Lab 5: Spectroscopy

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Abstract

Both of the experiments within this lab involve using the angles of diffraction of different bands from a spectrum to calculate the wavelengths of the light beams diffracted at those angles. While the calculated values of the wavelengths are very near their expected values, relatively small limitations of the equipment became extremely large errors after they were propagated through the equation relating the diffraction angle to the wavelength.

1 Experiment 1: Emission Spectrum

1.1 Objective

The purpose of this experiment was to determine the wavelengths of the colors present in the emission spectrum of mercury vapor. This was accomplished by shining a beam emitted by mercury vapor through a diffraction grating that was then rotated. The angles at which each color revealed itself was recorded, and that angle was used to calculate the wavelength of the colors.

1.2 Theory

All the atoms of a particular element have a certain set of discrete energy levels to which atoms' electrons can be excited. When the electrons fall back down to their normal positions, a photon with energy equal to one of the energy levels is emitted. An element's set of energy levels is referred to as its emission spectrum.

The energy contained within these energy levels is determined with $E = \frac{hc}{\lambda}$. Since hc is a constant, the energy is dependent solely upon the wavelength, λ, which is the value we are finding in this experiment. While the wavelength of a particular color cannot be measured directly, it can be found with

$$\lambda = d \sin(\lambda) \tag{1}$$

where d is the distance between the lines of the diffraction grating and θ is the angle of diffraction for a color.

1.3 Equipment

Figure 1: A list of the equipment used in Experiment 1.

Manufacturer	Model	Serial Number	Specifications
PASCO Scientific	Spectrophotometer Kit	OS-8537	n/a
PASCO Scientific	Aperture Bracket	OS-8534	n/a
PASCO Scientific	Mercury Spectral Tube	SE-9466	n/a
PASCO Scientific	Spectral Tube Power Supply	SE-9460	n/a
PASCO Scientific	Light Sensor	CI-6604	n/a
PASCO Scientific	Basic Optics Bench	OS-8515	n/a
PASCO Scientific	Data Acquisition Software	n/a	n/a

1.4 Procedures

Since we lacked the Rotary Motion Sensor, the procedures had to be modified from how they are printed in the manual to include the manual rotating of the degree plate.

Once the equipment is set up, rotate the degree plate to 40°. From there, slowly rotate the degree plate until a color becomes visible on the viewing screen. Record the color and the angle at which it became revealed, then continue rotating. After the central ray has been passed, the colors will repeat themselves. Record the negative angle at which each color reveals itself. This data can be used to calculate the wavelength of each of the observed colors.

1.5 Data and Analysis

Figure 2: The observed colors, the angles at which they were observed, the average of those two angles, and the calculated wavelengths of the colors.

Color	$\theta_1 \pm 500\text{m}^\circ$	$\theta_2 \pm 500\text{m}^\circ$	$\theta \pm 354\text{m}^\circ$	Wavelength (nm)
yellow	21	-19.5	20.25	577 ± 192
green	20	-17.5	18.75	536 ± 180
cyan	17.5	-16.5	17	487 ± 163
purple_1	16	-14	15	431 ± 144
purple_2	14.5	-13.5	14	403 ± 135
blue	13	-12.5	12.75	368 ± 123

Figure 3: The known values for the emission spectrum of mercury. (`https://en.wikipedia.org/wiki/Mercury-vapor_lamp#Emission_line_spectrum`)

Color	Wavelength (nm)
yellow	578.2
green	546.1
blue	435.8
violet	404.7
ultraviolet (UVA)	365.4

The goal of this experiment was to calculate the wavelength of the observed colors using only the known value of the diffraction slit distance, $d = 1.666\,\mu\text{m}$, and the measured values of the angles at which the colors appeared with Equation 1. The first step was to record the two angles, positive and negative, at which each color appeared. This data is shown in the first section of Figure 2.

Now that two raw angles for each color have been found, their average must be taken to obtain one value for each color's angle. This is done using the classic average formula $\theta = \frac{|\theta_1|+|\theta_2|}{2}$. The calculation for the color yellow is shown:

$$\begin{aligned}
\theta &= \frac{|\theta_1| + |\theta_2|}{2} \\
\theta_{\text{yellow}} &= \frac{|(21)| + |(-19.5)|}{2} \\
\theta_{\text{yellow}} &= 40.5^\circ
\end{aligned}$$

Since all the colors' angle measurements share a common error, the error of the average of the two measurements is uniform across the colors, therefore, it only need be calculated once. Since θ is calculated by dividing the sum of θ_1 and θ_2 by a constant, 2, the error of θ, $\delta\theta$, can be calculated with:

$$\begin{aligned}
\delta\theta &= \frac{1}{2}\sqrt{\delta\theta_1^2 + \delta\theta_2^2} \\
\delta\theta &= \frac{1}{2}\sqrt{(0.5)^2 + (0.5)^2} \\
\delta\theta &= 354\text{m}^\circ
\end{aligned}$$

The average angles at which each color was found is shown in the second section of Figure 2.

The wavelengths of the colors can be calculated with $\lambda(\theta) = d\sin(\theta)$, where $d = 1.666\,\mu\text{m}$ is the distance between the slits of the diffraction grating and θ is the angle at which the color was found. The calculation for the color yellow is shown:

$$\lambda_{\text{yellow}} = d\sin(\theta_{\text{yellow}})$$
$$\lambda_{\text{yellow}} = (1.666 \times 10^{-6})\sin(20.25)$$
$$\lambda_{\text{yellow}} = 577\,\text{nm}$$

In order to determine the propagation of error through a function with one variable, the derivative of that function must be found then multiplied by the accepted value of the function and the error of the value to be propagated. Therefore, the error of the wavelength, $\delta\lambda$, can be found with

$$\delta\lambda = \lambda\frac{d\lambda}{d\theta}\delta\theta$$
$$\delta\lambda = \lambda(\cos(\theta))\delta\theta$$

Again, the calculation for the color yellow will be shown as the example

$$\delta\lambda_{\text{yellow}} = \lambda_{\text{yellow}}\cos(\theta_{\text{yellow}})\delta\theta$$
$$\delta\lambda_{\text{yellow}} = (577 \times 10^{-9})\cos(20.25)(0.354)$$
$$\delta\lambda_{\text{yellow}} = 192\,\text{nm}$$

The results of the other colors are recorded in the third column of Figure

2.

1.6 Conclusion

While the uncertainty in the calculated wavelengths is quite high, the values of the wavelengths are very near their known values, listed in Figure 3! The high degree of uncertainty is due to the lack of precision in our ability to measure the angle at which the colors appeared. Since the degree table only had increments of 1°, the uncertainty for the degree measurements had to be $\pm 500\text{m}^\circ$, which propagated quite heavily through the calculations.

2 Experiment 2: Absorption Spectrum

2.1 Objective

The purpose of this experiment was to determine the sodium-emitted wavelengths absorbed by a red liquid sample. This was accomplished by first measuring the absorption spectrum of sodium through an empty cuvette, then measuring the spectrum again through a cuvette containing the sample. These two spectra can be compared to determine which wavelengths were absorbed by the liquid.

2.2 Theory

The fundamental theory behind Experiment 2 is similar to that of Experiment 1; the angles of particular regions of interest are used to find the wavelength of light in those regions with Equation 1. How those regions of interest are identified, however, is the opposite from Experiment 1. In Experiment 1, the regions of interest were where light was present, but in Experiment 2, those regions are where light is absent. By measuring the angles of these dark regions, the wavelengths of absorbed light can be calculated.

A base spectrum is first determined by measuring the emission spectrum of the sodium sample through a blank cuvette. This base is then compared to the spectrum of the sample shone through a cuvette filled with a sample. The difference between the two spectra, the angles at which the filled cuvette's spectrum is of lower intensity than the blank cuvette's, represents the absorption spectrum of the sample in the filled cuvette.

2.3 Equipment

Figure 4: A list of the equipment used in Experiment 2.

Manufacturer	Model	Serial Number	Specifications
PASCO Scientific	Spectrophotometer Kit	OS-8537	n/a
PASCO Scientific	Aperture Bracket	OS-8534	n/a
PASCO Scientific	Sodium Spectral Tube	SE-9466	n/a
PASCO Scientific	Spectral Tube Power Supply	SE-9460	n/a
PASCO Scientific	Light Sensor	CI-6604	n/a
PASCO Scientific	Basic Optics Bench	OS-8515	n/a
PASCO Scientific	Data Acquisition Software	n/a	n/a
n/a	Cuvette	n/a	x2
n/a	Red Colored Liquid	n/a	5 mL

2.4 Procedures

The procedures for Experiment 2 are very similar to that of Experiment 1. Again, since we lacked the Rotary Motion Sensor, the procedures printed here differ from the lab manual in that we had to manually rotate the degree plate and record the intensity of the beam at each angle.

Once the equipment is set up as it was in Experiment 1, place the blank cuvette into the holder between the diffraction grating and the light intensity sensor. Set up the software for the light intensity sensor. Begin by rotating the degree plate to $-40°$ and recording the intensity of the light in the data acquisition software. From there, rotate the degree plate in increments of one degree and record the intensity in the software for each angle up to $40°$. Save the data, reset the data acquisition software, replace the blank cuvette with the one containing the sample, and repeat the data acquisition process.

2.5 Data and Analysis

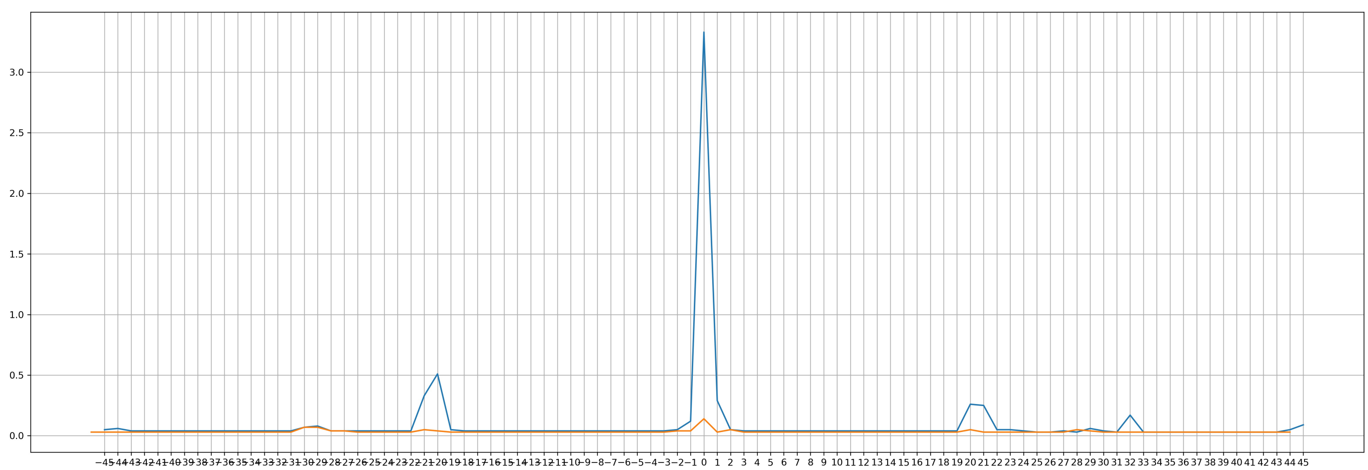

Figure 5: A plot of the Intensity (y-axis) as the Angle of the Degree Plate (x-axis) changes. The blue line is the intensity of the blank cuvette, and the orange line is the intensity of the filled cuvette.

Before calculations can be performed the graph must first be analyzed to identify the angles at which the sample absorbed the incident light. This is accomplished by noting where the blue line peaks and the orange line remains flat. This requirement automatically omits the central ray since the orange line also peaks, albeit at a far lower intensity, when $\theta = 0°$.

Additionally, in order to verify the authenticity of the data, both the negative and positive angle ranges were recorded. Since the peaks ought to mirror each other, any errors will be quickly identifiable because anomalies will not have a twin peak on the opposite side of the central ray. This validation requirement can be applied to the peak at $\theta = 32°$, which does not have a matching twin near $\theta = -32°$.

After all the limitations have been applied, the only two peaks of interest appear at $\theta_1 = -20°$ and $\theta_2 = 20°$. Because the smallest increment of measurement on the degree plate is $1°$, the two angle measurements share an error of $\delta\theta_1 = \delta\theta_2 = \pm 500\text{m}°$.

The wavelength of the light absorbed by the sample at $\theta = \pm 20°$ can be calculated using the same method as Experiment 1, using $\lambda = d \sin(\theta)$, where $d = 1.666\,\mu\text{m}$.

Since $|\theta_1| = |\theta_2|$, there is no need to find the average between the two, $\theta = 20°$. The error, however, does need to be calculated. Since the errors are the same as in Experiment 1, $\delta\theta$ in Experiment 2 equals $\delta\theta$ from Experiment 1. Therefore, $\delta\theta = 354\text{m}°$.

Now that the angle has been finalized to be $\theta = 20°$, the wavelength of the absorbed light can be found,

$$\lambda = d \sin(\theta)$$

$$\lambda = (1.666 \times 10^{-6}) \sin(20)$$

$$\lambda = 570\,\mathrm{nm}$$

The error in the wavelength is also calculated the same as in Experiment 1,

$$\delta\lambda = \lambda \cos(\theta)\delta\theta$$

$$\delta\lambda = (570 \times 10^{-9}) \cos(20)(0.354)$$

$$\delta\lambda = 190\,\mathrm{nm}$$

The wavelength of the absorbed light is $570 \pm 190\,\mathrm{nm}$, yellow.

2.6 Conclusion

As in Experiment 1, while the error in the calculated wavelength is quite high, the found value is near what is expected. Again, this high uncertainty is due to limitations present in the equipment itself, namely, the relatively low precision of the markings on the degree table.