Name ______________________ Section __________ Date __________

Laboratory 42

Diffraction Grating Measurement of the Wavelength of Light

PRELABORATORY ASSIGNMENT

Read carefully the entire description of the laboratory and answer the following questions based on the material contained in the reading assignment. Turn in the completed prelaboratory assignment at the beginning of the laboratory period prior to the performance of the laboratory.

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, or (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, or (d) there can never be more than four orders seen.

6. The grating used in this laboratory (a) can only produce 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, or (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 wavelength of mercury? Show your work.

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

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OBJECTIVES

Sources of visible light often produce many different wavelengths or colors. Light from sources utilizing hot solid metal filaments contain essentially a continuous distribution of wavelengths forming a white light. Light produced by a discharge in a gas of a single chemical element contains only a limited number of discrete wavelength components that are characteristic of the element. There are several methods that can be used to separate a light source into its component wavelengths. The technique that will be used in this laboratory employs a diffraction grating to accomplish the following objectives:

1. Demonstration of the difference between a continuous spectrum and a discrete spectrum
2. Demonstration of the fact that individual elements have spectra that are characteristic of the element
3. Determination of the average spacing between the lines of a diffraction grating by assuming the characteristic wavelengths of mercury are known
4. Determination of the characteristic wavelengths of helium

EQUIPMENT LIST

1. Optical bench
2. Diffraction grating (600 lines/mm replica grating)
3. Spectrum-tube power supply
4. Mercury and helium discharge tubes
5. Meter stick and slit arrangement
6. Incandescent light bulb (15 W)

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." It is given this name because there is no distinct beginning or end to any one color, but rather one color fades continuously into another. Generally, such sources of light are produced by heated solid metal filaments. For example, an ordinary incandescent light bulb with a tungsten filament produces such a continuous spectrum.

Other light sources produce only certain 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 sources are 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. This spectrum is called a "discrete spectrum" or a "line spectrum." The term *line spectrum* is used because the images produced are usually images of a narrow slit that is illuminated by the light source.

There are several methods that can be used to separate a light source into its component wavelengths and thus produce a spectrum. This laboratory will use a diffraction grating to produce spectra from an incandescent light bulb and from gas-discharge tubes of mercury and helium.

A transmission diffraction grating is a piece of transparent material on which has been ruled a large number of equally spaced parallel lines. The distance between the lines is called the "grating spacing," or d, and it is usually only a few times as large as a typical wavelength of visible light. Wavelengths of visible light are in the range from about 4×10^{-7} to 7×10^{-7} m. It is customary to express the wavelength of light in units of nm where 1 nm $= 1 \times 10^{-9}$ m. In those units the range of visible light is from 400 to 700 nm. Grating spacings d are thus in the range 1000 to 2000 nm.

The wavelengths of light are associated with the color of the light as seen by the human eye. Starting from short wavelength and going to long wavelength 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. If the deviated rays from adjacent rulings on the grating are in phase, an image of the source will be formed. This will be true when the adjacent rays differ in path length by an integral number of wavelengths of the light. Thus, for a given wavelength λ there will exist a series of angles at which an image is formed. The first time an image is formed will occur when the path difference between adjacent rays from adjacent ruled lines is exactly equal to one wavelength λ. According to Figure 42.1, that condition will be true at an angle θ_1 such that the equation

$$\lambda = d \sin\theta_1 \tag{1}$$

is satisfied. At some larger angle θ_2, when the path difference between adjacent rays from adjacent ruled lines is exactly equal to 2λ, then the equation

$$2\lambda = d \sin\theta_2 \tag{2}$$

is satisfied. In general, an image will be formed at any angle θn for which the adjacent rays from adjacent rulings have a path difference equal to $n\lambda$, where n is an integer called the "order number." Thus, the general case is described by the equation

$$n\lambda = d \sin\theta_n \tag{3}$$

The number of orders that can be seen are determined by d and λ. Equation 3 is valid only for integer values of n and for angles θ_n up to 90°. For a given λ and d, the maximum n is the one that gives the largest value of $\sin\theta$ less than 1. Although it will be possible to see both first-order ($n = 1$) and second-order ($n = 2$) for the experimental arrangement used in this laboratory, measurements will be made only on the first-order images.

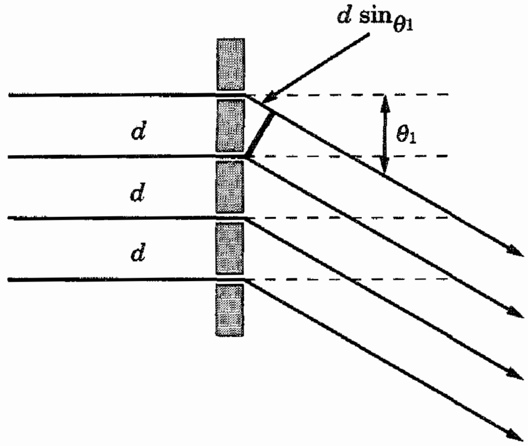

Figure 42.1 Ray diagram for the conditions of the first order diffraction image.

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 value and then kept fixed. If the source has a number of different wavelengths, the first-order image for each wavelength will occur at different angles and thus at different distances D from the slit as defined by Figure 42.2. The angle θ corresponding to each wavelength can be determined by measuring D with L fixed and known.

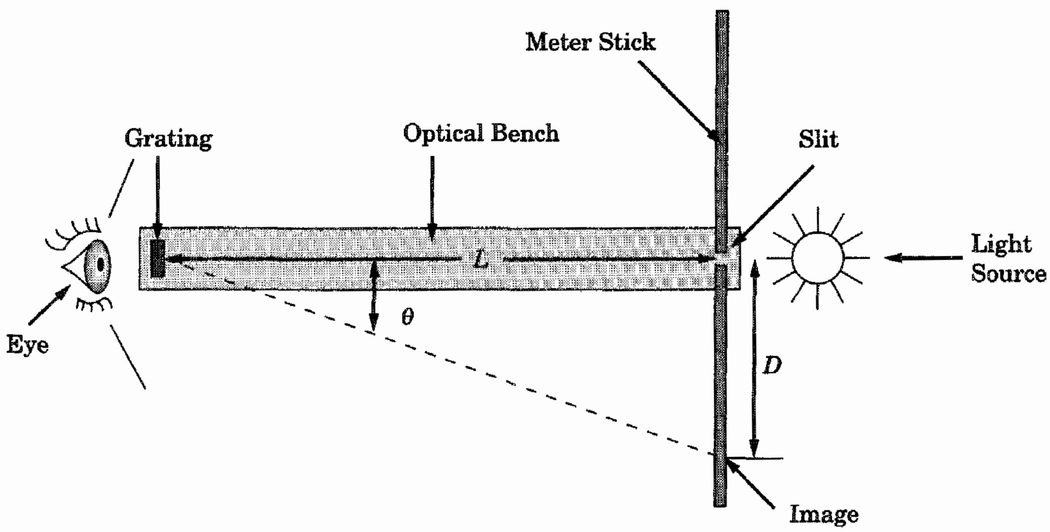

Figure 42.2 Arrangement of the diffraction grating, slit, light source, and optical bench.

If λ and n are assumed known in equation 3, then d can be determined. In the first part of the laboratory, a mercury light source will be used and its wavelengths given. A series of measurements will be made to accurately determine the value of the grating spacing d. In the second part of the laboratory, using this value of d for the grating, the wavelengths of a helium source will be determined.

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. The slit is located just above the meter stick so that its images will be just above the meter stick and can be easily located 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 0.1 mm) of L in Data Table 1 and take all the data at this same value for the grating to slit distance.

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 will probably be necessary to place blocks or books 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. *Turn on the power supply now. 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 critical that the light source be positioned such 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 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. 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 15-W light source to illuminate the meter stick to read the position once it has been located. Record (to the nearest 0.1 mm) the position P_R of each of the seven wavelengths in Data Table 1.

6. Repeat the process for the images on the left of the optical bench corresponding to the seven wavelengths. Record (to the nearest 0.1 mm) the position P_L of each image in Data Table 1.
7. Turn off the power supply and allow the discharge tube to cool. With the power supply still 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 as done previously for the mercury-discharge tube.
8. In Data 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 0.1 mm) the data in Data Table 2.
9. Place the 15-W light bulb 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, and (f) the longest wavelength visible. Record (to the nearest 0.1 mm) the position of these points in Data 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 those values (to four significant figures) in Calculations Table 1.
2. Each of the measurements on mercury is an independent measurement for d, the grating spacing. Using equation 1, calculate the seven values of d from the seven wavelengths and record them (to four significant figures) in Calculations Table 1.
3. Calculate the mean $\overline{d}$ and the standard error α_d for the seven values of d and record them in Calculations Table 1.
4. Calculate the values of D_R, D_L, and $\overline{D}$ for the helium data in Data Table 2 and calculate $\tan\theta = \overline{D}/L$, θ, and $\sin\theta$ for each image. Record those values (to four significant figures) in Calculations Table 2.
5. Using equation 1, calculate the wavelengths of helium from the values of $\sin\theta$ in step 4. Use the value of $\overline{d}$ determined in the mercury measurements for the grating spacing d. Record the results (to four significant figures) in Calculations Table 2.
6. From the data in Data Table 3 for the continuous spectrum, determine the wavelength corresponding to the various points in the spectrum that were located. Calculate and record all the information called for in Calculations Table 3.

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LABORATORY REPORT

Data Table 1

L = __________ cm			
Mercury Colors	λ (nm)	P_R (cm)	P_L (cm)
Violet	404.7		
Violet	407.8		
Blue	435.8		
Blue-green	491.6		
Green	546.1		
Yellow	577.0		
Yellow	579.0		

Calculations Table 1

λ (nm)	D_R (cm)	D_L (cm)	$\overline{D}$ (cm)	$\tan\theta$	θ	$\sin\theta$	d (nm)
404.7							
407.8							
435.8							
491.6							
546.1							
577.0							
579.0							
$\bar{d}$ = __________ nm				α_d = __________ nm			

Data Table 2

Helium Wavelengths	Helium Colors	P_R (cm)	P_L (cm)
	$L =$ ______ cm		
438.8 nm	Blue-violet		
447.1 nm	Deep Blue		
471.3 nm	Blue		
492.2 nm	Blue-green		
501.5 nm	Green		
587.6 nm	Yellow		
667.8 nm	Red		
706.5 nm	Red		

Calculations Table 2

D_R (cm)	D_L (cm)	$\overline{D}$ (cm)	$\tan\theta$	θ	$\sin\theta$	λ (nm)

SAMPLE CALCULATIONS

Data Table 3

Portion of Spectrum	P_R	P_L
Shortest Wavelength		
Division Blue and Green		
Division Green and Yellow		
Division Yellow and Orange		
Division Orange and Red		
Longest Wavelength		

Calculations Table 3

Portions of Spectrum	$\bar{D}$ (cm)	$\tan\theta$	θ	$\sin\theta$	λ (nm)
Shortest Wavelength					
Division Blue and Green					
Division Green and Yellow					
Division Yellow and Orange					
Division Orange and Red					
Longest Wavelength					

SAMPLE CALCULATIONS

QUESTIONS

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

2. The values for the eight wavelengths of helium are 438.8, 447.1, 471.3, 492.2, 501.5, 587.6, 667.8, and 706.5 nm. Calculate the percentage error in your measured values compared to these true values including the sign of the error. Comment on the accuracy of your measurements.

λ = 438.8 nm % Error = ________________

λ = 447.1 nm % Error = ________________

λ = 471.3 nm % Error = ________________

λ = 492.2 nm % Error = ________________

λ = 501.5 nm % Error = ________________

λ = 587.6 nm % Error = ________________

λ = 667.8 nm % Error = ________________

λ = 706.5 nm % Error = ________________

3. If all the errors in question 2 are of the same sign it might be evidence of a systematic error. Do your data show evidence of a systematic error?

4. If the grating were actually 600 lines/mm, the value of d would be 1667 nm. If you used that value of d with the values of $\sin\theta$ in Calculations Table 2 would the resulting wavelengths for helium be better or worse than the wavelength values in that table?

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.

6. In the continuous spectrum what is the range of yellow wavelengths? What is the range of orange wavelengths? What is the middle of the visible spectrum according to your measured values of the range of the visible spectrum?