Spectra Lab

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Abstract

In this lab we have observed and compared three separate atomic spectra; that of Helium, Hydrogen and Neon. In the study of the Helium and Hydrogen spectrum, we observed the degrees in which each spectral line differed from the center fringe and used each one of these lines to determine the the lines per millimeter of our diffraction grating. After determining these values, we were then able to make an estimate of the Rydberg constant for Hydrogen via the wavelengths given to us from our lab manuals [1]. As a final study, we diffracted the Helium-Neon laser simultaneously with the Neon tube and found the degree at which the red spectral line produced by the Neon tube coincided with that of the diffracted laser.

Introduction

Spectroscopy all began in 1666 with Sir Isaac Newton. Newton's experiment involved shining light through a prism, which to his surprise, projected a spectrum of different colors. Centuries later, his experiment lives on as we continue to explore the vast wonders of the electromagnetic spectrum. Spectroscopy is seen everywhere, applicable to many different fields of science and technology [2]. A wonderful example of this would be Magnetic Resonance Imaging (MRI). MRI's use radio-frequency spectroscopy to understand and picture what is going on inside certain sections of the human body [2]. This use of spectroscopy is a major part of the medical field and has helped save many lives as well as improve that of others. Whether it is a rainbow projected onto the floor by the light shining through a prism, or a massive machine meant to save lives; the use of spectroscopy is all around us.

The purpose of this lab was to gain a better grasp of how light projected through a diffraction grating can measured and used to determine specific scientific quantities. To better understand this we need to understand what an emission line spectra is and how it works. Emission lines occur when the atoms of a substance become excited, when we visualize this we see a dark band with bright lines. When an atoms excites, an electron will jump from one energy level to another. Because we are talking about the emission spectrum, we are talking about electrons that jump down in orbital shells; this jump is what creates the emission of a photon via the "dumping" of energy by the electron [3]. The wavelength of the emitted photon is determined by the size of the jump, or rather by the difference in energy between the orbital levels. This can be described by the following equation,

$$\lambda = \frac{hc}{E_1 - E_2} \tag{1}$$

where E_1 is the lower orbital and E_2 is the higher orbital. Higher energy light will produce shorter wavelengths, while lower energy light will produce larger wavelengths as seen from Figure 1.
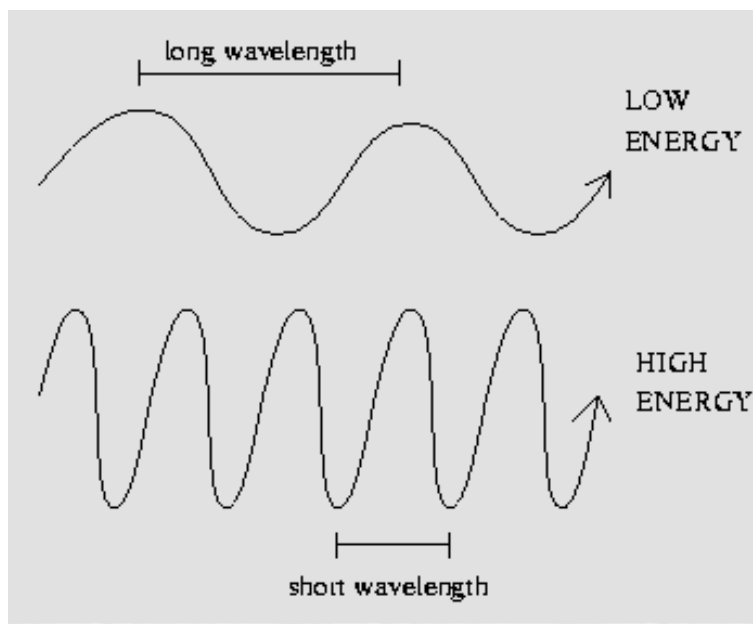

Figure 1: Depiction of the difference in energy versus wavelength [3].

In this experiment we used a diffraction grating which enabled us to see the specific wavelengths given off by a light source. Given the grating spacing d, the diffraction grating will separate the wavelengths into lines where constructive interference occurs.

$$dsin(\theta) = m\lambda \tag{2}$$

m is the order of the spectral line, λ is the wavelength and θ is the average of the θ_1 and θ_2 angle measurements. Armed with this equation we were able to make conclusions, such as wavelength, about each separate spectral line.

Apparatus and Procedure

For this experiment we used three different lamps; Helium, Neon and Hydrogen. Each lamp was placed in a power source. That would then project the lamps light through the spectrometer, past the diffraction grating and into the eye piece where we would then observe the projected spectrum. Once projected, we would then use the vernier scale to measure the angle of each spectral line in relation to the center beam. Before this could take place, our main instrument, the Spectrometer, had to be properly aligned and calibrated.

Alignment

Below (Figure 2) is a very similar instrument to the one we used and will be sufficient for the purpose of explaining how our mechanism was calibrated.
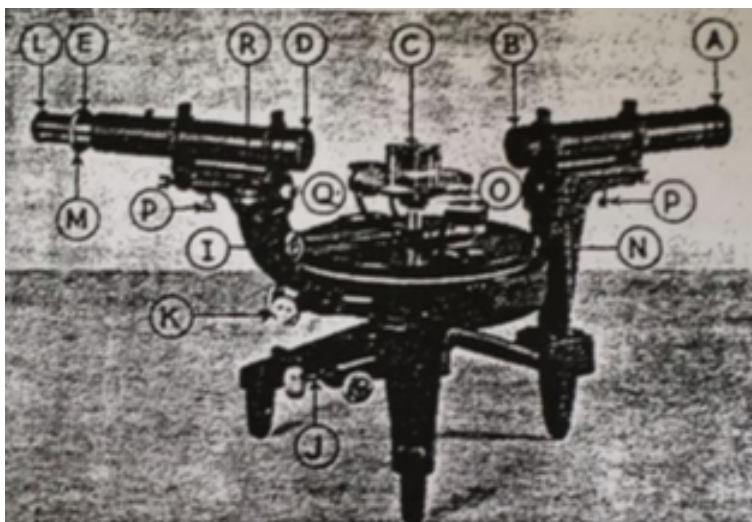

Figure 2: **Spectrometer**. A: Entrance slit; B: Collimator objective; C: Diffraction grating; D: Telescope objective; E: Plane of coss-hairs; I: Grating table clamping screw; J: Grating table clamping and tangent screws; K: Telescope arm clamping and tangent screws; L: Eyepiece ring; M: Telescope focusing ring; O: Grating table leveling screws; P: Collimator and telescope leveling screws

To start, we needed to align points A and L from Figure 2 and make sure that the cross hairs were in focus. To adjust and align the cross hairs we used knobs; P, M and R. At this point we then adjusted the normal to the mounting clamp by setting the vernier scale to 270 and 90 and securely clamping it down in at points I and J. We were then ready to align the grating table with the eyepiece. By placing a mirror, metallic side (as oppose to the initial glass layer) facing us, into the mounting clamp on the grating table, point C. Connecting a 12V battery to point A, we were then able to see the image of two separate cross hairs within our eyepiece. Using points O and N we carefully adjusted the the crosshairs until they were overlapping, making it look as if there was only a single crosshair. Once this last step was taken, our spectrometer was finally considered aligned and properly calibrated. We then replaced the mirror with the diffraction grating and turned off the battery projected light. From there on out we would make no further adjustments to the spectrometer (other than the moving from right to left of telescope), doing so would cause our instrument to be misaligned and skew any data.

Measurement of Helium and Hydrogen Spectrum

The procedure for both lamps will be the same; therefore we will focus on the first lamp used, Helium, and state that the same steps were then used for the Hydrogen lamp. Fist we placed the Helium lamp into its power source, situated in-front of point L in Figure 1. Turning on the variac at 0V, we adjusted the machines voltage until the Helium tube no longer flickered. Looking through the eye piece, we recorded the angle in which or center line was placed. We the measured the angle of each spectral line (all the way to the m = 2 series), starting from the left and then moving back to the right. To measure these angles we used the vernier scale similar to the one found in Figure 3.
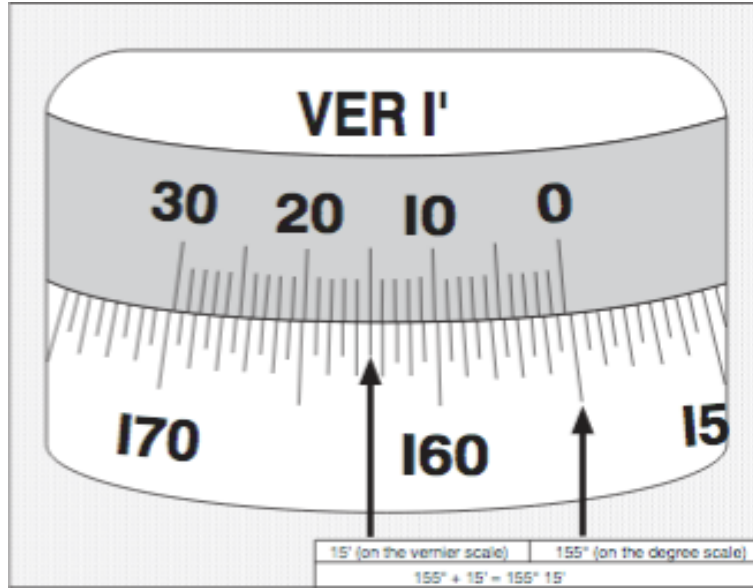
Figure 3: Vernier Scale. To make proper measurements one must also record minutes. There are 30 minutes, seen above the degree scale. To find the number of minutes we look for the first tick mark on the vernier scale that aligns with a mark on the degree scale. The minute measurement may then be divided by 60 to convert it to degrees, to which it is then added to the degree measurement.

Measurement of Helium-Neon Laser Compared with Neon and Helium Lamp

As previously stated for Hydrogen and Helium, the process taking place during this part of the experiment will be the same for both the Helium and Neon lamp. We will describe the process for the Neon lamp and state that it was also applied to the Helium Lamp. For this part of the experiment we covered half of the lamp with a thick piece of paper so that only half of the light from the neon lamp could show through the slit of the collimator. We then pointed the laser beam at the paper covering the lamp. By doing this we were able to project the Neon spectrum to the top of our eyepiece and the diffracted laser to the bottom of the eyepiece. It was at this point that we found and measured the angle in which the diffracted laser beam corresponded closest to a spectral line within the Neon spectrum.

Results

$(d_{actual})^{-1} = 297(mm^{-1})$

d is the diffraction grating spacing, determined by

$$d = \frac{m\lambda}{sin(\theta)} \tag{3}$$

This is an approximation we were able to make due to Δ being so small; which we found by using

$$\Delta = \frac{1}{2}(\alpha_1 - \alpha_2) \tag{4}$$

In this approximation, m is the order of the spectral line, λ is the wavelength and θ is the average of the θ_1 and θ_2 angle measurements. All values of λ we acquired from our lab manual [1]. The error for each measurement of d is given by,

$$\sigma_d = \pm\sqrt{(-\cos\theta \csc\theta)^2 \sigma_\theta} \tag{5}$$

To find the lines per mm for the grating of each measurement, we divide 1 by d. For the average of θ we used,

$$\theta = \frac{1}{2}(\alpha_1 + \alpha_2) \tag{6}$$

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We calculated the error of θ and Δ via Equations 7 and 8

$$\sigma_\theta = \sqrt{[\frac{1}{2}(1+\alpha_2)]^2\sigma_{\alpha_1} + [\frac{1}{2}(\alpha_2+1)]^2\sigma_{\alpha_2}} \tag{7}$$

$$\sigma_\Delta = \sqrt{[\frac{1}{2}(1-\alpha_2)]^2\sigma_{\alpha_1} + [\frac{1}{2}(\alpha_2-1)]^2\sigma_{\alpha_2}} \tag{8}$$

Helium

For m = 1 of the Helium spectrum, we found the mean of d to be 3.366 μm $\pm$ $5.5 \cdot 10^{-3}$ μm. We found that the lines per mm had a mean of 297.11 mm^{-1} $\pm$ 0.486 mm^{-1} with an average percent error of .33% $\pm$ $9.48 * 10^{-4}$.

For m = 2 of the Helium spectrum, we found the mean of d to be 3.39 μm $\pm$ $1.32 \cdot 10^{-2}$ μm. We found that the lines per mm had a mean of 295.31 mm^{-1} $\pm$ 1.153 mm^{-1} with an average percent error of .85% $\pm$ $2.64 \cdot 10^{-3}$.

Helium									
θ_o(°):	270.017								
m:	1.00								
Color	λ (nm)	α_1 (°)	± α_1 error (°)	α_2 (°)	± α_2 (°) error	θ (°)	± θ error (°)	Δ (°)	± Δ error (°)
Purple	388.87	6.517	0.016						
Blue	447.15	7.517	0.016	7.733	0.016	7.625	0.098	-0.108	0.075
Light Blue	471.31	7.934	0.016	8.066	0.016	8.000	0.102	-0.066	0.079
Blue Green	492.19	8.384	0.016	8.483	0.016	8.434	0.107	-0.050	0.084
Green	501.57	8.517	0.016	8.649	0.016	8.583	0.108	-0.066	0.086
Yellow	587.56	9.934	0.016	10.133	0.016	10.034	0.125	-0.100	0.102
Red	667.82	11.351	0.016	11.483	0.016	11.417	0.140	-0.066	0.118
Dark Red	706.52	11.951	0.016	12.463	0.016	12.207	0.149	-0.256	0.127
m:	2.00								
Color	λ (nm)	α_1 (°)	± α_1 error (°)	α_2 (°)	± α_2 (°) error	θ (°)	± θ error (°)	Δ (°)	± Δ error (°)
Purple	388.87								
Blue	447.15	14.767	0.016	15.533	0.016	15.150	0.183	-0.383	0.160
Light Blue	471.31	16.017	0.016	16.783	0.016	16.400	0.197	-0.383	0.174
Blue Green	492.19	16.884	0.016	17.116	0.016	17.000	0.204	-0.116	0.181
Green	501.57	16.701	0.016	17.899	0.016	17.300	0.207	-0.599	0.185
Yellow	587.60	19.767	0.016	20.483	0.016	20.125	0.239	-0.358	0.216
Red	667.82	22.684	0.016	23.533	0.016	23.109	0.273	-0.425	0.250
Dark Red	706.52								

Table 1: Error for θ_1 and θ_2 were approximated by eye when looking at the vernier scale and determining minutes. Error for θ, Δ, and d were calculated via error approximation.

m:	1.00			
Color	d (μm)	± d error (μm)	1/d (mm⁻¹)	1/d %error
Purple				
Blue	3.370	1.04E-02	296.744941	0.09%
Light Blue	3.387	7.13E-03	295.287057	0.58%
Blue Green	3.356	4.11E-02	297.975361	0.33%
Green	3.361	6.51E-02	297.550933	0.19%
Yellow	3.372	1.84E-01	296.520113	0.16%
Red	3.374	4.61E-02	296.411707	0.20%
Dark Red	3.341	7.99E-01	299.276040	0.77%
m:	2.00			
Color	d (μm)	± d error (μm)	1/d (mm⁻¹)	1/d %error
Purple				
Blue	3.42	4.95E-01	292.24	1.60%
Light Blue	3.34	3.51E-01	299.53	0.85%
Blue Green	3.37	5.97E-02	297.01	0.00%
Green	3.37	4.42E-03	296.45	0.19%
Yellow	3.42	8.93E-02	292.78	1.42%
Red	3.40	1.98E-01	293.85	1.06%
Dark Red				

Table 2 : Error for θ_1 and θ_2 were approximated by eye when looking at the vernier scale and determining minutes. Error for θ, Δ and d were calculated via error approximation.

Hydrogen

For m = 1 of the Hydrogen spectrum, we found the mean of d to be 3.35 μm $\pm$ $1.53 \cdot 10^{-2}$ μm. We found that the lines per mm had a mean of 298.30 $mm^{-1} \pm 1.361$ with an average percent error of .59% $\pm 3.65 \cdot 10^{-3}$.

For m = 2 of the Hydrogen spectrum, we found the mean of d to be $3.36 \mu m$ $\pm$ $3.59 \cdot 10^{-2}$ μm. We found that the lines per mm had a mean of 297.25 mm^{-1} $\pm$ 3.203 mm^{-1} with an average percent error of 1.38% $\pm 4.43 \cdot 10^{-3}$.

Hydrogen									
θ_0(°):	270.08								
m:	1.00								
Color	λ (nm)	α_1 (°)	$\pm \alpha_1$ error (°)	α_2 (°)	$\pm \alpha_2$ (°) error	θ (°)	$\pm \theta$ error (°)	Δ (°)	$\pm \Delta$ error (°)
Blue	434.05	7.330	0.030	7.450	0.030	7.390	0.178	-0.060	0.136
Aqua	486.13	7.870	0.030	8.770	0.030	8.320	0.198	-0.450	0.156
Red	656.29	11.080	0.030	11.700	0.030	11.390	0.263	-0.310	0.221
m:	2.00								
Color	λ (nm)	α_1 (°)	$\pm \alpha_1$ error (°)	α_2 (°)	$\pm \alpha_2$ (°) error	θ (°)	$\pm \theta$ error (°)	Δ (°)	$\pm \Delta$ error (°)
Blue	434.05	15.640	0.030	14.920	0.030	15.280	0.345	0.360	0.303
Aqua	486.13	16.250	0.030	16.880	0.030	16.565	0.373	-0.315	0.330
Red	656.27	22.614	0.030	22.936	0.030	22.775	0.504	-0.161	0.462

Table 3: Error for θ_1 and θ_2 were approximated by eye when looking at the vernier scale and determining minutes. Error for θ, Δ and d were calculated via error approximation.

m:	1.00			
Color	d (μm)	$\pm$ d error (μm)	1/d (mm^{-1})	1/d %error
Blue	3.37	4.32E-02	296.33	0.22%
Aqua	3.36	5.42E-02	297.66	0.22%
Red	3.32	7.78E-02	300.92	1.32%
m:	2.00			
Color	d (μm)	$\pm$ d error (μm)	1/d (mm^{-1})	1/d %error
Blue	3.29	1.58E+00	303.58	2.22%
Aqua	3.41	4.15E-01	293.24	1.27%
Red	3.39	9.41E-01	294.93	0.70%

Table 4: Error for θ_1 and θ_2 were approximated by eye when looking at the vernier scale and determining minutes. Error for θ, Δ and d were calculated via error approximation.

Rydberg Calculations for Hydrogen

Using equations 9 through 11 we were able to determine the mean of the Rynberg constant to be $10,970,979.35\ m$ $\pm$ $40.8\ m$ with a percent error of 0.03%

Rydberg Constant							
R (m):	10,967,758.00						
Color	λ (nm)	n_1	n_2	R (m^{-1})	R Mean (m)	R σ_Mean (m^{-1})	%error
Blue	434.05	5	2	10,970,942.69	10,970,979.35	4.08E+01	0.03%
Aqua	486.13	4	2	10,970,934.57			
Red	656.27	3	2	10,971,060.78			

Table 5: Rydberg Data

To determine the mean of the Rydberg constants we applied

$$R_{H_i}^- = \frac{\sum_{i=3}^{5} R_{H_i}}{3} \qquad (9)$$

With R_{H_i} being calculated for each wavelength as well as set of n's by

$$R_{H_i} = \frac{1}{\lambda(\frac{1}{n_2^2} - \frac{1}{n_i^2})} \qquad (10)$$

Lastly, the uncertainty of the Rydberg constant was found using the standard deviation of the mean

$$\sigma_{R_{H_i}^-} = \frac{\sqrt{\sum_{i=3}^{5}(R_{H_i} - \bar{R_H})^2}}{\sqrt{3}} \qquad (11)$$

The way in which we determined the uncertainty of the Rydberg constant was the similar in the way of which we determined the uncertainty over **all values** of d, $\frac{1}{d}$ and the % error for $\frac{1}{d}$; we calculated the mean and then the standard deviation of the mean. For each separate data point where the % error was calculated, the equation used was

$$\%error = (\frac{|Experimental - Actual|}{Actual}) * 100\% \qquad (12)$$

Helium-Neon Laser

We found that the helium-neon laser had matching spectral lines with the Neon lamp, but not the Helium lamp. We found this by eye as well as by measuring the wavelength of the corresponding lines. The equation we used to measure,

$$\lambda = \frac{sin(\theta)d}{m} \qquad (13)$$

We found through this calculation that $\lambda = 633.799$ nm which relates more closely to wavelengths on the Neon spectrum rather than those on the Helium spectrum. From both the theory as well as the data taken we can determine that the reason we only find matching spectral lines between the Neon lamp and the laser is due to the fact that they both share a similar wavelength, unlike helium.

Discussion and Analysis

For the first order Helium spectrum we were able to view almost all expected wavelength, with the exclusion of purple. It is predicted that this may have been due to the way our spectrometer had been aligned. Alignment was likely to be the largest source of error in all of the data taken. Mainly, if the spectrometer was not tightly clamped at points I and J from Figure 2, then each reading would be completely off and un-relatable to the next. Another related source of error may have been from the lamp itself. It is wondered if age affects the lamps ability to project its full spectrum; something that could be a whole other experiment all on its own. Because of the size of the minutes on the vernier scale, it was very hard to determine where exactly each tick mark aligned. This was probably another major source of error that would have had an affect on all other calculations related to each specific fringe that had been incorrectly measured.

All in all, our calculation came fairly close to the expected values with average % errors no more than 1.39%; and even then, that was a much larger error than the majority of our data. Because this % error is smaller than the scientifically acceptable % error of 5%, we can conclude that our data, as well as our calculations, coincide with accepted values.

Conclusion

Through this experiment we have been able to proudly further our understanding of spectroscopy. We have properly shown, with acceptable error, how the measurement of emission lines can give you a vast amount of detail related to a specific element. We were also able to show, through the experiment with the helium-neon laser, how different light sources can be related via their wavelength.

It can be said that even though our data was found fairly agreeable, there is still plenty of room for improvement. Further experiments could be done to understand how the lifetime of a specific lamp affects it's spectrum. Even further still, improvement could be made upon equipment. The possibility of relying less on eyesight when taking measurements with the

vernier scale could enhance data taking, and electronic read out would have been extremely helpful and far more accurate. With that said, we see this experiment as a success; something to proudly add to the years of study done in the field of spectroscopy.

References

[1] Brown, G. (2018). *Physics 133 Lab Manual*. Santa Cruz: University of California, Santa Cruz, pp.1-12.

[2] Stoner, J. and Hurst, G. (2018). *Spectroscopy*. [online] britannica.com. Available at: https://www.britannica.com/science/spectroscopy [Accessed 25 Jul. 2018].

[3] Kulesa, C. (2000). *What is Spectroscopy?*. [online] Loke.as.arizona.edu. Available at: http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy_intro.html [Accessed 25 Jul. 2018].