

# Spectrometry Project

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## Abstract

This experiment investigated the emission spectra of gases using spectrometry. We used mercury to calibrate our spectrometer and then used it to analyze the spectral lines of hydrogen, helium, and an unknown gas. In the case of hydrogen, we found high agreement with the theoretical Balmer series, detecting a peak at  $1.87 \pm 0.05\text{eV}$ , within uncertainty of the expected  $1.89\text{eV}$ , and another peak at  $2.54 \pm 0.04\text{eV}$ , within uncertainties of the expected  $2.55\text{eV}$ , after calibrating the spectrometer. In the case of helium also, we found our calibrated wavelengths matched with reference observations within uncertainties. We then used spectrometry to determine the elemental composition of an unknown pure gas, determining it to be krypton due to the high agreement between the three peaks observed in the spectrum and reference peaks provided. We then used the spectrometer to analyze dyed water solutions and verified that which wavelengths were present at high transmittance matched with the observed color. We then attempted to explore fluorescence in a sample with known fluorescent properties, but ultimately failed to find any signs of fluorescence.

## Introduction

In the fields of astronomy, chemistry, and materials sciences, it is often necessary to find the elemental composition of an object, whether it be a star or planet, or a composite molecule of unknown makeup. In these cases, one powerful tool often used is optical spectrometry, using the spectrum emitted by the target to determine elemental composition, a technique called spectrometry.

When an atom absorbs energy, it transitions to a higher energy quantum state as an electron in its outer orbital rises to a higher level. Soon afterward, the atom can transition back down to a lower energy state as an electron in an outer shell fills the vacancy. Accompanying this transition is the emission of a photon with energy equal to the energy lost by the atom in the process. For a hydrogen-like ion, that is, an atom with  $Z$  protons in its nucleus and only one electron, such as  $\text{He}^+$ , the energy is given by<sup>1</sup>

$$E_n = -\frac{Z^2 k_e e^2}{2n^2 a_0} \approx -\frac{13.6 Z^2}{n^2} \text{eV} \quad (1)$$

In equation 1,  $k_e = 8.99 \times 10^9 \text{N m}^2 \text{C}^{-2}$  is Coulomb's constant,  $e = 1.602 \times 10^{-19} \text{C}$  is the charge of the electron,  $n$  is principal quantum number of the particular state and  $a_0 = 0.0529 \text{nm}$  is the Bohr radius. The unit eV refers to the electron volt, the energy possessed by an electron accelerated through a 1V voltage difference, and obeys the conversion  $1\text{eV} = 1.602 \times 10^{-19} \text{J}$ .

In general, the energy of a photon with a particular wavelength and frequency is given by the equation:

$$E = hf = \frac{hc}{\lambda} \quad (2)$$

In equation 2,  $h = 6.626 \times 10^{-34} \text{J Hz}^{-1}$  is the Planck constant,  $f$  is the frequency of the photon,  $c = 3.00 \times 10^8 \text{ms}^{-1}$  is the speed of light in a vacuum and  $\lambda$  is the wavelength of the photon.

With this, we can see that as a hydrogen-like ion transition between the states with principal quantum numbers  $m$  and  $n$ , a photon is emitted with energy<sup>1</sup>

$$hf = R_{EH} Z^2 \left( \frac{1}{m^2} - \frac{1}{n^2} \right) \quad (3)$$

In equation 3,  $R_{EH} = 13.6\text{eV}$  is the Rydberg constant for hydrogen. Although this does not generalize perfectly to all atoms, the principle remains that every atom has its unique spectrum, characterized by strong peaks at energies where transitions are possible, called spectral lines<sup>1</sup>. Thus, detecting the photons emitted when the atoms in an object transition to a lower energy state can be used to determine the object's atomic makeup. In this experiment, we use spectrometry to analyze elemental gas inside of gas discharge tube. A gas discharge tube consists of a tube containing a gas at low pressure, with an anode at one end and a cathode at the other end creating a high voltage difference.

The high voltage difference causes electrons to accelerate across the tube, resulting in collisions with atoms in the gas. Some of these collisions result in the ionization of the atom, and the positive ions then move in the opposite direction to the electrons, further increasing collision rates. In these collisions, the atoms transition to higher energy states, and the filling of vacancies in electron shells described previously emits photons related to the unique spectrum of the atom.<sup>1</sup>

In this experiment, our spectrometer uses a diffraction grating to disperse different wavelengths of light. The intensity of oncoming light is then binned according to the wavelength, creating a spectrum, a curve representing the number of photons of a particular wavelength incident on the fiber optic cable from the gas discharge tube. In the first part of this experiment, we calibrated the spectrometer using a spectrum generated by a mercury gas discharge tube.

In the second part of our experiment, we use this spectrum to experimentally verify the accuracy of the Rydberg equation 3 for hydrogen. In the third part, we find a spectrum for a helium gas discharge tube, and use it to find the selection rule for helium in a gas discharge tube; constraints on the possible transitions between quantum states in terms of the three quantum numbers,  $n$ , the principal quantum number,  $l$ , the spin quantum number and  $J$ , the angular momentum quantum number. In the fourth part, we use a spectrum gathered for an unknown element and then compare it with a series of known spectral lines to determine the elemental gas present in the gas discharge tube.

In most cases, light incident on a material is partially absorbed and partially transmitted based on its wavelength. Photons coming into a material can deposit their energy into the material, typically in the form of thermal energy. This absorption is exactly what gives a particular substance its color. Namely, a substance with a particular color absorbs light of most other wavelengths, only letting through light with a wavelength corresponding to the color we see.

There are two numbers associated with the absorption and transmission of particular wavelengths of light by a substance. They are the transmittance  $T$  and the absorbance  $A$ . These are given by

$$T = I/I_0 \quad (4a)$$

$$A = -\log_{10}(T) \quad (4b)$$

In equation 4a  $I$  is the intensity of light transmitted through the material, and  $I_0$  is the initial intensity of light shone on the material.  $T$  then represents the fraction of light let through by the material.  $A$ , on the other hand, is a measure of how much light is absorbed. The more light transmitted, the less light absorbed, and so on. In the fifth part of our experiment, we experimentally verify the determination of color by the absorbance and transmittance of other wavelengths of light.

The same principles behind emission spectra govern fluorescence<sup>1</sup>. When light incident on a fluorescent material has energy almost exactly equal to the energy difference between two of the atom's quantum states, the atom is excited. Even if the incident photon doesn't have exactly the required energy, but only an energy very similar, the difference can be compensated by depositing or removing kinetic energy from the atom. After excitation, the atom transitions back to a lower energy state and emits a photon of the wavelengths corresponding to the energy lost in the transition. The resulting emissions are called fluorescence. In the sixth part of our experiment, we attempted to excite a sample of dyed fluorescent water to determine the absorption edge, where absorption jumps significantly, to determine the point at which fluorescence occurred.

## Methods

In the calibration step and the first three parts of the experiment, we used the experimental setup depicted in figure 1.

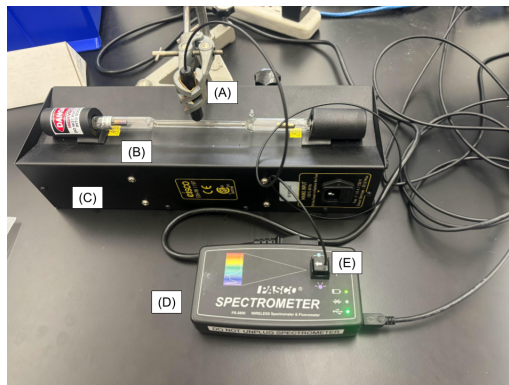


Figure 1: Experimental setup for spectroscopic analysis of gas discharge tube. The PS-2601 fiber optic probe is positioned up se to the gas discharge tube and is labeled (A). The installed gas discharge tube is labeled (B). The tubes were PASCO SE-9460 series spectral tubes. The EISCO Premium Spectrum Tube Power Supply is labeled with a (C). The PS-2600 wireless spectrometer is labeled with (D). The other end of the fiber optic cable, connected to the spectrometer, is labeled with an (E).

To start the experiment, we calibrated the spectrometer by finding the spectrum of mercury. We connected the spectrometer to the computer and then plugged the gas discharge tube into the power supply. During this process, the power supply was turned off and unplugged for safety reasons. The rectangular end of the fiber

optic cable was plugged into the spectrometer, with the arrow pointing to the left as shown in figure 1, labeled with an (E).

We then positioned the cylindrical probe of the fiber optic cable 0.1cm - 0.4cm away from the center of the discharge tube using the clamp to hold it in place. Once the initial positioning was complete, we turned the power supply on. Once active, we started collecting data using the PASCO free spectrometry software, under the analyze light option. As initial settings, we set the integration time to  $\sim 500$ ns, and the number of scans to average to 1. The smoothing setting was set to zero for the entire experiment.

To enhance the resolution of the results we adjusted the position of the probe. We first moved the probe closer to the tube and then moved it forward and backward until the intensity reached a maximum. We then moved the probe closer again, and moved it until the intensity returned to a maximum. We repeated this process until the probe was close to but not touching the gas discharge tube, and the peaks had a large enough amplitude that they were distinguishable from the background noise.

With this setup complete, we set the integration time to 1000ns and the number of samples to average to 10 to generate a spectrum. The integration time chosen was the longest available to increase the amplitude of detected peaks. The number of samples to average was chosen to ensure that a spectrum could be generated expeditiously without noise significantly affecting the results. We then used the coordinate option to place coordinates at the positions of the various peaks in the spectrum. To complete calibration, we matched the observed peaks with known peaks in Mercury's spectrum at similar wavelengths. We then used a linear function to fit these peaks and used it to convert from wavelengths detected pre-calibration to actual wavelengths.

We then unplugged the power supply, waited for the tube to cool down, then removed it, and repeated the data collection process with gas discharge tubes containing hydrogen, helium, and a tube containing an unknown elemental gas. To analyze the hydrogen spectrum, equation 3 was used to compute the wavelengths of photons in the Balmer series for hydrogen, where  $m = 2$ . We then compared these results to the peaks visible in our spectrum for hydrogen.

We then compared our spectrum for helium to a series of known peaks for helium and used this to come to a conclusion on the selection rules, which allowed quantum state transitions, for helium in a gas discharge tube. Finally, we compare our spectrum for the unknown gas to a collection of reference peaks for known gases and use this comparison to determine the elemental gas present in the tube.

In the fifth and sixth parts of the experiment, we set aside the power supply, removed the fiber optic cable, and returned to the analyze solution option. We started by pressing the calibrate dark option, waiting for the calibration to complete, then inserting a rectangular cuvette containing water into the rectangular opening, with the smooth sides facing the light, and pressing the calibrate light option.

Once calibration was complete, we inserted the red-dyed water into the opening, once more with the smooth side facing the light. After this, we took an absorbance and transmittance spectrum of the water and then analyzed the spectrum to determine the color of the dye. We repeated this with the blue and green dyed water. Finally, we switched to the fluorescence options and inserted the yellow cuvette into the opening, and attempted to detect fluorescence under excitation by 405nm and 500nm light.

## Results and Analysis

### Calibration

In the first part of the experiment, we obtained a mercury emission spectrum using a fiber optic cable pointed at a mercury gas discharge tube. A figure depicting this spectrum can be seen in figure 3, in Appendix A.

Table 1: Expected and experimental wavelengths of peaks in Hg emission spectrum.

Color	Expected $\lambda$ (nm)	Experiment $\lambda$ (nm)	Expected E (eV)	Experiment E (eV)
Violet	405	$414 \pm 2$	3.07	$2.99 \pm 0.01$
Violet	408		3.04	
Blue	436	$445 \pm 2$	2.85	$2.79 \pm 0.01$
Green	546	$548 \pm 2$	2.27	$2.26 \pm 0.01$
Yellow	577	$580 \pm 2$	2.15	$2.14 \pm 0.01$
Yellow	579		2.14	

In table 1, the empty cells in the experimental energy and wavelength columns denote instances where two adjacent peaks were too close to distinguish within uncertainties. The experimental uncertainty of 2 nanometers was found in the product page for the PS-2600 spectrometer<sup>2</sup>, and is used in the rest of the report.

Using these peaks, we produced a plot for the calibration of the spectrometer, seen in figure 2. Unfortunately, in this context, the various goodness of fit metrics are not effective in determining whether the calibration is effective because of the low number of data points. However, we can say that the linear fit chosen effectively fit through all four points for both plots. This means that a linear calibration is indeed effective in converting from the reference wavelengths to measured wavelengths, similarly with energy.

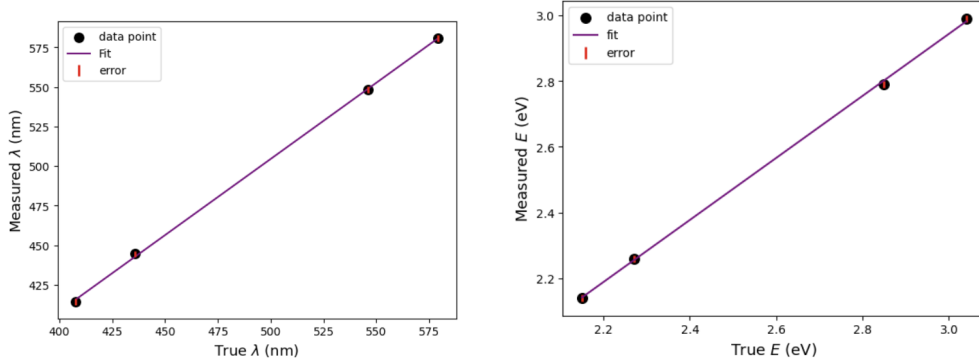


Figure 2: Calibration of wavelength spectrum and energy peaks of mercury gas discharge tube. The left plot depicts the calibration of the wavelength and the right plot depicts the calibration of the energy, both based on the four peaks in the spectrum which were distinguishable within uncertainties. A linear function  $ax + b$  is fitted to both data sets. For wavelength, the best fit parameters were  $a = 0.96 \pm 0.01$  and  $b = 23 \pm 6$ . The  $\chi^2_{red}$  metric for the wavelength fit was  $\chi^2_{red} = 0.67$ . In the energy plot, the best fit parameters were  $a = 0.94 \pm 0.01$  and  $b = 0.11 \pm 0.04$ . The  $\chi^2_{red}$  metric for the fit was  $\chi^2_{red} = 1.25$ . The residuals for the wavelength fit can be found in figure 10 in Appendix B. The presence of only four points in the plot means it is not effective in determining goodness of fit, and so a corresponding residuals plot for the energy fit was not created.

## Energy of the quantum states of hydrogen (H)

In this second part of the experiment, we produced a spectrum as with the mercury spectrum, and recorded the peaks within the detectable range of wavelengths.

Table 2: Quantum state energy calculated from 1 and expected, measured, and calibrated transition energies for Balmer series.

n	Quantum State Energy (eV)	Expected Transition Energy (eV)	Expected Transition λ (nm)	Measured Transition Energy (eV)	Calibrated Transition Energy (eV)
3	-1.51	1.89	657.5	$1.88 \pm 0.01$	$1.87 \pm 0.05$
4	-0.85	2.55	487.0	$2.51 \pm 0.01$	$2.54 \pm 0.04$
5	-0.544	2.85	389.6	n/a	n/a

As we can see from table 2, the calibrated energies are in splendid agreement with the reference energies, well within uncertainties for both of the present peaks. There are some minor deviations, which could have been caused by the obstruction provided by the gas, attenuation when moving through air and the fiber optic cable, or due to the nonzero resolution of the spectrometer.

A plot of the raw spectrum can be found in figure 4 from Appendix A. Something notable is the fact that the lower wavelength peak has a much lower intensity relative to the peak at the higher wavelength. This is an observation that also can be seen in the spectra of mercury, helium, and the unknown gas, also in Appendix A. This is because, for a given atom, certain transitions are more likely than others.

For hydrogen, the relative intensity can tell us some information about the voltage across the tube. Namely, we can tell that the voltage cannot be too high, as otherwise, the electrons would have much more energy, and hence deposit more energy into the hydrogen atoms. This would then result in more transitions into the  $n = 4$  state, and hence more emissions from the transition from  $n = 4$  to  $m = 2$ .

## Energy of the quantum states and transitions of helium

Helium is the first atom with more than one electron, and so is the first that cannot be accurately described by the Bohr model in its neutral state. To see this, consider the strongest transition in helium, with a peak at  $\lambda \approx 588\text{nm}$ . If the Bohr model applies appropriately, equation 3 states that the transition energy and wavelength would be

$$E = 13.6(2)^2 \left( \frac{1}{4} - \frac{1}{9} \right) = -7.55\text{eV}, \quad \lambda = \frac{hc}{E} = 164.4\text{nm}$$

This result is clearly incorrect. This is because the first electron in the atom affects the second electron with its own electric field, reducing the pull on the second electron by the atom, hence decreasing the energy required to excite the second electron. This makes equation 3 incorrect for computing transition energies. After taking our spectrum for helium, which can be seen in figure 5 in Appendix A, we produced table 3.

Table 3: States, wavelengths, energies, and selection rules associated with high-intensity emission lines in helium spectrum.  
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Initial Quantum State	Final Quantum State	Reference intensity (arbitrary units)	Reference wave-length (nm)	Calibrated wave-length (nm)	Energy of initial state $E_n$ (eV)	Energy of final state $E_m$ (eV)	Selection rules $\Delta n, \Delta l, \Delta J$
1s2p (1)	1s <sup>2</sup> (0)	1000	58.43	n/a	-3.35	-24.57	-1,-1,-1
1s3s (1)	1s2p (2)	200	706.51	$710 \pm 10$	-1.84	-3.60	-1,1,1
1s3p (1)	1s2s (1)	500	388.86	$393 \pm 7$	-1.56	-4.75	-1,-1,0
1s3d (3)	1s2p (2)	500	587.56	$591 \pm 9$	-1.49	-3.60	-1,-2,-1
1s3d (2)	1s2p (1)	100	667.81	$670 \pm 10$	-1.49	-3.35	-1,-1,-1
1s3p (1)	1s2s (0)	100	501.56	$504 \pm 8$	-1.48	-3.95	-1,-1,-1
1s4d (1)	1s2p (2)	200	447.15	$451 \pm 8$	-0.825	-3.60	-2,-1,1

From table 3, we can see that there were five peaks corresponding to transitions from  $n = 3$  to  $m = 2$ . This stands in stark contrast to the hydrogen atom, in which there was only one such transition. This is because there are several quantum states corresponding to  $n = 3$  and several quantum states corresponding to  $m = 2$ . Different combinations of transitions yield different results. In hydrogen, there is only one energy state corresponding to each principal quantum number. Also from table 3, we can see that the only possible transitions with visible wavelengths are  $-2 \leq \Delta n \leq -1$ ,  $-2 \leq \Delta l \leq 1$  and  $-1 \leq \Delta J \leq 1$ . As a final observation, we see excellent agreement between the calibrated and reference wavelengths provided within uncertainties.

## Determining the Unknown Gas

Taking a spectrum of the unknown gas yielded figure 6, which can be seen in Appendix A.

Table 4: Intensity and wavelength of unknown gas spectral lines

Unknown Gas	1st peak	2nd peak	3rd peak
Measured Intensity in Arbitrary Units	100.0	86.53	52.51
Calibrated Wavelength $\lambda$ (nm)	$764.7 \pm 11$	$819.3 \pm 11$	$839.3 \pm 11$

The spectrum plotted in figure 6 had only three peaks, described in table 4. Using the wavelengths of these three peaks, and a reference table containing wavelengths of peaks in various gases, table 8 in Appendix E, we determined that the most likely gas to be contained in the tube was krypton, as the wavelengths and the order of peaks matched well with the final three peaks in the reference table.

## Transmittance and Absorbance of photons on solutions

In this part of the experiment, we generated absorption spectra for three dyed waters, with red, green and blue coloring, all available in Appendix A. For each, we considered points at which the absorbance or transmittance reached an extremum, or increased rapidly. The transmittance and absorbance for the blue dye can be found below in table 5. Corresponding tables for the red and green water can be found in Appendix C.

Table 5: Transmittance and Absorbance of blue dye solution at extrema and inflection points

	$393 \pm 2\text{nm}$	$420 \pm 2\text{nm}$	$453 \pm 2\text{nm}$	$538 \pm 2\text{nm}$	$595 \pm 2\text{nm}$	$644 \pm 2\text{nm}$
Measured $T$	59.2	53.7	63.9	39.3	12.6	56.4
Measured $A$	0.23	0.27	0.19	0.40	0.90	0.25
Calculated $A$	0.23	0.27	0.19	0.41	0.89	0.25

As can be seen in the absorbance and transmittance spectrum for the blue dye in figure 7, Appendix C, the absorbance is highest for  $\lambda \approx 590\text{nm}$  in the visible part of the spectrum. Hence, colors around that wavelength, namely, green all the way to the infrared, where the absorbance is at least 0.5, are all mostly cut out by the dye. Transmittance is highest in the wavelength range from 400nm to 500nm, which is the blue range. This explains the color of the dyed water.

A similar analysis can be conducted for the red and green dyes, with spectra in figures 8 and 9 respectively. In figure 8, the transmittance is low in the range of about 400nm to 550nm, while being fairly high for longer wavelengths; it is clear then, that the color of the dye whose spectrum is being taken is red colored. Similarly, in figure 9, the transmittance is low in the range of about 400nm to 460nm and from about 550nm to 650nm. The wavelengths transmitted are then the green and light blue wavelengths, and the deep red wavelengths. Although there is some red light transmitted, most of the light is green, by virtue of the larger range of wavelengths transmitted in that range.

## Fluorescence

In this part of the experiment, we gathered a spectrum of water with a yellow fluorescent dye when excited with water of wavelengths 405nm and 500nm, with the intent of observing photons emitted as the excited atoms transitioned to a lower energy state, with a characteristic wavelength. However, no such peaks were distinguishable from what would be expected merely from the visible color of the solution itself.

Figure 11 is the spectrum detected when the yellow dye solution was illuminated by 500nm light. As can be seen, the only detected light was light with a wavelength slightly above 500nm, which can be entirely explained by ordinary absorbance and transmittance. The incident light would be mostly 500nm light, but some would be of higher and some of lower wavelengths, as can be observed in figure 19, where no sample was present. Then, the yellow dye would, to some small degree, filter out some of the 500nm and below light while transmitting more light at the higher wavelengths, thus producing the effect of slightly shifting the peak.

In figure 12, the solution is illuminated by 405nm light. However, we do not see a peak at this wavelength, which is explained by the color of the water itself; most of the low wavelength 405nm light would be absorbed. This is further confirmed by the spectra of the red and green solutions illuminated by the same wavelengths seen in figures 15, 16, 17 and 18. We would expect from the wavelength of green light and the transmittance plot 9 that most of the 500nm light is transmitted and most of the 405nm light is absorbed by the green solution. By a similar argument, the red dye should absorb both wavelengths. This is what we observe.

There is one wrinkle to this explanation, which is the seeming fluorescence exhibited by the blue dyed solution. In both plots of the blue solution, observe one peak in the wavelength range around the incident light, which is what we would expect from the wavelengths corresponding to the color blue and the high transmittance of 405nm and 500nm light, as can be seen in figure 7. However, in both plots, there is another peak present at 650nm, which would suggest the presence of fluorescence in the blue dye. As the blue dye is not supposed to be fluorescent, while the yellow dye is, this phenomenon is, as of yet unexplained. Possible explanations include damage to the spectrometer, faulty samples, the blue dye being fluorescent, or software error. More testing might be in order to determine the cause of the observations.

## Conclusion

In this experiment, we studied and analyzed the emission spectra of various elemental gases and the absorption and transmission spectra of various colors. We used mercury, which possesses several high-intensity spectral lines in its emission spectrum to calibrate our spectrometer's readings. We then examined the spectral lines of hydrogen and helium and found complete agreement with expectation within uncertainties. We used spectrometry to identify the elemental composition of an unknown gas to be krypton by matching the observed peaks to reference peaks within uncertainties, verifying the effectiveness of the method for distinguishing elements. We then analyzed the absorbance and transmittance spectra dyed solutions to determine if their shape was in agreement with their visible color, concluding that there was a strong correlation between what wavelengths were highly transmitted and what wavelengths corresponded to the actual color of the dye. We also attempted to analyze fluorescence in samples known to have fluorescent properties, but failed to find any such signs.

## References

- [1] Natalia Krasnopolskia. *PHY324 Spectrometry Manual*. University of Toronto, 2025.
- [2] *Spectrometry Software*. 2010. URL: <https://www.pasco.com/products/software/spectrometry>.

## Use of AI Statement

No AI was used to make this report.

## Appendix

### Appendix A: Raw Spectrum Images

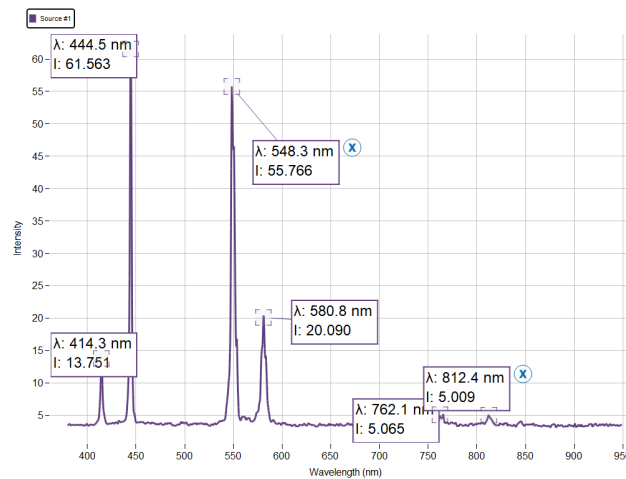


Figure 3: Raw mercury emission spectrum. 6 peaks are present, with the first four from the left being in the visible spectrum and in the reference wavelengths provided<sup>1</sup>. The wavelengths  $\lambda$  and intensity  $I$ , in arbitrary units, of the peaks are indicated in the figure.

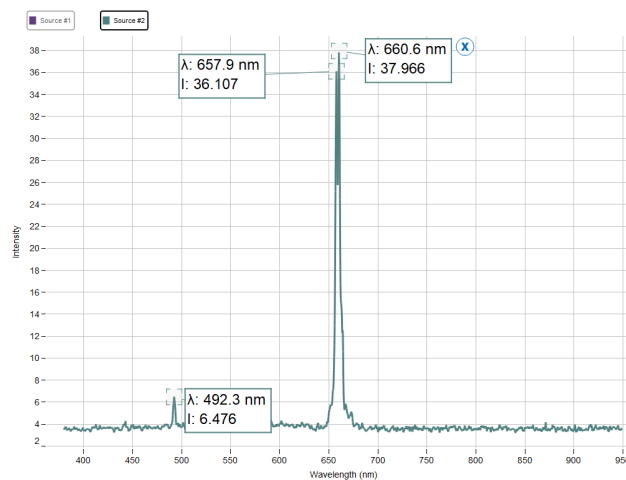


Figure 4: Raw hydrogen emission spectrum. Both peaks present are present in the reference wavelengths provided<sup>1</sup>. Wavelengths and intensity of the peaks are indicated in the figure.



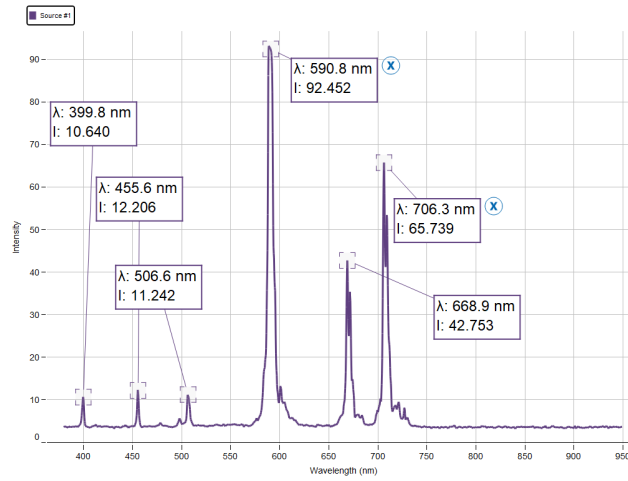


Figure 5: Raw helium Emission spectrum. All 6 peaks present can be found in the reference wavelengths<sup>1</sup>. Wavelengths and intensity of the peaks are indicated in the figure.

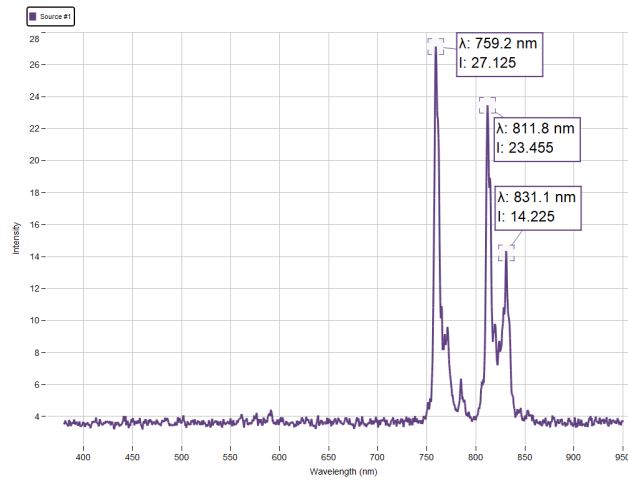


Figure 6: Raw emission spectrum of unknown gas. Peaks present match with the final three peaks of krypton in the reference wavelengths provided Wavelengths and intensity of the peaks are indicated in the figure<sup>1</sup>. Wavelengths and intensity of the peaks are indicated in the figure.

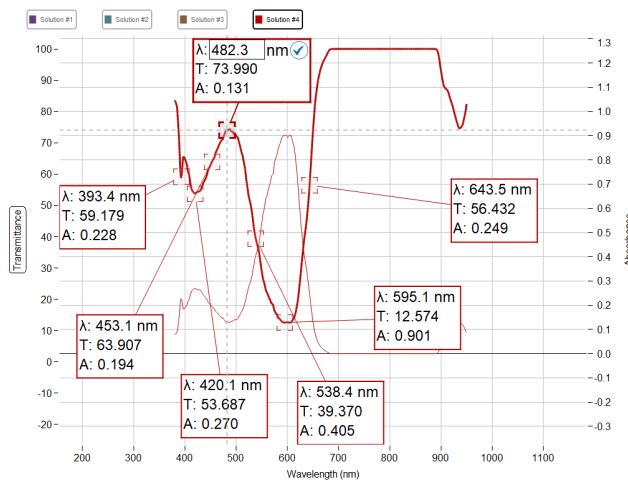


Figure 7: Transmittance and Absorbance of blue dye solution. Extrema and points of rapid growth have their transmittance, absorbance and wavelengths indicated.

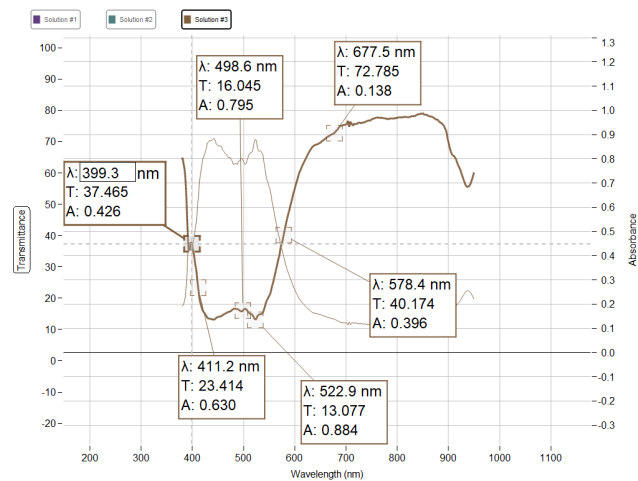


Figure 8: Transmittance and Absorbance of red dye solution. Extrema and points of rapid growth have their transmittance, absorbance and wavelengths indicated.

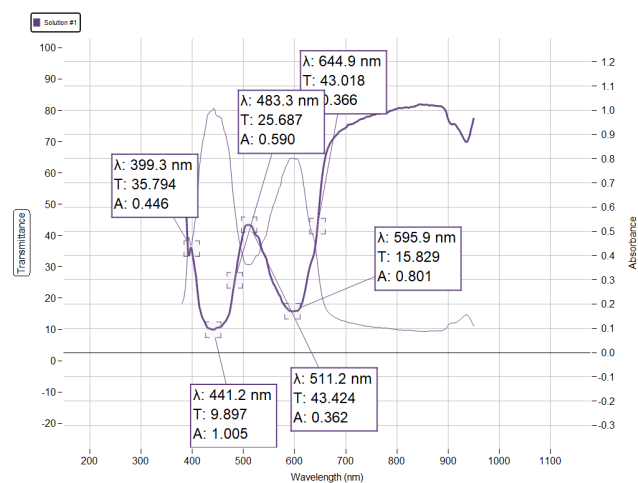


Figure 9: Transmittance and Absorbance of green dye solution. Extrema and points of rapid growth have their transmittance, absorbance and wavelengths indicated.

## Appendix B: Residuals

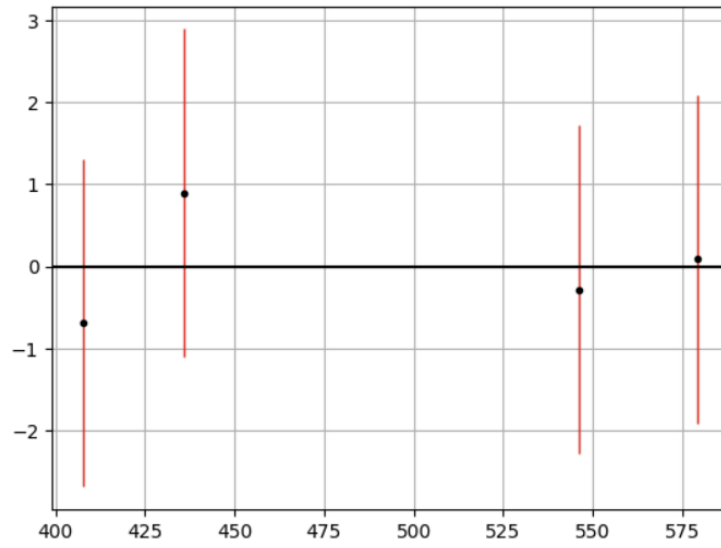


Figure 10: Residuals to fit of measured wavelength against reference wavelength of detected peaks. All points touch the zero line within uncertainties, though the low number of points makes the utility of this plot dubious.

## Appendix C: Absorbance and Transmittance Spectra of Colored Dye Solutions

Table 6: Transmittance and Absorbance of green dye solution.

$\lambda$ (nm)	$399 \pm 2$	$441 \pm 2$	$483 \pm 2$	$511 \pm 2$	$596 \pm 2$	$645 \pm 2$
Measured Transmittance T	35.8	9.9	25.7	43.4	15.8	43.0
Measured Absorbance A	0.45	1.0	0.6	0.36	0.8	0.37
Theoretical Absorbance	0.45	1	0.6	0.36	0.8	0.37

Table 7: Transmittance and Absorbance of red dye solution.

$\lambda$ (nm)	$399 \pm 2$	$411 \pm 2$	$499 \pm 2$	$523 \pm 2$	$578 \pm 2$	$677.5 \pm 2$
Measured Transmittance T	37.5	23.4	16.0	13.0	40.2	72.8
Measured Absorbance A	0.43	0.63	0.79	0.88	0.40	0.14
Theoretical Absorbance	0.43	0.63	0.79	0.88	0.40	0.14

## Appendix D: Part 6 Images

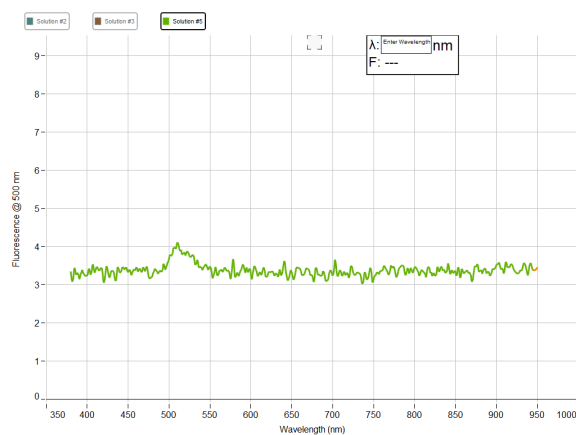


Figure 11: Spectrum from yellow dye illuminated by 500nm light. The peak present can be explained by the color of the dyed water and the spread of wavelengths around 500nm observed when no sample is present, as in figure 19, uncharacteristic of the known fluorescent properties.

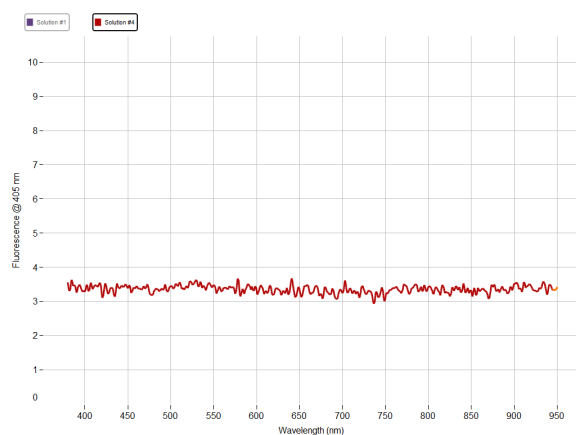


Figure 12: Spectrum from yellow dye illuminated by 405nm light. No peaks are observed, uncharacteristic of the known fluorescent properties.

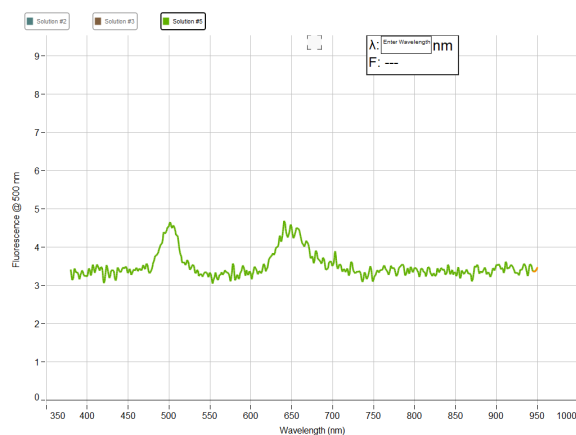


Figure 13: Spectrum from blue dye illuminated by 500nm light. The peak at 500nm is well explained by the color of the solution, but the other peak has no neat explanation under the assumptions provided<sup>1</sup>. Further experimentation may determine the cause of this other peak.

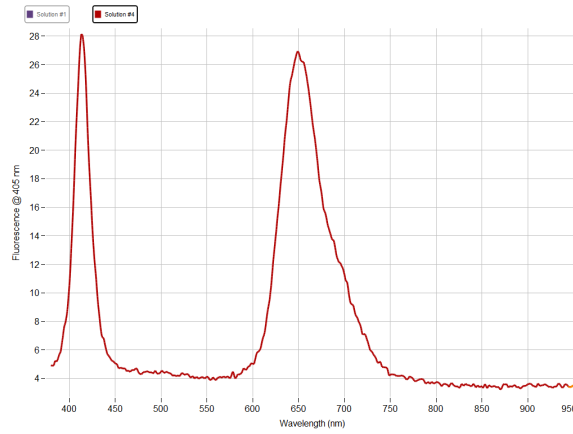


Figure 14: Spectrum from blue dye illuminated by 405nm light. The peak at 405nm is well explained by the color of the solution, but the other peak has no neat explanation under the assumptions provided<sup>1</sup>. Further experimentation may determine the cause of this other peak.

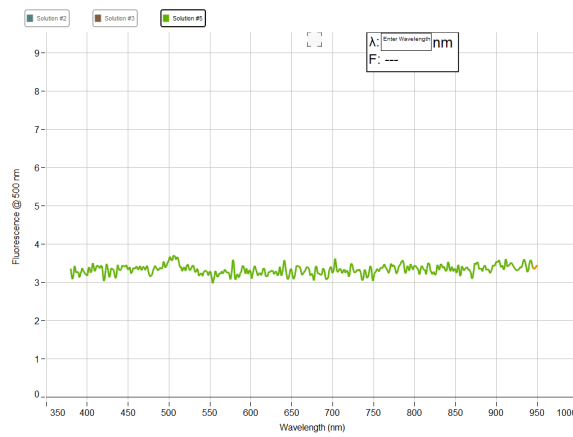


Figure 15: Spectrum from green dye illuminated by 500nm light. The slight peak at 500nm is well explained by the color of the solution.

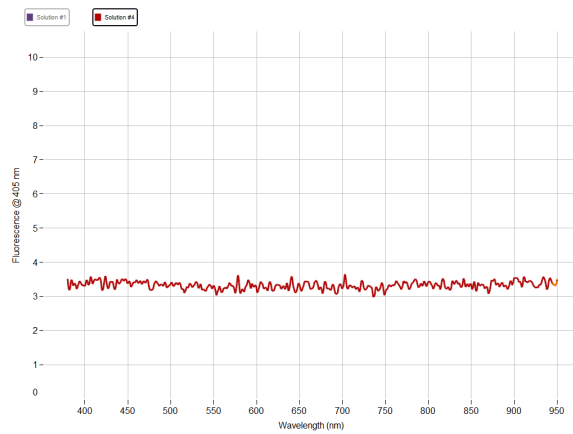


Figure 16: Spectrum from green dye illuminated by 405nm light. The absence of any peak at 405nm is well explained by the color of the solution.

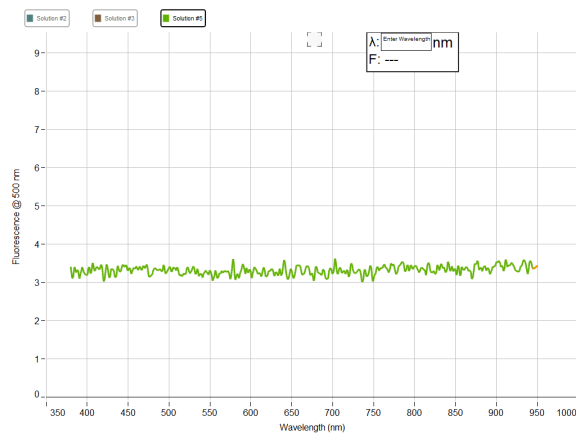


Figure 17: Spectrum from red dye illuminated by 500nm light. The absence of any peak at 500nm is well explained by the color of the solution.

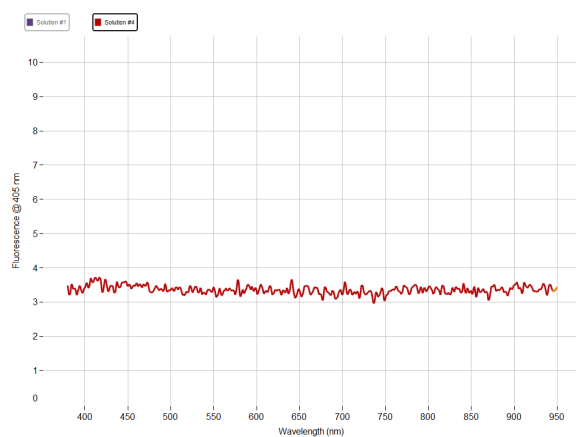


Figure 18: Spectrum from red dye illuminated by 405nm light. The absence of any peak at 405nm is well explained by the color of the solution.

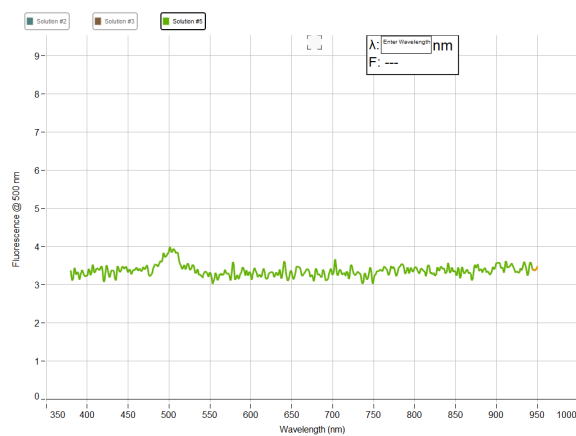


Figure 19: Spectrum generated by illuminating the detector with 500nm light. As expected, there is a peak at 500nm.

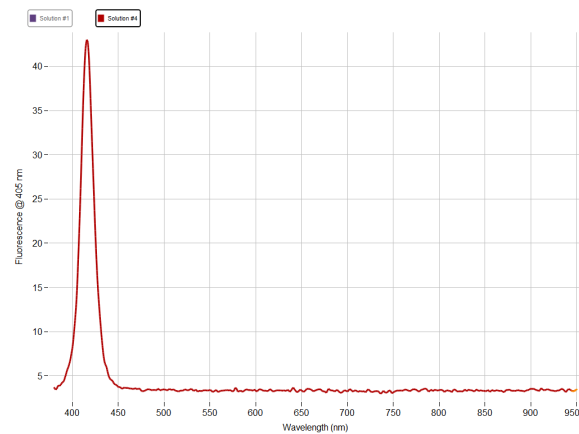


Figure 20: Spectrum generated by illuminating the detector with 405nm light. As expected, there is a peak at 405nm.

## Appendix E: Reference Wavelengths

Table 8: Reference Table: Wavelength of strongest lines in emission spectra of assorted gasses in nm<sup>1</sup>

Gas	1	2	3	4	5	6	7	8	9
Neon	540	585	622	640	660	693	703	717	725
Argon	427	435	440	459	473	476	502	696	
Krypton	427	432	557	587	646	759	769	810	826
Xenon	484	529	534	542	597	605	610	681	699
Sodium	588	590							
Nitrogen	404	444	463	501	568	575	594	648	661
Oxygen	412	423	533	559	605	616	626	637	645