Diffraction Grating Measurement of the Wavelength of Light

OBJECTIVES

- ❑ Investigate the difference between continuous and discrete spectra.
- ❑ Investigate the characteristic spectra of individual gaseous elements.
- ❑ Determine the average line spacing for a diffraction grating assuming mercury wavelengths as known, and use it to determine the wavelengths of helium.

EQUIPMENT LIST

- Optical bench, diffraction grating (600 lines/mm replica grating)
- Spectrum tube power supply, mercury and helium discharge tubes
- Meter stick and slit arrangement, incandescent lightbulb (15 watt)

THEORY

When light is separated into its component **wavelengths,** the resulting array of colors is called a spectrum. If a light source produces all the colors of visible light, it is called a **continuous spectrum.** Generally, such sources of light are produced by heated solid metal filaments. An ordinary incandescent lightbulb with a tungsten filament produces a continuous spectrum.

Some light sources produce discrete wavelengths of light, and the spectrum appears as mostly dark with a few discrete lines of color at the wavelengths emitted by the source. Such light is produced by hot discharges of gas of a single chemical element, and the wavelengths of light emitted are characteristic of the electronic structure of that element. The spectrum is called a **discrete spectrum** or a line spectrum. The term **line spectrum** is used because the images produced usually are images of a narrow slit that is illuminated by the light source.

We can use several methods to separate light into its component wavelengths and produce a spectrum. This laboratory will use a **diffraction grating** to produce spectra from an incandescent lightbulb and from gas discharge tubes of mercury and helium. A transmission diffraction grating is a piece of transparent material ruled with a large number of equally spaced parallel lines. The distance between the lines is called the grating spacing d, and it is usually only a few times as large as a typical wavelength of visible light. The range of visible light wavelengths is from approximately 4×10^{-7} m to 7×10^{-7} m. It is customary to express the wavelength of light in units of nm (10^{-9} m). In those units the range of visible light is from 400 nm to 700 nm. A typical grating spacing d is in the range 1000 nm to 2000 nm.

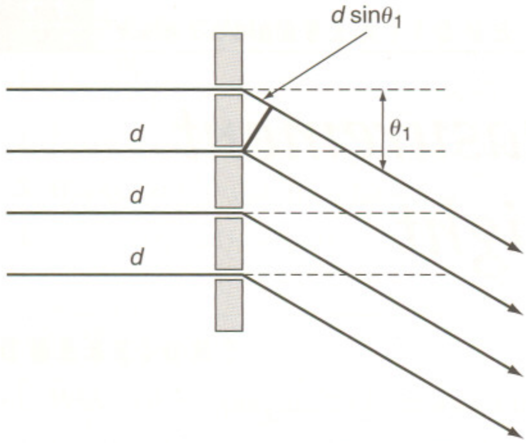

Figure 42-1 Ray diagram for the conditions of the first-order diffraction image.

The wavelengths of light determine the color of the light seen by the human eye. Starting from short wavelengths and going to long wavelengths, the order of colors is violet, blue, green, yellow, orange, and red. The actual range of the visible spectrum is somewhat different for individuals, and there may be a distinct difference in the ability of two laboratory partners to see the wavelengths at either end of the spectrum. It is often very difficult for some people to see the very short wavelengths.

Light rays that strike the transparent portion of the grating between the ruled lines will pass through the grating at all angles with respect to their original path. When deviated rays from adjacent rulings on the grating are in phase, an image of the source will be formed. This condition is satisfied when the adjacent rays differ in path length by an integral number of wavelengths of the light. Thus for a given wavelength λ a series of images will appear at angles θ_m that satisfy the equation

$$m\lambda = d \sin \theta_m \qquad \text{(Eq. 1)}$$

with m an integer. The first value of θ is θ_1 when $m = 1$, the second is θ_2 when $m = 2$. Figure 42-1 shows that the limit to the values of θ will be at $\theta = 90°$. This is referred to as the number of orders that can be seen and is determined by d and λ. Although it will be possible to see both first-order ($m = 1$) and second-order ($m = 2$) for the experimental arrangement used in this laboratory, measurements will be made only on the first-order images.

The experimental arrangement is shown in Figure 42-2. The discharge tube light source is viewed through the grating as shown. The distance L from the grating to the slit is chosen at a convenient fixed

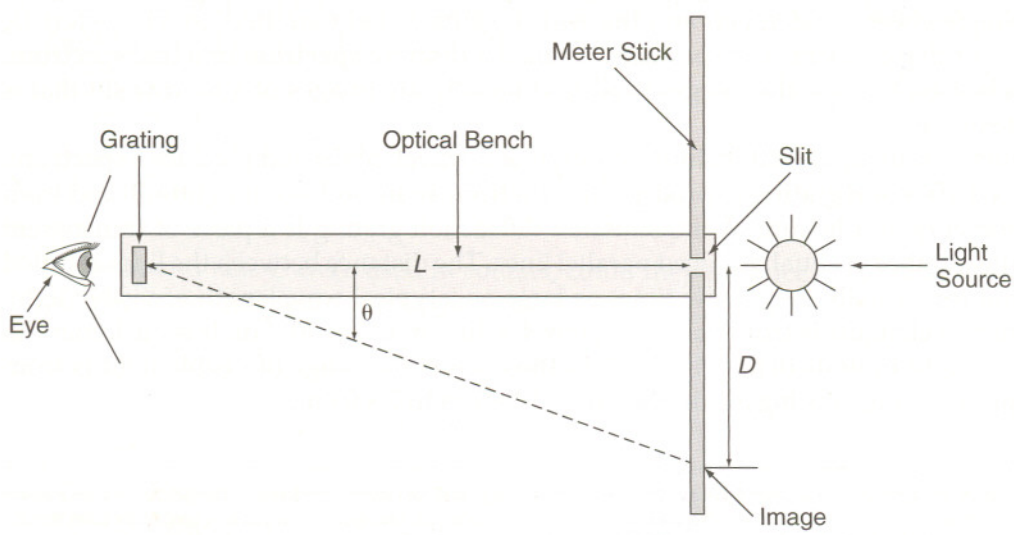

Figure 42-2 Arrangement of the diffraction grating, slit, light source, and optical bench.

value. The different wavelengths of the source will produce a first-order image at different angles and thus at different distances D from the slit as defined by Figure 42-2. We determine the angle θ corresponding to each wavelength by measuring D with L known.

If λ and m are known, we can determine d from Equation 1. First, a mercury light source will be used and its wavelengths given. A series of measurements will accurately determine the value of the grating spacing d. In the second part of the laboratory using this value of d for the grating, we will determine the wavelengths of a helium source.

EXPERIMENTAL PROCEDURE

1. Set up the experimental arrangement shown in Figure 42-2. Place the slit near one end of the optical bench just above the meter stick, which is held by the same holder that holds the slit. The meter stick should be perpendicular to the axis of the optical bench and should be level. The zero of the meter stick should be to the left with the markings increasing to the right. The slit should be at the 50.00 cm mark on the meter stick just above the meter stick so that its images can be located easily relative to a mark on the meter stick. Place the grating some distance L away from the slit with the plane of the grating perpendicular to the axis of the optical bench. Record the value (to the nearest 1 mm) of L in Data Table 1 and take all the data at this same value of L.
2. *Use extreme caution with the discharge tube power supply. It produces 5000 V and sufficient current to make it potentially lethal. Do not touch the supply electrodes while the supply is turned on.* With the power supply turned off and unplugged, place the mercury discharge tube into the electrode receptacles. Place the supply behind the slit with the discharge tube as close to the slit as possible. It may be necessary to place a block under the power supply to adjust the height of the discharge tube. The narrow portion of the discharge tube (which is the most intense) must be at the height of the slit.
3. *Now turn on the power supply. Do not accidentally touch the power supply electrodes while making the following adjustments.* While one partner looks through the grating directly at the slit, the other partner should make very fine adjustments in the position of the power supply to place the bright narrow portion of the discharge tube in alignment with the slit. Proper alignment is achieved when the slit is as bright as possible as seen by the person looking through the grating directly at the slit. It is extremely critical that the light source is positioned so that the slit is as bright as possible. The slightest movement of the light source relative to the slit after this adjustment has been made may severely alter the brightness of the images seen.
4. Look through the grating to the right and left of the slit. Just above the meter stick there should appear a series of images of the slit in various colors. It may be necessary to rotate the grating in its holder to place the images in the horizontal. The images may originally appear at any angle to the horizontal up to the extreme case of 90°, in which case they would be in the vertical. Rotate the grating until the images are horizontal and just above the meter stick.
5. In Data and Calculations Table 1 are listed seven wavelengths of mercury that should be prominent. They are listed in the order of increasing wavelength. They should appear in this order with the smallest wavelength at the smallest angle. Try to match the images that you see with the wavelengths given. It may be difficult to identify all seven of the lines. In particular, many people have difficulty seeing the violet lines clearly. While looking through the grating, locate the position of the first-order images that are to the right of the optical bench above the meter stick. One partner should locate the position of a given line by having the other partner move a small pointer (for example, a pencil point) along the meter stick until the pointer is in line with a given image. It may be helpful to use the small 15-watt light source to illuminate the meter stick to read the position once it has been located. Record (to the nearest 1 mm) the position P_R of each of the seven wavelengths in Data and Calculations Table 1.
6. Repeat the process for the images on the left of the optical bench that correspond to the seven wavelengths. Record (to the nearest 1 mm) the position P_L of each image in Data and Calculations Table 1.

7. Turn off the power supply and allow the discharge tube to cool. With the power supply turned off, remove the mercury discharge tube and replace it with the helium discharge tube. Position the power supply with the discharge tube aligned with the slit. Turn on the power supply and adjust the position of the supply for maximum brightness.
8. In Data and Calculations Table 2 are listed eight wavelengths of helium that should be visible. Again try to match the images that you see with the wavelengths given. Perform the same procedure as done above for mercury, measuring the positions P_R and P_L of each image on the right and the left. Record (to the nearest 1 mm) the data in Data and Calculations Table 2.
9. Place the 15-watt lightbulb behind the slit and observe the continuous spectrum. Locate the positions P_R and P_L of the following parts of the spectrum: (a) the shortest wavelength visible (b) the division between blue and green (c) the division between green and yellow (d) the division between yellow and orange (e) the division between orange and red (f) the longest wavelength visible. Record (to the nearest 1 mm) the position of these points in Data and Calculations Table 3.

CALCULATIONS

1. Calculate the distance D_R from the slit to each image on the right ($D_R = P_R - 50.0$) and calculate the distance D_L from the slit to each image on the left ($D_L = 50.0 - P_L$) for the mercury data in Data Table 1. Calculate the average distance $\overline{D} = (D_R + D_L)/2$ and calculate $\tan\theta = \overline{D}/L$, θ, and $\sin\theta$ for each image. Record (to three significant figures) those values in Data and Calculations Table 1.
2. Each of the measurements for mercury is an independent measurement for d the grating spacing. Use Equation 1 to calculate the seven values of d, and record them (to four significant figures) in Data and Calculations Table 1. Calculate the mean $\overline{d}$ and the standard error α_d for d and record them in Data and Calculations Table 1.
3. Calculate the values of D_R, D_L, and $\overline{D}$ for the helium data and use them to calculate $\tan\theta = \overline{D}/L$, θ, and $\sin\theta$ for each image. Use those values of $\sin\theta$ and $\overline{d}$ in Equation 1 to calculate the wavelengths of helium. Record all values (to three significant figures) in Data and Calculations Table 2.
4. From the data for the continuous spectrum, determine the wavelength that corresponds to the various points in the spectrum that were located. Calculate and record all the information called for in Data and Calculations Table 3.

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LABORATORY 42 *Diffraction Grating Measurement of the Wavelength of Light*

PRE-LABORATORY ASSIGNMENT

1. What is a continuous spectrum? What is a discrete spectrum?

2. What kind of light sources produce each type of spectrum?

3. The wavelengths produced by a hot gas of helium (a) form a discrete spectrum (b) form a line spectrum (c) are characteristic of the electronic structure of helium (d) all of the above are true.

4. A diffraction grating has a grating spacing of $d = 1500$ nm. It is used with light of wavelength 500 nm. At what angle will the first-order diffraction image be seen? Show your work.

5. For a given wavelength λ and a diffraction grating of spacing d (a) an image is formed at only one angle (b) at least two orders are always seen (c) the number of orders seen can be any number and depends on d and λ (d) there can never be more than four orders seen.

6. The grating used in this laboratory (a) can produce only images in the horizontal (b) must be rotated in its holder until it produces the desired horizontal pattern (c) produces images only in the vertical direction (d) produces images only to the left of the slit.

7. A diffraction grating with $d = 2000$ nm is used with a mercury discharge tube. At what angle will the first-order blue-green wavelength of mercury appear? What other orders can be seen, and at what angle will they appear? Show your work.

8. The diffraction grating of Question 7 is used at a distance $L = 50.0$ cm from the slit. What is the distance D from the slit to the first-order image for the blue-green wavelength of mercury? Show your work.

9. What is the voltage and current of the spectrum tube power supply?

Name _______________ Section _______ Date _______

Lab Partners _______________

LABORATORY 42 *Diffraction Grating Measurement of the Wavelength of Light*

LABORATORY REPORT

Data and Calculations Table 1 (Mercury Spectrum)

Colors	λ (nm)	P_R (cm)	P_L (cm)	D_R (cm)	D_L (cm)	$\overline{D}$ (cm)	$\tan\theta$	θ	$\sin\theta$	d (nm)
Violet	404.7									
Violet	407.8									
Blue	435.8									
Blu-Gr	491.6									
Green	546.1									
Yellow	577.0									
Yellow	579.0									
$L =$ cm				$\bar{d} =$ nm				$\alpha_d =$ nm		

Data and Calculations Table 2 (Helium Spectrum)

Colors	λ (nm)	P_R (cm)	P_L (cm)	D_R (cm)	D_L (cm)	$\overline{D}$ (cm)	*tan* θ	θ	*sin* θ	λ (nm)
Blue	438.8									
Blue	447.1									
Blue	471.3									
Blu-Gr	492.2									
Green	501.5									
Yellow	587.6									
Red	667.8									
Red	706.5									

Data and Calculations Table 3 (Continuous Spectrum)

Portion of Spectrum	P_R (cm)	P_L (cm)	$\overline{D}$ (cm)	*tan* θ	θ	*sin* θ	λ (nm)
Shortest Wavelength							
Division Blue and Green							
Division Green and Yellow							
Division Yellow and Orange							
Division Orange and Red							
Longest Wavelength							

SAMPLE CALCULATIONS

1. $D_R = P_R - 50.0 =$ and $D_L = 50.0 - P_L =$
2. $\overline{D} = (D_R + D_L)/2 =$
3. $\tan\theta = \overline{D}/L =$ and $\theta = \tan^{-1}(\theta) =$
4. $\sin\theta =$
5. $d = \lambda/\sin\theta =$
6. $\lambda = \overline{d}\sin\theta =$

QUESTIONS

1. Comment on the precision of your measurement of d.

2. List the accepted values of the eight wavelengths of helium below. Beside each one, show the percentage error in your measured values compared to these values including the sign of the error. Comment on the accuracy of your measurements.

3. If all the errors in Question 2 are of the same sign, it might be evidence of a systematic error. Based on this criterion, do your data show evidence of a systematic error? State your evidence for or against a systematic error.

4. If the grating had exactly 600 lines/mm, d would be 1667 nm. Use that value of d with the values of $\sin\theta$ in Table 2 to recalculate the wavelengths for helium. Are their percentage differences from the accepted values better or worse than in Question 2? Show your work.

5. Hydrogen has known emission lines of wavelength 656.3 nm and 434.1 nm. At what distance D away from the slit would each of these lines be observed in your experimental arrangement? Show your work.