate the wavelengths of visible light emitted by hydrogen gas. These lines are in the Balmer series. Please show your work, and give your answers in nm. You will attempt to measure these wavelengths in the lab.
5. In this lab, you will use a spectrometer like that described in Section 1.2. You have the ability to measure the minimum deviation angle,  $\beta_{min}$ , of a glass prism for different wavelengths. The index of refraction (IOR) of the prism depends on the wavelength of light.
- (1 pt) Write the equation that relates the IOR to the minimum deviation angle.
  - (1 pt) The Cauchy equation (2) relates the IOR of a material to the wavelength of light. What are the units of the fit parameters  $A$  and  $B$ ?
6. (1 pt) Each element can only emit and absorb specific wavelengths of light. Below, the picture on the left shows a process in which a photon is *absorbed* by the electron in a hydrogen atom, depositing its energy by causing the electron to transition from the  $n = 2$  to  $n = 3$  state. It is impossible for the electron to absorb photons with energies that do not correspond to the energy difference between two states.

You are an astronomer studying starlight using a spectrometer. You observe the line spectrum shown in the picture on the right. What are the possible causes of the dark lines?



7. (1 pt) Determine the angle shown in the picture below as precisely as possible and estimate the uncertainty.



## 4 Experimental Setup

At your bench, you have an analog spectrometer like that described in Section 1.2. While device has many adjustable parts, the design is relatively simple. The key components are labeled in Figure 13.

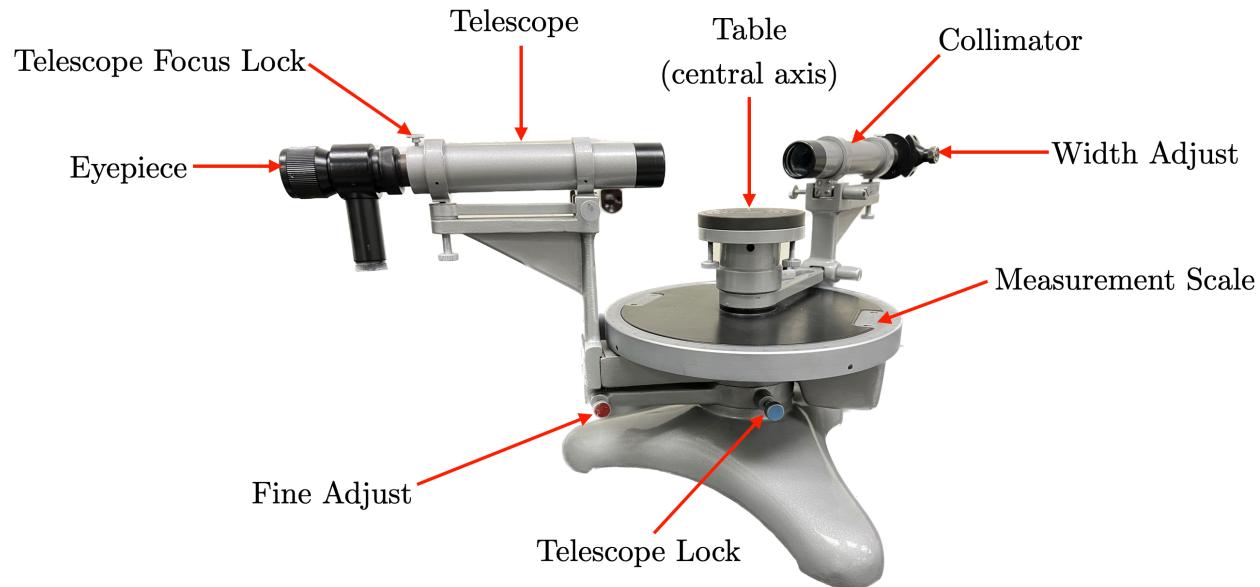


Figure 13: A diagram of the important spectrometer components.

Component	Description
Eyepiece	Contains crosshairs forming a sight. Rotating a ring around the outer surface of the eyepiece focuses the crosshairs for aiming at spectral lines.
Focus Lock	A screw that can be loosened to adjust the eyepiece and tightened to lock it in place.
Telescope	A lens assembly that rotates around the central axis, focusing light from the prism or grating.
Table	Adjustable stand that holds the prism or diffraction grating between the two arms.
Collimator	A fixed lens assembly that points directly at light source. Focusing adjustments are identical to the telescope. Rotating orients the slit (which should remain vertical).
Width Adjust	The adjustment for the opening that collects light. A wider slit collects more light but reduces measurement precision. The slit should be relatively wide during setup, but as narrow as possible during measurements.
Measurement Scale	The Vernier scale for measuring the angle between the two arms.
Telescope Lock	A knob that can be loosened to allow the telescope arm to rotate freely and tightened for making precision measurements.
Fine Adjust	A knob with a limited range allowing for very small angle adjustments.

The spectrometer on its own simply collects and focuses light from the collimator. Take some time to become familiar with apparatus:

- Identify each component. Loosen the telescope lock (blue-painted knob) and rotate the telescope around the central axis to understand what moves and what remains stationary.
- Loosen the telescope focus lock screw and feel how the eyepiece moves to focus the lenses. Notice that the eyepiece can be rotated for vertical alignment. The collimator focuses and adjusts in the same way.
- Identify the white knob opposite from the telescope-lock knob (not pictured). This can be loosened, allowing the outer scale to be rotated. This should be locked in place when using the device.
- Pay attention to what the scale measures: the angle between the two arms. Think about how this angle is related to  $\beta_{min}$  and  $\theta_m$ .

You should have two discharge tubes: hydrogen ( $H_2$ ) and helium (He). Your tubes should be stored on the foam pad when not in use. The tubes fit into the black, spring-loaded lamp as shown in Figure 14. **Always be extremely careful when handling the tubes.**

- **Turn off the lamp whenever you are not making measurements.** They have a finite lifespan, deteriorating quickly with prolonged use.
- **Allow the tube to cool before removal.** The hydrogen tube gets particularly hot. Gently touch the bulb with your finger to test the temperature after allowing some time to cool.
- Always be mindful of your lamp when adjusting your spectrometer.

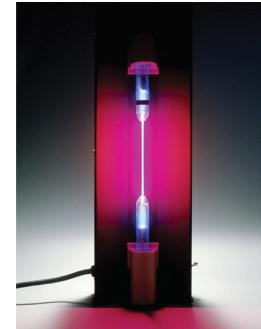


Figure 14

You should also have two dispersing elements: a glass prism and a diffraction grating. **Always handle the dispersing elements by the plastic holders. Do not directly touch the prism or grating.**

## 4.1 Focusing & Alignment

It is important that you take your time aligning the apparatus. In order to make high-precision measurements, you must ensure that your spectrometer is aligned with no dispersing element in place. A rough outline of the procedure is as follows:

1. Loosen the telescope lock knob so your telescope rotates freely.
2. Point the telescope at a distant object (not the collimator). Loosen the telescope focus lock screw and slide the eyepiece in or out to focus. Rotate the eyepiece as needed to vertically align the crosshairs, and tighten the lock screw when completed.
3. With the helium tube installed, turn on the lamp using the switch located near the base. Position the lamp near the opening of the collimator.
4. Point the telescope towards the collimator and look for the light. Make sure the slit is open sufficiently wide, and orient the lamp to maximize the brightness of the light.
5. While looking through the telescope, rotate the eyepiece ring to focus the crosshairs. There is an opening at the bottom of the eyepiece. You can illuminate the crosshairs by shining a light into the opening.
6. Ensure that the slit is positioned vertically and appears clear. You can loosen the collimator focus lock screw and adjust by sliding the end in or out. **Important: do not bump the lamp when adjusting the collimator!** Rotate the slit as needed to vertically align with the crosshairs. Once the edges of the slit appear sharp and aligned, tighten the lock screw.

- Align the spectrometer by iteratively closing the slit and aligning the crosshairs. Try to get the slit as narrow as possible with the crosshairs directly in the center. When this is achieved, loosen the white-painted knob on the left side, opposite from the telescope lock knob. Point a light at the Vernier scale. Use the magnifying glass to align the outer ring with the  $0'$  line on the Vernier scale. Tighten the white-painted knob to lock the position, and **do not move it throughout the measurement process**. The outer ring should *only* move as the telescope is rotated.

## 5 The Prism Spectrometer

You should now be in a position to observe the helium spectrum. For this section of the lab, you will use the prism as your dispersing element. **The prism has an apex angle  $\alpha = 60^\circ$**  and is held by a plastic holder in the shape of a "C." If your slit is still very narrow from the alignment process, open it slightly to allow more light through.

- Place your prism on the table. Think about how the light from the collimator focuses onto the prism (see Figure 8).
- Swing the telescope out of the way, and look at the prism directly with your head in the plane of the telescope.
- Rotate the prism and look for the spectral lines. You should be able to see the lines directly before looking through the telescope.
- Once you have located the spectrum by eye, rotate the telescope into place and look for the individual emission lines.

You are now in a position to perform your experiment. First, you will calibrate your prism by measuring  $\beta$  for each wavelength emitted by helium. You will calculate  $n(\beta)$  for each spectral line. Paired with the known wavelengths in Table 2, the IOR can be plotted and fit to Cauchy's equation. With this curve, you can calculate the wavelengths of light emitted by a different gas.

Color	$\lambda$ (nm)
Red (weak)	678
Red	645
Yellow	577
Green	500
Blue	490
Violet	468
Violet	443

Table 2: The known wavelengths of the visible helium spectrum

- (2 pt) Write an introduction to this part of the lab. Describe the independent and dependent variables and write the relevant equations. You may want to return to this after performing your experiment.
- (1 pt) Sketch a diagram of the spectrometer, labeling the important components and showing the path of a light ray at the minimum deviation angle.
- Find the minimum deviation angle for the bright yellow spectral line. Start by locating the line. Then, rotate the prism so you see the line move to the right, reverse direction, and then move to the left. The minimum deviation angle corresponds to the turning point. Leave your prism in this position for all helium line measurements. We can approximate  $\beta_{min} \approx \beta$  for the remaining wavelengths. Then, the IOR can be calculated using

$$n(\beta) = \frac{\sin\left(\frac{\alpha+\beta}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)}. \quad (11)$$

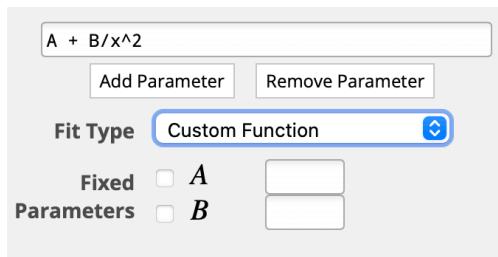
4. Measure the deviation angles for each spectral line of helium. Open the slit wide enough to easily locate a given line. Then, narrow the slit as much as possible while using the fine-adjustment knob to carefully center the crosshairs. Use the Vernier scale to measure the angle. A magnifying glass is helpful for reading the scale.
  - (a) (1 pt) Estimate the measurement uncertainty  $\delta\beta$ . *Note:* this uncertainty is not calculated; it is based on your confidence in a given measurement.
  - (b) (1 pt) Repeat this process for each visible line. Organize your measurements into a table. Include a column indicating the brightness of each line as weak, medium, or strong.
5. (2 pt) Calculate the IOR for each angle using Equation 11.
6. (2 pt) Assume the uncertainty in the apex angle,  $\alpha$ , is negligible. The uncertainty propagation formula can be used to find the uncertainty in the IOR:

$$\delta n = \left| \frac{dn}{d\beta} \cdot \delta\beta \right|. \quad (12)$$

Calculate  $\delta n$  for each color and include the values in your data table.

7. (2 pt) At this point, you can calibrate your prism. You have data points  $(\lambda, n \pm \delta n)$  for each known wavelength. Use your values to determine  $A$  and  $B$  in Cauchy's equation for your prism. Generate a plot, including vertical error bars and axes labels. Choose from one of the following curve fitting methods:

- Linearize your data such that Cauchy's equation can be expressed as  $n = A + Bx$ . *Hint:* define  $x = 1/\lambda^2$ .
- Define a "custom function" in [curve.fit](#) as shown below.



8. (2 pt) The values of  $A$  and  $B$  characterize your prism. Using Cauchy's equation, you can determine the wavelength of light from an arbitrary source. Solve Cauchy's equation for  $\lambda$  in terms of  $A$ ,  $B$ , and  $n$ . State your values of  $A \pm \delta A$  and  $B \pm \delta B$  (with units).
9. Carefully exchange your helium tube for the hydrogen tube. Locate the minimum deviation angle for the bright blue line, and leave your prism in place for the remaining measurements. Following the same procedure, measure the deviation angles for the red, blue, and violet lines. Use Equation 11 to calculate  $n$  for each spectral line. **Turn off the lamp when not in use.**
10. (2 pt) Use your results from calibration to calculate the wavelengths of the bright spectral lines of hydrogen. Explain your process for obtaining the values.
11. (2 pt) Compare your measured wavelengths to the visible wavelengths calculated from using the Rydberg formula,  $\lambda_{calc}$ , in theory Question 4. Calculate the relative error for each of your three measurements (in percent).
12. (2 pt) Include a table with the color, brightness,  $\beta$ ,  $n$ ,  $\lambda_{calc}$ ,  $\lambda_{meas}$ , and the relative error. Comment on your results.
13. (1 pt) Explain how you could use your prism spectrometer to analyze the spectrum of the sun. Would it be possible to identify elements in the sun's atmosphere using your system?

## 6 The Grating Spectrometer

In this part of the experiment, you will use an alternative dispersion mechanism for your spectrometer. Recall that a diffraction grating creates a pattern of sharp, widely-spaced intensity maxima on either side of the central maximum. In the diffraction lab, the light transmitted through the a diffraction grating was projected onto a screen. In this experiment, instead of looking at a screen, you will look *directly* at the grating through the telescope.

You have a high-quality diffraction grating held by a white plastic frame. **Always handle your grating by the frame. Never touch the glass with your fingers.** In this experiment, you are using a *blazed* diffraction grating, which has a sawtooth-like profile as shown in Figure 15. Most of the light incident on a standard grating is transmitted along the central maximum ( $m = 0$ ). This bright spot consists of a combination of all incident wavelengths, making it useless for spectroscopic analysis. The sawtooth pattern on a blazed envelope, producing significantly more intense first-order ( $m = 1$ ) maxima at the expense of the wasted zero-order peak. The effect is illustrated in the two plots in Figure 16, in which the dotted line represents the diffraction envelope. Notice that the peak at  $\theta = 0$  is reduced in the plot on the right, with a large enhancement of the first-order maximum.

Blazing leaves the angular locations of the intensity maxima unchanged. It is important to notice that the principle peaks are the same in both plots. Only the brightness changes, increasing the intensity of dispersed light. For this reason, blazed gratings are ideal for spectroscopy.

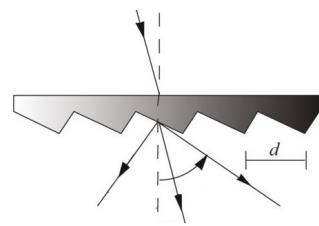


Figure 15: A blazed diffraction grating profile with line separation  $d$ .

grating shifts the diffraction

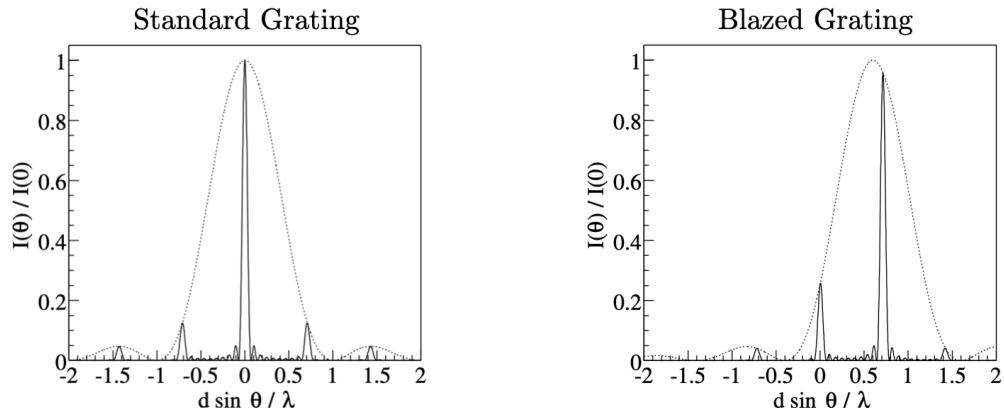


Figure 16: Intensity distribution for a standard diffraction grating compared to a blazed grating, with the dotted line indicating the diffraction envelope (Kenyon, 2008).

1. (2 pt) Write an introduction to this part of the lab. **Explain how a diffraction grating disperses light.** The grating equation (6) gives the condition for constructive interference for a specific wavelength of light. Discuss the meaning of the order number,  $m$ . State the independent and dependent variables in your experiment.
2. (2 pt) Explain why the  $m = 1$  maxima should be used for your measurements. In an ideal setting, could the  $m = 2$  maxima be measured?
3. (2 pt) Explain why the diffraction grating does not require calibration (i.e. characterizing using a known set of wavelengths).
4. (2 pt) Insert the helium tube in the lamp, and carefully align your spectrometer. Then, place your diffraction grating on the spectrometer as shown in Figure 17. The label ( $G = 600$  lines/mm) should be oriented vertically and pointed toward the lamp. Describe your alignment process in a technical format, including as much information as possible in the fewest words.



Figure 17

5. (6 pt) Use what you know about diffraction gratings and the spectrometer to measure the visible wavelengths for both hydrogen and helium. Organize your measurements into a table and include the table in your lab report. Consider left-right averaging to minimize your uncertainty. Explain your procedure.
6. (2 pt) Determine your uncertainties  $\delta\lambda$  for each wavelength. If you left-right averaged, use the uncertainty in the mean (standard error). If you measured each wavelength once, use the uncertainty propagation formula.
7. **Summarize your results:**
  - (a) (3 pt) Organize a table for each gas including the observed colors, known and measured wavelengths, uncertainties, fractional uncertainties, and percent errors. For hydrogen, use the wavelengths calculated with the Rydberg formula as the "known" values.
  - (b) (1 pt) Comment on the precision and accuracy of each method (consider the fractional uncertainties and errors).