Exploring Emission Spectra: Identifying an Element Based on Observed Emission Lines

Ethan Fahnestock*
(Dated: January 31, 2017)

The objective of this lab was separated into two parts. First, the emission lines of a known element, mercury, were observed. The results were compared with the known spectral lines recorded in the National Institute of Standards and Technology (NIST) Database to measure accuracy. Second, the emission spectrum for an unknown element was observed in a similar manner and compared to spectral lines of common elements in an attempt to identify the element. The lines matched the Balmer series for hydrogen with high levels of accuracy. The spectral lines for mercury in the NIST database matched the observed colors recorded during the experiment; however the calculated wavelengths did not correlate very well.

I. INTRODUCTION

A. Purpose

The purpose of this lab was to identify and compare emission spectra with known values. This was done twice: once for a known element and once for an unknown element. The emission spectra of elements has been used to better understand the structure of atoms as well as identify them, as each element has a unique emission spectrum. Using this spectrum to identify an element can be applied to identify the composition of other planet's atmospheres or other elements that emit light. A database created by the National Institute of Standards and Technology hosts a collection of elements and their spectral lines.

B. Theory and Background

Many of the atomic models for hydrogen are based on the observed emission spectrum for the element. An emission spectrum is the set of wavelengths of photons an excited atom produces. The current model explains these emissions as a consequence of electrons transitioning to a lower, more stable, energy level. The change in energy is released as a photon. The energy of a photon is calculated using the equation below:

$$E = hf \qquad \text{(Plank-Einstein Relation)}$$

To separate the wavelengths released by an excited element, a diffraction grating was used to separate the polychromatic light. Diffraction gratings act in a similar way as a double slit. Representing an incoming light source as a plane wave, Figure 1 shows the interference pattern formed at a radius R from the center of the slits. Where two circles overlap the represented waves constructively interfere, creating a bright spot on the screen. Since this occurs where the path length difference is equal to an integer multiple of the wavelength, the following equation represents the predicted locations of the bright spots:

$$m\lambda = h\sin\theta \qquad \text{(Diffraction Equation)}$$

Where m is the number of spots from the center, λ is the wavelength, h is the number of meters per slit, and θ is the angle from center.

As apparent in this relation, the angle is directly related to the wavelength. This makes sense because changing the wavelength will change the locations at which the difference in path length is equal to an integer multiple of that length. Exploiting this relation allows the calculation of the wavelength of light if the angles at which these bright spots appear are measured by re-arranging the Diffraction Equation.

$$\lambda = \frac{h\sin\theta}{m} \qquad \text{(Re-arranged Diffraction Equation)}$$

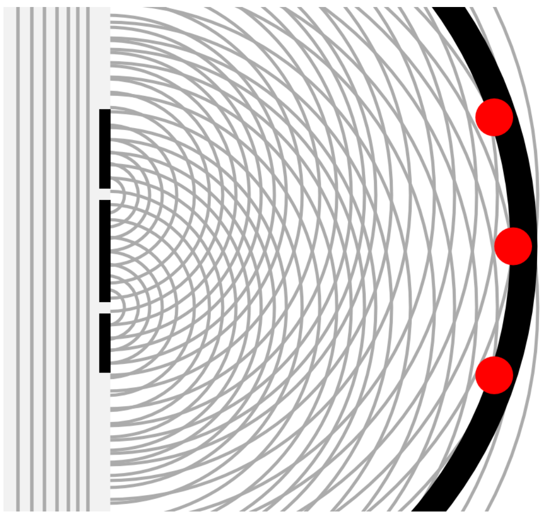

Figure 1: Diffraction Diagram

*Electronic address: aknh9189@gmail.com

II. MATERIALS AND METHODS

A. Tools

For both parts of this lab a gas discharge lamp was used. As visible in Figure 2, a collimator was aligned with the light source - helping to remove excess light - which was then passed through a diffraction grating with 1000 lines per mm. All room lights were shut off while measurements were being performed.

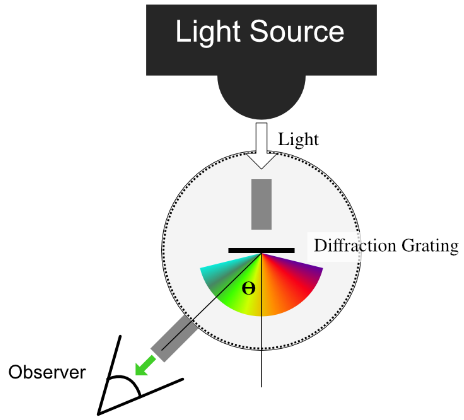

Figure 2: Setup of the Lab

B. Procedure

For each light source the following procedure was followed.

1. First, θ as seen in Figure 2, was set to zero. The angle measurement on the turntable was recorded.

2. The turntable was slowly rotated until a spectral line was observed through the sight. Once found, its location would be verified by others in the group. Once confirmed, the angle value, uncertainty, color, and intensity were recorded. The uncertainty in the angle was determined based on the location of the indication arrow with relation to the measurement lines.

3. Next, the turntable was further shifted in the original direction. Step 2 was repeated whenever a line was observed and confirmed.

4. Once all of the observed lines were recorded the turntable was reset to $\theta = 0$ and steps 2 and 3 were repeated while the turntable was rotated in the opposite direction.

III. RESULTS AND ANALYSIS

A. Data

For both of the used diffraction gratings the rating was 1000 lines per mm. This translates into h=10e-6 meters per line.

1. *Mercury*

The center angle, in radians, was recorded to be 3.077±0.006.

Angle (rad)	Color	$\delta\theta$	Intensity
2.513	Orange	0.008	Very Dim
2.548	Dark Green	0.004	Medium Brightness
2.591	Green	0.006	Dim
2.635	Blue	0.008	Bright
2.670	Purple	0.004	Bright
3.481	Purple	0.004	Bright
3.516	Blue	0.006	Bright
3.560	Green	0.006	Dim
3.586	Brown/Red	0.004	Medium Brightness
3.621	Orange	0.008	Dim

Table I: Recorded Data for Mercury Emission Lines

θ_{avg} (rad)	λ (nm)	$\delta\lambda$ (nm)	Actual λ (nm)	% Error	Energy (eV)
0.554	526.214	8.418	579.065	9.127	2.358
0.519	496.217	6.139	576.959	13.994	2.501
0.484	465.615	7.509	546.074	14.734	2.665
0.441	426.448	8.241	435.835	2.154	2.910
0.406	394.744	6.497	404.656	2.450	3.143

Table II: Calculated Data for Mercury Emission Lines

2. *Unknown Element*

The middle angle was recorded to be 1.659±0.009

Angle (rad)	Color	$\delta\theta$	Intensity
2.381	Red	0.009	Bright
2.165	Cyan	0.005	Dim
2.108	Purple	0.005	Dim
1.213	Purple	0.005	Dim
1.155	Cyan	0.009	Dim
0.947	Red	0.005	Bright

Table III: Recorded Data for the Unknown Element's Emission Lines

θ_{avg} (rad)	λ (nm)	$\delta\lambda$ (nm)	Actual λ (nm)	% Error (%)
0.715	655.907	8.342	656.272	0.055
0.505	484.234	9.669	486.133	0.390
0.448	432.873	8.924	434.047	0.270

Table IV: Calculated Data for the Unknown Element's Emission Lines

B. Calculations

To start, the following equation was applied to every angle. θ_c represents the measured center angle and θ_n represents the new angle. The absolute value brings the angles to the "same side" of the turn table. This does not effect the calculated result because $\sin\theta = \sin -\theta$.

$$\theta_n = |\theta - \theta_c| \tag{1}$$

This equation does change the uncertainty to $\delta\theta + \delta\theta_c$.

Applying equation 1 to the red angle measurements for the unknown element results in angles of 0.722 and 0.712 and uncertainties of 0.018 and 0.014 respectively.

Now these values are put into a weighted average based on their uncertainties.

$$\theta_{avg} = \frac{\sum \frac{\theta_i}{(\delta\theta_i)^2}}{\sum \frac{1}{(\delta\theta_i)^2}} = \frac{\frac{0.722}{(0.018)^2} + \frac{0.712}{(0.014)^2}}{\frac{1}{(0.018)^2} + \frac{1}{(0.014)^2}} = 0.715 \tag{2}$$

At this point the uncertainty in the angle is recalculated.

$$\delta\theta_{avg} = \frac{1}{[\sum \frac{1}{(\delta\theta_i)^2}]^{1/2}} = \frac{1}{[\frac{1}{(0.018)^2} + \frac{1}{(0.014)^2}]^{1/2}} = 0.011 \tag{3}$$

To find the wavelength of the emission line the rearranged diffraction equation is used. For all of the observed emission lines in this lab $m = 1$ because second order lines were not observed.

Using the weighted angle, the calculated wavelength was found as follows.

$$\lambda = h \sin\theta_{avg} = 0.000001 \sin 0.715 = 655.9nm \tag{4}$$

To find the uncertainty in this wavelength $\frac{d}{d\theta_{avg}}\lambda(\theta_{avg})$ is taken and multiplied by $\delta\theta_{avg}$ as follows.

$$\delta\lambda = \delta\theta_{avg} h \cos\theta_{avg} = 0.011{*}0.000001{*}\cos(0.715) = 8.34nm \tag{5}$$

C. Summary

After analyzing emission lines for various elements, hydrogen's emission spectrum matched the observed with the most accuracy. Elements with low atomic numbers were checked first because of the relative simplicity of the observed spectrum. As the number of electrons increases, the number of possible transitions between energy levels increases, resulting in a complicated emission spectrum.

The observed wavelengths matched Hydrogen's Balmer series with high levels of accuracy. The Balmer series is made up of photons released when electrons transition from a higher energy level to the n=2 level. These transitions release photons with a fixed frequency (ie fixed energy), three of which are in the visible spectrum ($400 < \lambda < 700$) corresponding to the three observed spectral lines. The color of the lamp was also observed to match pictures of a hydrogen discharge lamp.

Other atoms such as He^+ and Li^{2+} have the same number of electrons as hydrogen and thus have similar electron configurations. However the number of protons in the nucleus is larger than hydrogen for both atoms. These additional protons decrease the binding energy for the single electron to more negative values than -13.6eV; the binding energy of a hydrogen atom. This can be understood conceptually using the coulomb potential, $\frac{kq_1q_2}{r}$. This additional binding energy changes the emission spectrum.

The emission spectrum is not continuous because of the quantization of the electron's state in the atom. Each electron in an atom can be represented by four quantum numbers: n, l, m_l, and m_s. To release a significant amount of energy an electron must change its orbital quantum number, n. Since electrons only give off photons with discrete energies as they translate between discrete energy levels, atoms have a discontinuous emission spectrum.

The measured line spectra for mercury did not correlate well with the actual emission values, differing by more than 100 nm in some cases. With more electrons mercury has a more complex visible emission spectrum. The "known" wavelengths were collected based on their color compared to the observed color as some of the emission lines were missed during data collection. For the dark green and green emission spectra the observed color did not match the calculated wavelength's color, lying in the blue range instead of green. Since the photons were observed to be green, the error must have occurred through measurement because the method used to calculate the wavelengths of the unidentified element were accurate. This uncertainty did not have a large effect on the lab because the element was already known.

Besides making more accurate measurements of every known element, the identification of unknown elements could be made more accurate using specific wavelength filters to more accurately determine the wavelength. Using the same turn table, decreasing the distance between slits in the diffraction grating would result in finer resolution spectral lines, allowing the angle measurement to increase in accuracy. This, in combination with a digital image sensor would allow the detection of spectral lines outside of the visible range, further increasing the accuracy of the identification of an element.

IV. CONCLUSION

Using more complicated models of the atom the idea of discontinuous spectral lines can be understood as the product of electrons changing energy levels. Unique to each atom, these spectral lines can be used to identify unknown elements as was done in the case of hydrogen in this lab with very high accuracy. The recorded spectral wavelengths for mercury however did not match up well with the known values, reaching 14% error for some measurements. Overall the ability to identify elements based on their emissions is uniquely valuable in fields such as astronomy, where it can be used to accurately determine the atmosphere composition of stars resting thousands of light years away.

[1] *Strong lines of mercury*, http://physics.nist.gov/PhysRefData/Handbook/Tables/mercurytable2_a.htm, accessed: January 31, 2017.

[2] *Atomic spectra*, http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect2.html, accessed: January 31, 2017.