

Modern Physics—PHYS 220

Fall 2025

Lab: Spectra and Spectrometers, Vernier Spectrometer, & Balmer Spectrum of Hydrogen

Josh Diamond, John Cummings, & George Hassel

Theory

In this experiment, we display continuous and discrete emission spectra and explore the use of several types of spectrometers. Observations are compared to standard tabulated values and to theoretical predictions.

General features of spectra

Many light sources in nature produce a mixture of wavelengths. Separating and displaying the individual wavelength components produces a spectrum.

Electromagnetic waves that have been observed cover a tremendous range of wavelength: from radio waves with wavelengths of hundreds of meters all the way down to gamma rays with wavelength smaller than the size of an atomic nucleus.

In this experiment, observations are restricted to the relatively tiny visible portion of the electromagnetic spectrum, for which the wavelengths cover the range 400-700 nm.¹

In general, spectra can be classified as

1. a *continuous spectrum*, containing a continuous band of wavelengths;
2. a *discrete or line spectrum*, containing only certain wavelengths (either in absorption or emission); or
3. a combination of a continuous and discrete spectrum.

One kind of source for a continuous spectrum is any hot, glowing object—such as the filament of an ordinary incandescent light bulb. A common light source producing a discrete or line spectrum is the gas-filled electrical discharge tube—e.g. as in a “neon sign”. And the spectrum of a star (e.g., the Sun) is an example of a combined continuous and discrete (absorption-line) spectrum.

¹ Note: Common units for visible light wavelengths are the Angstrom (\AA), $1 = 1 \times 10^{-10}\text{m}$ and the nanometer (nm), $1\text{nm} = 1 \times 10^{-9}\text{m}$.

Observation of spectra

Spectra are displayed by passing light from the source through a suitable optical device. The simplest such device is a prism, which bends light through angles depending on wavelength. Thus, for example, a single beam of “white” light emerges from a prism as a diverging set of beams which produce the familiar rainbow spectrum on a screen or the retina of the eye (see Fig. 1)

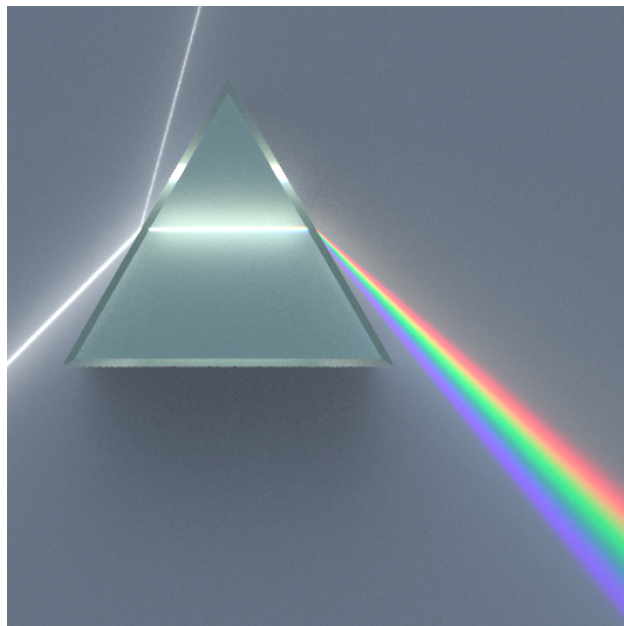


Figure 1: White light split into colors by a prism. The light beam enters the prism from the left. Note the reflected beam scattering off to the top of the image.

The other common device is a diffraction grating—a transparent sheet with closely-spaced parallel rulings. The rulings interrupt the passage of light, so that the effect is analogous to an opaque plate with multiple parallel slits. If monochromatic light (i.e., light having a single wavelength) in a collimated beam falls on a grating, then due to the phenomenon of interference, the light emerging from the grating is concentrated into several beams, symmetrically deflected with respect to the original beam direction, as shown in Fig. 2. The beams are labeled by their “order”, given by an integer m , where $m = 0, 1, 2, \dots$

One can show theoretically that the m^{th} -order beam is deflected by an angle θ , given by the equation:

$$d \sin \theta = m\lambda \quad (1)$$

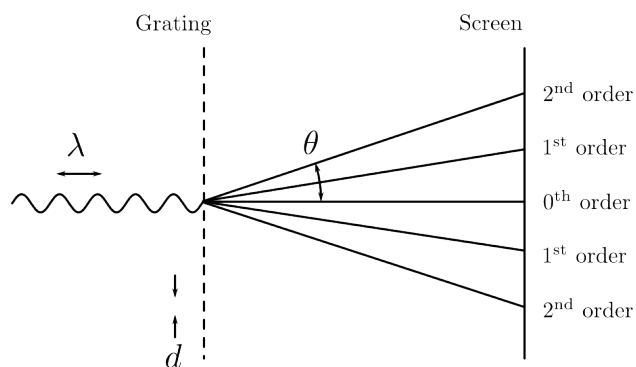


Figure 2: Spectral lines created by a diffraction grating

where λ is the light wavelength and d is the separation between adjacent rulings (assumed constant over the entire grating).

Because the angle θ depends on wavelength, if the incoming light contains several wavelengths, a complete spectrum will be formed at each order (except the zeroth). Restrictions on angle limit one's actual observations to the few lowest orders.

Theoretical predictions for spectra

Balmer spectrum of hydrogen

The visible spectrum of hydrogen gas is a discrete or line spectrum, and is one of the simplest observed in nature. A look at a photograph of the spectrum makes it clear that there exists some regularity in the spectral wavelengths. In 1885, Johann Balmer found an empirical formula for the visible part of the hydrogen spectrum (the "Balmer series", in which the wavelength λ of the spectral lines is given by:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{2^2} - \frac{1}{n^2} \right) \quad (2)$$

where $n = 3, 4, 5, \dots$ corresponds to each spectral line of the Balmer series and $R_H = 1.097 \times 10^7 \text{m}^{-1}$ is the *Rydberg constant*.

Eq. 2 provides an accurate numerical prediction of the Balmer series wavelengths, but not a scientific understanding of why the visible spectrum of hydrogen has that behavior.²

Blackbody radiation spectrum

In 1900, Max Planck calculated theoretically the spectrum of light emitted by an object at a fixed temperature. The spectrum is continuous, and has the simplest form if one assumes that the object is a "black body", i.e. that it is a perfect absorber

² An initial semi-classical understanding first came in 1913 with the Bohr model of the hydrogen atom, and, ultimately, with the quantum-mechanical description of the hydrogen atom provided by Schrödinger's equation.

of electromagnetic radiation. In this case, if the intensity of emitted light is plotted as a function of the light wavelength λ , the graph has a single, broad peak. The wavelength λ_m at the peak is related to the absolute temperature T of the blackbody by a relation known as Wien's displacement law:

$$\lambda_m T = 2.898 \times 10^{-3} \text{ mK} \quad (3)$$

In Planck's theory, the crucial notion of quantization was first introduced. Planck assumed that the light was emitted in discrete packets of energy, called quanta or photons. The energy E of a photon was given in terms of a new fundamental constant h as:

$$E = h\nu = \frac{hc}{\lambda} \quad (4)$$

where ν and λ are the photon frequency and wavelength, and c is the speed of light.³

³ Planck's constant $h = 6.63 \times 10^{-34}$ J·s.

Preliminary Questions

1. A diffraction grating has 400 grooves/mm.
 - (a) Find the physical spacing between the grooves in mm.
 - (b) Calculate the angle at which the first order green mercury spectral line will occur. The mercury green line has wavelength = 546 nm.
 - (c) Calculate the angles at which one would observe all the higher orders of the green mercury line. What is the highest order that can be observed?
2. Consider Eq. 2 for the wavelengths of visible spectral lines emitted by Hydrogen atoms (the Balmer series). Which of the allowed values of the integer n yields the longest wavelength λ ? Explain briefly. Now use the equation to compute the three longest wavelengths in this series. For each wavelength, indicate the color expected of the emitted light.
3. We shall assume in this problem that we can apply the Wien displacement law to ordinary objects (as opposed to just blackbodies).

- Calculate the wavelength at which the maximum amount of light would be emitted by a person at room temperature. In what part of the electromagnetic spectrum is this wavelength?
- Repeat part a for molten steel heated to a temperature of 2000°C .
- The wavelength at which peak radiation from the sun is emitted is approximately 550 nm . Determine the surface temperature of the sun.

Equipment

Incandescent light source, mercury, sodium and hydrogen vapor lamps, grating, student spectrometer, Vernier spectrometer with optical fiber.

Notes on Equipment

Student spectrometer

A schematic top view of the student spectrometer is shown in Fig. 3.

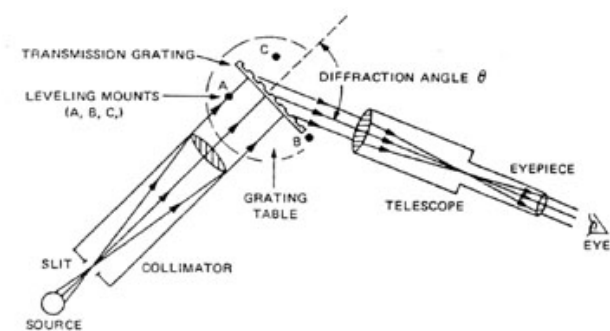


Figure 3: Schematic view of student spectrometer

Light from the source enters the collimator through a narrow vertically-oriented slit, which then acts like a new source of light. At the other end of the collimator tube is a converging lens, placed so that its focus is at the slit location. Under these conditions light will emerge from this lens in a collimated beam (parallel rays). If this beam travels unimpeded into the telescope, an observer looking through the telescope eyepiece will (when the apparatus is properly adjusted) see a sharp im-

age of the illuminated collimator slit, which will appear as a bright vertical line.

Fig. 3 shows the spectrometer outfitted with a diffraction grating mounted on a table at the center of the spectrometer. As discussed above, the effect of the grating is to divide the light into several beams labeled by their order, and within each order (except the zeroth) to further separate the different wavelengths present. When the telescope is in line with the collimator ($\theta = 0^\circ$ in Fig. 3), the zero order (undeflected) beam will be observed as a bright vertical line with the same color as appears looking directly at the light source. When the telescope is moved away from $\theta = 0^\circ$, the higher-order beams will appear in succession. If light from the source consists of several individual wavelengths, then each wavelength produces (in each order) its own image of the slit. These images take the form of distinct colored lines and are known as “spectral lines”. We can take quantitative measurements of a spectral line by moving the telescope so that the line is centered on the telescope cross hair and recording the angular scale reading.

The deflection angle θ entering Eq. 1 is then determined by:

$$\theta = |(\text{angle reading}) - (\text{zeroth order angle reading})| \quad (5)$$

It is usually most convenient to adjust the spectrometer so that the zeroth order is at 0 degrees on the angular scale. Then the angular scale reading of the spectral line gives θ directly.

Vernier spectrometer

The Vernier spectrometer, *SpectroVis Plus*, uses a diffraction grating and CCD detector to measure spectra in the range of 380-950 nm. The unit interfaces with LoggerPro to collect and record data. We will use the optical fiber accessory for the measurements in this activity.

Procedure

Note: Please answer all questions in the *Procedure* section during the laboratory period and include as part of your data.

Adjustment of the student spectrometer

1. Place the spectrometer on a flat level surface.

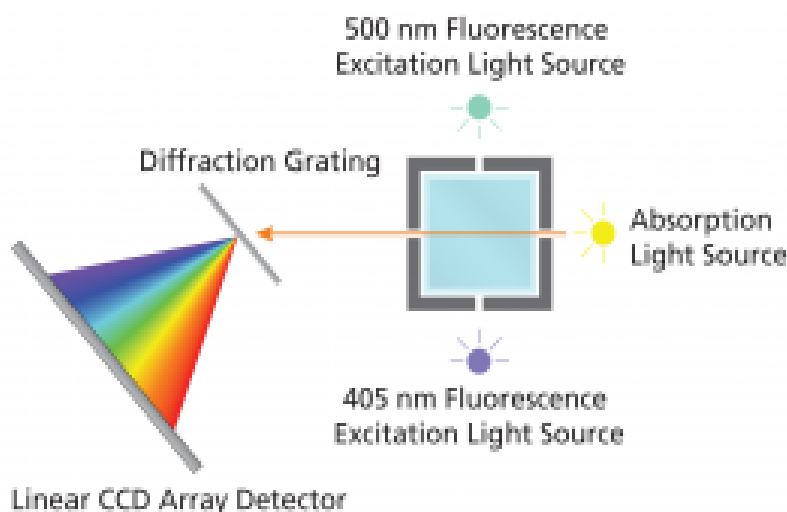


Figure 4: SpectroVis diagram

2. Point the telescope so that it is not in line with the collimator. Move the eyepiece so that the cross hairs are in focus.
3. Look through the telescope at a distant object (out a window or across the room) and move the entire front tube of the telescope until the object is in focus. The sharpness of the image of the cross hairs should not be affected by this step.
4. Align the telescope and collimator. Open the collimator slit to its maximum size. Loosen the screw holding the sleeve at the slit end of the collimator tube. Move this tube until the image of the slit as viewed through the telescope is in focus and aligned vertically.⁴ Now tighten the sleeve screw. The spectrometer should now be satisfactorily adjusted optically.
5. Narrow the slit and align the telescope so that the slit appears accurately centered on the cross-hairs. Check the angular scale reading. If it is not already zero, adjust the scale table so that the reading is zero. Make sure the telescope slit stays aligned with the cross-hairs in this process (the telescope can actually be locked in place temporarily for this purpose).
6. If the slit image appears too high or too low in the telescope field-of-view, the telescope may be tilted up or down by use of the adjustment screws on its mount. Small adjustments

⁴ During this adjustment, the sleeve should be held in position so that its "V point" fits into the V-shaped notch on the collimator mounting.

should be sufficient.

Student grating spectrometer

Note: Record all angular position readings to the nearest tenth of a degree. It is not necessary to use the Vernier scale for measurements in this experiment.

1. Install the grating holder and mount a grating on the spectrometer table as shown in Fig. 3. Observe the incandescent light spectrum. Starting from the zero order position, move the telescope gradually to the maximum meaningful value of deflection angle θ . What is this maximum value of θ . How many orders of the spectrum are visible?

For the first-order spectrum, record the deflection angle θ of the extreme edges of the spectrum (i.e., the extreme red and extreme violet).⁵

2. Observe the spectrum of a sodium lamp. How many orders are visible? Record the deflection angle θ at which the bright yellow line appears, for all orders you can see.
3. Now use the mercury vapor lamp or discharge tube.⁶ Starting with the first order, carefully list all the spectral lines you can see as the angle θ is increased from zero. Record the angular position of each line. Tabulate your results, including the color, order and deflection angle θ of each line. Also give an indication of the brightness of each line (e.g. strong=s, medium=m, weak=w).
4. Note in your data table for the previous step any instances in which a higher-order line of one color appeared before a lower-order line of a different color (i.e., the higher-order line had a smaller deflection angle than the lower-order line). This phenomenon is called “overlapping of orders”.
5. Record the number of rulings per unit length for the grating.

Vernier Spectrometer

1. Set up the spectrograph:
 - (a) Connect the *SpectroVis Plus* directly to the laptop using the USB cable (not through the LabPro or other interface).

⁵ Important note: Check your angular scale reading for the zeroth order. Is it zero? If you have not zeroed the angular scale as described in the procedure above, the zeroth order angle must also be recorded, and then the deflection angle θ for non-zero orders obtained using Eq. 5. This correction will also be needed in steps 2 and 3 below.

⁶ Note: Spectral lines from this source tend to be dimmer, so your eyes should be well dark-adapted. Also, it helps to widen the collimator slit somewhat.

Place the optical fiber in the square opening in the spectrometer.

- (b) Start LoggerPro. Choose Experiment → Calibrate and follow the instructions to calibrate the spectrograph.
 - (c) Choose Experiment → Change Units to change to an Intensity graph.
2. Place the H emission tube in the power supply and turn it on. Bring the optical fiber near but not touching the tube, and record the spectrum by pressing the Collect (green "Play" button)
 3. Click the red "Stop" button when you obtain a suitable spectrum. Use the Examine button to identify the wavelengths of the discrete lines.
 4. Repeat the previous steps for an Hg emission tube. Turn off the power supply before changing tubes and be aware that the tube may be hot.
 5. Repeat the previous steps for a mystery tube. Turn off the power supply before changing tubes and be aware that the tube may be hot.

Analysis

1. Use the data of step 5.3.1 of the procedure to calculate the wavelengths of the limits of the incandescent light spectrum. These will be the limits of your vision.
2. Based on the values of θ measured with the student grating spectrometer, use Eq. 1 to compute the wavelength of the bright yellow line of the sodium lamp spectrum. If you observed more than one order, find the wavelength for each order and compute the average. Compare with the value tabulated below.
3. Use the measured values of the angle θ to calculate the wavelength of the lines in the mercury vapor spectrum observed with the student grating spectrometer. Each line should be identified by its color and order. If a line was observed in more than one order, calculate the average wavelength for that color. Compare these calculated average wavelengths

Sodium	Mercury	Helium	Cadmium	Hydrogen
5889.95 (s)	4046.56 (m)	4387.93 (w)	4678.16 (m)	4101.47 (w)
5895.92 (m)	4077.81 (m)	4437.55 (w)	4799.92 (s)	4340.46 (w)
	4358.35 (s)	4471.48 (s)	5085.82 (s)	4861.33 (m)
	4916.04 (w)	4713.14 (m)	6438.47 (s)	6562.82 (s)
	5460.74 (s)	4921.93 (m)		
	5769.59 (s)	5015.67 (s)		
	5790.65 (s)	5047.74 (w)		
	6152 (m)	5875.62 (s)		
	6910 (m)	6678.15 (s)		

Table 1: Wavelengths of selected spectral lines [\AA]. s: strong, m: medium, w: weak

to the wavelengths measured for the same lines with the Vernier spectrometer. Also compare to the standard wavelength values tabulated above. Try to account for any discrepancies.

- In *Preliminary Question 2*, you calculated predicted wavelengths of the visible spectrum of hydrogen (from Balmer's empirical formula—Eq. 2) and noted the corresponding colors. Compare the predicted hydrogen wavelengths to those you observed using the Vernier spectrometer. For each predicted wavelength, identify the observed spectral line (if any) whose wavelength appears to approximate the predicted value. Indicate the value of the integer n (in the Balmer series formula, Eq. 2) for each spectral line so identified.
- Use Table 1 and your measured spectrum to identify the gas in the mystery tube.

References

- Thornton and Rex, *Modern Physics* 3rd edition, pp. 92-103
- Tipler and Llewellyn, *Modern Physics* 5th edition, pp. 119-121, 147-150.
- Vernier SpectroVis Plus Spectrophotometer Manual (SVIS-PL)