Quantum States and Spectra of Gases

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1 Introduction

A spectrum, sometimes referred as intensity, is a function of energy and it is proportional to the number of photons of different amount of energy.

$$E_f = hf = \frac{hc}{\lambda} \tag{1}$$

According to Equation 1, the energy may be replaced by a frequency or wavelength. All atomic spectra is continuous and linear, where h is the Planck's constant $6.626 \cdot 10^{-34} Js$ and c is the speed of light in vacuum $c = 2.998 \cdot 10^{8} \frac{m}{s}$.

In the experiment, the emission spectra and/or absorption spectra of Mercury, Hydrogen, Helium, and an unknown gas is studied. Emitted light is incident on a diffraction grating and then passes a Charge-Coupled Device (CCD) array which detects specific incident energy. A plasma, which is a mixture of free electrons and ions, produced in a gas by collisions between the accelerated electrons and the atoms of the gas under high voltage and low pressure. The number of electrons captured by the ions is equal to the number of electrons released due to ionization and this number stays constant for the set pressure and excitation energy.

Emission of photons is a result of an electron or ion ionizes the neutral atom, transits from a higher energy state to a lower energy state. As they release the energy, they emit photons and depend on the wavelength of the photons, it could be visible to human eyes. In the other hand, absorption of a photon occurs when the atom or a molecule undergoes a transition from a lower energy state to a higher energy state, since they have to absorb energy. Thus, if we know the energy of the two states participating in the transition, we can expect the energy of the emitted photon to equal the difference of the energies of the states:

$$hf = R_{EH} Z^2 (\frac{1}{m^2} - \frac{1}{n^2}) \tag{2}$$

where R_{EH} is the Rydberg constant for hydrogen and $R_{EH} = 13.605693 eV = 2.179872 \cdot 10^{-18} J$, and n is the excited state and m is the ground state. Equation 2 permit calculating the value of energy of the state with a particular principal quantum number.

Using Bohr's postulates, the energy E_n of the n^{th} level of any stationary state of the hydrogen-like atom is given by:

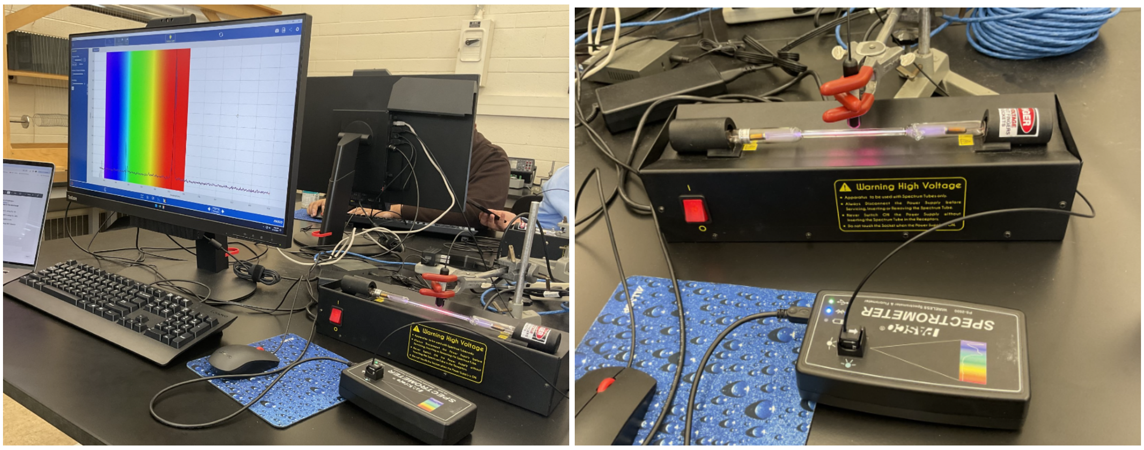
$$E_n = -\frac{Z^2 k_e e^2}{2n^2 a_0} \approx -\frac{13.6 Z^2}{n^2} eV \tag{3}$$

where k_e is Coulomb's constant, e is the elementary charge, and $a_0 = 0.0529 nm$ is the Bohr radius. Note the Bohr's model works for just hydrogen and hydrogen-like ions that have one electron.

Intensity of a spectral line depends on the probability of the transition, the lifetime of the excited state, the probability of fluorescent yield and on the absorption of the photons in a medium. There are many peaks presented with different intensities in the emission spectrum due to a nonzero probability for an incident photon to excite the atom at any state with the ionization potential lower than the energy of the photon.

2 Materials and Methods

2.1 Materials



(a) Experimental Set-up with coloured spectrum data on the PASCO Spectrometry Software Application **(b)** Magnified View of the Spectrometer and the Gas Discharge Tube connected to an electrical power source

Figure 1: Experimental Set-up

Apparatus (refer to figure 1 for the experimental set-up):

- PASCO wireless spectrometer PS-2600
- Fibre optics cable PS-2601 with probe
- PASCO Spectrometry Sofware application
- High voltage power supply
- Discharge tubes with different gases (Hydrogen, Helium, Mercury and Unknown Sample)
- Set of cuvvettes with dyes of different colours (Colorless, Green, Red, Blue and Yellow)
- Adjustable clamp with holder

2.2 Methods

2.2.1 Part 1: Calibration of the spectrometer with a Mercury (Hg) Discharge tube

The spectrometer was switched on and a Mercury (Hg) Gas Discharge Tube was carefully inserted into a high voltage supply. One end of the fibre optics cable was positioned above the discharge to tube and the other was placed inside the Spectrometer's cuvette opening and was directed to towards the built-in detector. The power supply was plugged in and switched on. The PASCO Spectrometry Software application was used to select the "ANALYZE LIGHT" function (from the application tools) and record preliminary test spectrums by initiating collect data and adjusting the integration time for optimal data acquisition. Preliminary test spectrums were collected to determine the optimal height to position the probe of fibre optics cable from the discharge tube based upon the expected peaks. Reference Arrows were utilized to compare the test spectrum with the standard one. The spectrometer was then calibrated for true wavelengths and energy measurements.

2.2.2 Part 2: Calculating the Energy of the Quantum States of Hydrogen (H), Helium (He), and an Unknown Sample

After the mercury tube cooled, it was replaced with the Hydrogen (H) discharge tube and a spectrum for the hydrogen discharge tube was recorded. Calculations were performed to determine the energies of quantum states of the hydrogen sample with $n = 3, 4$ and 5, as well as the expected energy of different n values with the spectrals lines of the Balmer Series. The theoretical energy values were converted to wavelengths and literature and experimental values of the spectrum peak energy were examined to identify errors. Similarly the quantum states and the permitted transitions of helium were recorded. Finally the an unknown sample discharge tube was tested and the produced spectrum from this tube was compared with the calibration curve and the standard spectra (available on the PASCO spectrometer software) with known wavelengths to determine the unknown sample.

2.2.3 Part 3: Transmittance and absorbance measurements from coloured dyes

The fibre optics cable were removed from the spectrometer and the voltage supply was unplugged. The ANALYZE SOLUTION tool was selected and CALIBRATE DARK was pressed on PASCO Spectrometer Software. The colourless cuvette was inserted in the spectrometer (with the glossy side of the cuvette facing the white light symbol). The light source was warmed for approximately 1-2 minutes a CALIBRATE REFERENCE was selected. A colourless sample was used set a reference point for the spectrometer. This colourless cuvette sample was replaced by by blue coloured dye and the ABSORBANCE/TRANSMITTANCE were recorded for roughly 3 minutes. The Show Dual Y-Axes Application tool was selected to observe both the absorbance and transmittence and points of interest were identified using the ADD COORDINATE feature. These steps were repeated with red and green colored dyes in cuvettes. Lastly this same procedure was repeated for the yellow dye with however the glossy side (facing the violet and blue light in the spectrometer) to observe fluorescence behavior.

3 Data and Analysis

The experiment results are are summarized below from the data collection of the discharge tubes and the absorbance and transmittance of coloured dyes. A few important considerations and observations that were made while recording the spectrum:

- **Probe Distance:** The distance of fibre optic cable probe had a significant impact on the intensity peaks observed on the spectrum. Subsequently as the distance of the probe to the discharge tube increases, less light (fewer photons) are absorbed by the probe itself, which results in significant drops in intensity peaks. As such, to minimize random error and ensure consistency, the probe distance was fixed to $0.5cm$ by clamping the cable to the clamp jaw.
- **Smoothing:** It was observed that when smoothing number was increased, the noise of the curve decreased, by combining the peaks that were close to each other and subsequently taking the average of their intensities. It is known that smoothing the values of intensity leads to inaccuracies; nevertheless this functionality tends to yield cleaner spectrum graphs and helps in better drawing conclusions regarding the characteristic values from the graphs.
- **No. of Scans to Average:** Increasing the number of scans can ultimately allow the system to take more trials into consideration, which would result in a better average value. Modifications for this parameter is only required when vibrations in the graph are perceptible during data collection.

3.1 Mercury (Hg)

To improve the accuracy of the data collected, calibrating the spectrometer for true wavelength vs. measured wavelength and true energy vs. measured energy was obtained. Equation 1 was used to perform the energy calculations from the wavelengths. Table 1 provides the summary of the expected and experiment wavelengths and energies. The linear function of the measured value vs. expected value is shown in Figure 2 and 4, including the slope and y-intercept with their uncertainties and reduced chi-squared values. Figure 3 and 5 are the residuals plot of the linear function.

Table 1: Strong spectral lines of mercury

	Violet	Violet	Blue	Green	Yellow	Yellow
Expected λ, nm	404.7	407.8	435.8	546.1	576.9	579.1
Expected energy, eV	3.064	3.040	2.845	2.270	2.149	2.141
Experiment λ, nm	415.2 ± 0.5	430.6 ± 0.5	445.3 ± 0.5	548.9 ± 0.5	551.1 ± 0.5	581.6 ± 0.5
Experiment energy, eV	2.986 ± 0.0004	2.870 ± 0.0003	2.784 ± 0.0003	2.259 ± 0.0002	2.250 ± 0.0002	2.132 ± 0.0002

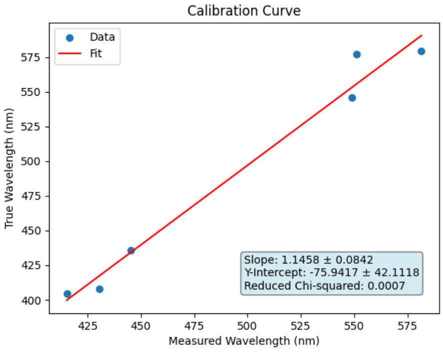


Figure 2: Wavelength Calibration Curve

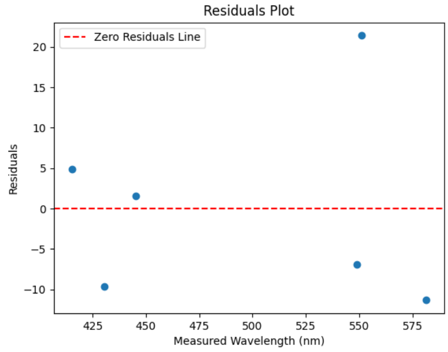


Figure 3: Wavelength Residuals Plot

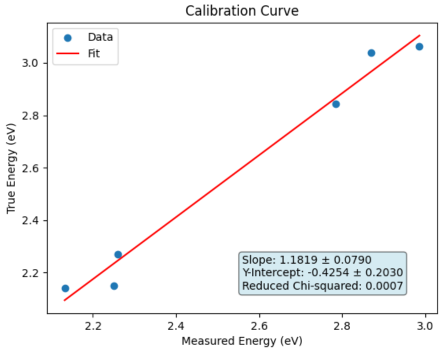


Figure 4: Energy Calibration Curve

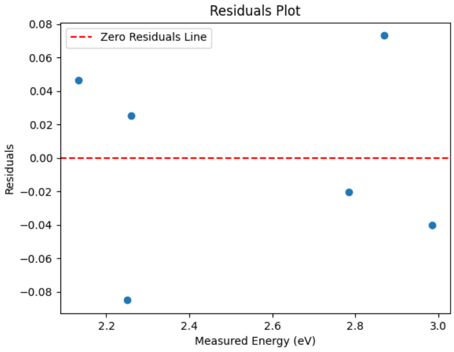


Figure 5: Energy Residuals Plot

3.2 Hydrogen (H)

3.2.1 Energies of Quantum States of a Hydrogen Atom

Using Equation 3, Calculate energies of quantum states of a hydrogen atom with n = 3, 4 and 5.

Table 2: Energies of quantum states of a hydrogen atom with specific quantum numbers

Quantum number (n)	Quantum state energy (eV)
3	-1.511
4	-0.850
5	0.544

3.2.2 Expected Energy and Wavelengths of Spectral Lines

Calculate the expected energy and the principal quantum numbers of the states of spectral lines of Balmer series, which was obtained by Johann Balmer in 1885 for a visible spectrum of hydrogen, similar to Equation 2:

$$E_f = hf = R_{EH}(\frac{1}{2^2} - \frac{1}{n^2}) \tag{4}$$

Since Hydrogen's $Z = 1$ and ground state $m = 2$. From Equation 1 and 4, wavelengths from the expected energies can be calculated and summarized in Table 3. Percentage error between the expected and experiment values are summarized in Table 4 and 5. Experimental uncertainties further explained in Section 4.1.

Table 3: Expected energies and wavelengths

Excited state (n)	Expected energy (eV)	Expected Wavelength (nm)	Experiment energy (eV)	Experiment Wavelength (nm)
3	1.890	650.0	1.884 ± 0.0001	658.2 ± 0.05
4	2.551	486.0	2.513 ± 0.0003	493.4 ± 0.05
5	2.857	433.9	2.846 ± 0.0003	435.6 ± 0.05
6	3.023	410.1	3.007 ± 0.0004	412.3 ± 0.05

Table 4: Energy percentage Error

Excited state	Percentage error
3	0.317 ± 0.005
4	1.488 ± 0.010
5	0.387 ± 0.010
6	0.529 ± 0.010

Table 5: Wavelength percentage Error

Excited state	Percentage error
3	1.262 ± 0.008
4	1.523 ± 0.010
5	0.392 ± 0.012
6	0.536 ± 0.012

The disparities between the expected nd observed values could arise from various factors. Firstly, certain photons emitted from the hydrogen tube might inadvertently disperse from the probe, resulting in an overall lengthened wavelength and therefore, diminished energy. Additionally, external light sources could also introduce some excess photons to the probe, causing an overall reduction in wavelength and a general elevation in energy levels. Furthermore, the inherent limitations of the equipment, for instance inaccuracies in scanning frequency and/or graph zoom-in scale, may also play a role in introducing errors that cannot be precisely quantified.

3.3 Helium (He)

The transition responsible for emission of the strongest peak with wavelength 588 nm takes place between the quantum states with m=2 and n=3. Using Equation 3, energies of the each quantum states, expected energy for the ion transition between the two states, and converted wavelength from the expected energy of the He^+ ion is calculated and summarized in Table 6.

Table 6: Expected energy and wavelength of He^+ ion

$E_3(eV)$	$E_2(eV)$	$\Delta E(eV)$	$\lambda(nm)$
-6.044	-13.60	7.556	164.2

The measured wavelength is $490.0 \pm 0.005nm$ (Figure 9 in Appendix B), which does not equal to the calculated one because He^+ atom is a hydrogen-like atom, while He is not. Equation 3 is only applicable to the hydrogen-like ions, which means only one electron is orbiting in the outer shell. Since He^+ ion lost one electron and only one left electron is travelling around the orbit, it could be treated like the hydrogen-like atom. On the other hand, non-ionized He atom cannot use 3 thus the measured wavelength of He atom does not equal to the calculated wavelength of He^+ atom.

Using the data for the reference wavelength λ_r, and Equation 1, the initial state energy E_n of the spectral line in eV is calculated.

$$\Delta E = E_n - E_m = \frac{hc}{\lambda_r} \cdot \frac{1eV}{1.60218 \cdot 10^{-19}J} \rightarrow E_n = \Delta E + E_m = \frac{hc}{\lambda_r} \cdot \frac{1eV}{1.60218 \cdot 10^{-19}J} + E_m \qquad (5)$$

Difference in the quantum numbers obeying selection rule, Δn, Δl, and ΔJ in the observed transitions are calculated as well. For the principle quantum number n and the angular quantum number l, the quantum state that is changed is use. “S-state” corresponds to l=0, “p-state” corresponds to l=1, ”d-state” corresponds to l=2, and so on. Also note that the quantum number J, is a combination of the spin quantum number and it is given in brackets. Electron configuration of different quantum states of He atom and corresponding calculated values are summarized in Table 7.

Table 7: Electron configuration and permitted transitions in the He atom

Electron configuration (initial state, upper level)	Electron configuration (final state, lower level)	Reference intensity	Reference wavelength λ_r (nm)	Measured wavelength λ_{exp} (nm)	Excited state energy E_n (eV)	Ground state energy E_m (eV)	Δn	Δl	ΔJ
1s2p (1)	$1s^2$ (0)	1000	58.43	N/A	-3.350	-24.57	$1-2=-1$	$0-1=-1$	-1
1s3s (1)	1s2p (2)	200	706.5	707.1 ± 0.05	-1.845	-3.60	$2-3=-1$	$1-0=+1$	+1
1s3p (1)	1s2s (1)	500	388.9	400.3 ± 0.05	-1.562	-4.75	$2-3=-1$	$0-1=-1$	0
1s3d (3)	1s2p (2)	500	587.6	592.2 ± 0.05	-1.489	-3.60	$2-3=-1$	$1-2=-1$	-1
1s3d (2)	1s2p (1)	100	667.8	669.7 ± 0.05	-1.493	-3.35	$2-3=-1$	$1-2=-1$	-1
1s3p (1)	1s2s (0)	100	501.6	507.4 ± 0.05	-1.478	-3.95	$2-3=-1$	$0-1=-1$	-1
1s4d (1)	1s2p (2)	200	447.1	456.1 ± 0.05	-0.827	-3.60	$2-4=-2$	$1-2=-1$	-1

There are 5 spectral lines correspond to the transition of the atom of He from n=3 to m=2 in the experiment based on the Table 7. The same result cannot be observed for a hydrogen atom since it contains a single electron, there is no available electron to make a transition. Recall the discussion about expected energy and wavelength of He^+ ion, the main difference between the hydrogen-like ion and the He atom is that hydrogen-like atoms contain only one electrons, while neutral He atom has two electrons. Thus Equation 2 is not applicable to neutral He atom because the condition to use the following equation is that the atom must be a hydrogen-like atom. The selection rules in terms of all possible values are $\Delta n = -1, -2$, $\Delta l = 1, -1$, and $\Delta J = 1, 0, -1$ for transitions corresponding to the spectral lines registered in the experiment.

3.4 Unknown Gas

The equations 2 and 3 demonstrates that atoms have a specific, or characteristic, set of spectral lines that correspond to transitions between the two specific quantum states. The atomic spectrum, sometimes called characteristic spectrum, is a tool to determine elemental composition of any substance.

The table in Appendix 2 from the lab manual [1] provides wavelengths of the strongest lines in emission spectra of gases in nm and it is used to determine the unknown gas, which is analyzed to be Krypton. Krypton has intensity peaks at 759nm, 810nm, and 826nm, which are the wavelength values closest to the particular experimental intensity peaks at wavelengths $760.8 \pm 0.05 nm$, $813.2 \pm 0.05 nm$, and $831.9 \pm 0.05 nm$. The list of experimental wavelengths for all spectral lines in emission spectra of gases in nm [1]. List of experimental wavelengths for all spectral lines and their relative intensity compared to the strongest line in the spectrum, which is $1.650 \frac{W}{m^2}$, are summarized in Table 8.

Table 8: Unknown Gas

	1	2	3	4	5	6	7	8	9
Experimental wavelength (nm)	417.2 ± 0.05	438.554± 0.05	516.911± 0.05	589.168± 0.05	646.014± 0.05	760.8 ± 0.05	773.708± 0.05	813.2 ± 0.05	831.9 ± 0.05
Intensity $(\frac{W}{m^2})$	1.360 ± 0.005	1.367 ± 0.005	1.380 ± 0.005	1.384 ± 0.005	1.362 ± 0.005	1.650 ± 0.005	1.415 ± 0.005	1.161 ± 0.005	1.518 ± 0.005
Relative intensity $(\frac{W}{m^2})$	0.290 ± 0.007	0.283 ± 0.007	0.290 ± 0.007	0.270 ± 0.007	0.266 ± 0.007	0.288 ± 0.007	0.000 ± 0.007	0.235 ± 0.007	0.132 ± 0.007

3.5 Transmittance and Absorbance

The probability of transmission (in percentage) is computed by taking the ratio of the total number of photons that successfully pass through a solution sample to the ratio of incident photons upon the surface of teh sample. Alternatively this can also be computed by taking the ratio of the indicident light, I_o and exit light, I, given by the equation below:

$$T = \frac{I}{I_0} \tag{6}$$

The absorbance (in percentage), however can be related to the transmittance using the expression below:

$$A = -\log_{10}\frac{T}{100} \tag{7}$$

The experimental data for A and T, along with the predicted values for A, are listed in Table 9-11. These sets of A and T values are chosen from the graphs' points of extreme change and intensity minima and maxima observed in the spectra (see Appendix B).

The fact that the observed data shows nearly identical discrepancies between the experimental and predicted absorbances indicates that the spectrometer's data is reliable and suitable for more research.

Table 9: Wavelength, Transmittance, Experimental and Expected values of Absorbance for Blue Dye

Wavelength (±0.5 nm)	424.4	497.7	578.6	658.2	564.4	503.9	452.8	4.545
$T_{experimental}$ (±0.005)	7.980	63.501	5.814	3.447	8.122	58.584	10.931	68.510
$A_{expected}$ (±0.005)	1.098	0.197	1.285	1.461	1.090	0.232	0.962	0.163
$A_{experimental}$ (±0.005)	1.098	0.197	1.263	1.462	1.091	0.233	0.961	0.164

Table 10: Wavelength, Transmittance, Experimental and Expected values of Absorbance for Green Dye

Wavelength (±0.5 nm)	424.3	638.1	519.6	506.6	564.4	491.5	482.3	519.4
$T_{experimental}$ (±0.005)	2.539	3.200	3.573	48.494	15.517	13.244	6.848	59.258
$A_{expected}$ (±0.005)	1.595	1.494	1.485	0.314	0.809	0.877	1.164	0.277
$A_{experimental}$ (±0.005)	1.595	1.495	1.447	0.314	0.809	0.879	1.165	0.227

Table 11: Wavelength, Transmittance, Experimental and Expected values of Absorbance for Red Dye

Wavelength (±0.5 nm)	433.5	697.4	590.00	700.3	590.1	427.8	703.6	394.1
$T_{experimental}$ (±0.005)	0.284	8.442	4.714	8.495	4.714	0.549	39.899	23.920
$A_{expected}$ (±0.005)	2.546	1.073	1.326	1.070	1.327	2.260	0.399	0.629
$A_{experimental}$ (±0.005)	2.557	1.074	1.327	1.071	1.327	2.268	0.398	0.621

Spectrum produced by the PASCO Spectroscopy software describes how each solution absorbs/-transmits colors from the original white light. Spectrums produced in part 5 for the greendy e, makes it evident that the liquid is absorbing the most of the white light's red and blue wavelengths, resulting in the production of only the color green. Similarly for the blue dye sample, the spectra demonstrates that the liquid sample is absorbing the least of the white light's blue wavelength region, producing the color blue. These thicker lines in the graphs indicate the amount of light being absorbed by the sample solution at each wavelength. This also applies to the red dye sample.

On the other hand, the graphs' thinner lines show the sample solutions' transmittance, which is the inverse of absorbance. The color of the transmitted light is implied by the wavelength area with the maximum intensity in each graph.

3.6 Fluorescence

The absorption edge, which is the wavelength at which absorption jumps significantly, from the spectra at 405-nm excitation and 500-nm is obtained from Figure 13 and 14. The wavelength of the absorption edge is used to calculate the band gap energy of the yellow dye cuvette using Equation 8 and summarized in Table 12.

$$E(eV) = \frac{1240}{\lambda} \tag{8}$$

Table 12: Absorption edge and band gap energy

	Absorption edge (nm)	Band gap energy (eV)
405nm	476.9 ± 0.05	2.599 ± 0.0003
500nm	488.0 ± 0.05	2.541 ± 0.0003

Generally, conventional semiconductors have an acceptable band gap of approximately 0.6 to 1.6 eV. This range can be considered as the literature threshold for the semi-conductors. However the value compute for the band gap of the yellow-dye at both 405nm and 500 nm excitation suggest that it is well beyond this threshold. As such, yellow dye does possess such properties. It's possible that the yellow dye doesn't have the perfect characteristics needed for effective use in conventional photovoltaic technologies, based on the calculated band gap energy value. Nevertheless, more investigation further research can be done to investigate possible uses for the yellow dye, such as in specialized photovoltaic systems or other domains that could profit from materials having broad band gaps and band gaps that are close to semiconductor level.

4 Discussion

4.1 Error Analysis

Through the use of residual analysis, the accuracy of the spectrometry experiment was carefully examined. This revealed a calibration that was generally successful while also identifying particular locations where an error might have been introduced. The calibration process revealed the largest source of such errors, as the residuals were higher than the predicted uncertainty range. This implies that there might have been a systematic divergence (or deviation) in the measured values due to the calibration's possible incomplete accounting for all factors.

The spectrometer's age and state should also be taken into account. Variance in the results may arise from a gradual reduction in sensitivity caused by instrumental drift with time and usage. This may not be immediately apparent. Without comprehensive records of the device's usage history and maintenance routine, this is especially difficult to quantify. Future research might benefit from having a regular calibration schedule in place, tracking the spectrometer's performance over time, and taking into account usage data from the past when interpreting results in order to reduce this kind of inaccuracy. These steps would guarantee that the results are as precise as possible given the constraints of the technology utilized and assist preserve the integrity of the data that was gathered.

Additionally it is important to note that there were impurities present in the cuvettes containing the dyes (or coloured water solutions), which can possibly impact the accuracy of the absorbance of particular colours. For example, during the experiment, it was observed that cuvette containing the red dye contained some residues of impurities that were suspended at the bottom of the cuvette. These impurities can impact the amount of light transmitted/absorbed which can also influence the readings.

Additionally the cuvettes utilized were old, and have been utilized in multiple practical demonstrations which means that the surface of the cuvettes are imperfect and slightly scratched. This too can impact the accuracy of the absorbance/transmittance readings which explain the difference in the expected and measured values of absorbance. Nevertheless these errors were inevitable in the experiment due to experimental constraints.

4.2 Result Discussion

While acknowledging the constraints and potential sources of error that could have affected result accuracy, the review of the experiment's data highlighted the overall success in reaching the lab objectives. One important source of mistake that was found was calibration, which may have caused differences between measured and predicted values. In order to reduce these disparities, the debate emphasized the importance of exact calibration methodologies and suggested that future investigations employ stricter calibration protocols. The ramifications of the data were also discussed, providing insights into the behavior of the gases and dyes under investigation. Thanks to careful experimental setup and diligent data collection techniques, most experiment facets showed a considerable alignment between expected and measured values.

5 Conclusion

Ultimately, the experiment yielded in a thorough grasp of spectroscopy and photophysics principles and demonstration of quantitatively understanding the behaviour of quantum states and spectra, shedding light on gas and dye behaviors across diverse experimental settings. Exploring the origins of (both random and systematic) errors and further enhancements and improvements in calibration techniques could enhance future experiments within this domain, facilitating more accurate and insightful findings.

References

[1] PHY294, *Quantum States and Spectra of Gases*, 2024.

[2] PHY294, *Error Analysis for 2nd Year Experimental Physics*, 2024.

6 Appendix A

6.1 Section 3.1

Sample Calculation:

$$\begin{aligned} E &= \frac{(6.626 \cdot 10^{-34} Js) \cdot (2.998 \cdot 10^{8} \frac{m}{s})}{404.7 \cdot 10^{-9} m} \\ &= 4.909 \cdot 10^{-19} J \\ &= 4.909 \cdot 10^{-19} J \cdot \frac{1eV}{1.60218 \cdot 10^{-19} J} \\ &= 3.064 eV \end{aligned} \tag{9}$$

Sample Uncertainty Calculation:

$$\sqrt{(-(\frac{\frac{10^{-34-9} \cdot 1.60218}{10000000000000000000}}{(1.60218 \cdot 10^{-9-19} \cdot 581.6)^2} \cdot 1986495797.992) \cdot \delta m_1)^2} \tag{10}$$

6.2 Section 3.2.2

Sample Calculation:

$$\begin{aligned} \lambda &= \frac{(6.626 \cdot 10^{-34} Js) \cdot (2.998 \cdot 10^{8} \frac{m}{s})}{(1.890 eV) \cdot \frac{1.60218 \cdot 10^{-}19 J}{1eV}} \\ &= 6.560 m = 656.0 nm \end{aligned} \tag{11}$$

Sample Uncertainty Calculation:

$$\begin{gathered}\frac{6.626 \cdot 10^{-34} \cdot 2.998 \cdot 10^{8}}{m_1 \cdot 10^{-9} \cdot 1.60218 \cdot 10^{-19}} \\ \sqrt{(-(\frac{\frac{10^{-34-9} \cdot 1.60218}{10000000000000000000}}{(1.60218 \cdot 10^{-9-19} \cdot m_1)^2} \cdot 1986474800) \cdot \delta m_1)^2}\end{gathered} \tag{12}$$

6.3 Section 3.3

Sample calculation for E_n using λ_r:

$$E_n = \Delta E + E_m = \frac{hc}{58.43 \cdot 10^{-9}} \cdot \frac{1eV}{1.60218 \cdot 10^{-19} J} - 24.57 = -3.350eV \tag{13}$$

7 Appendix B

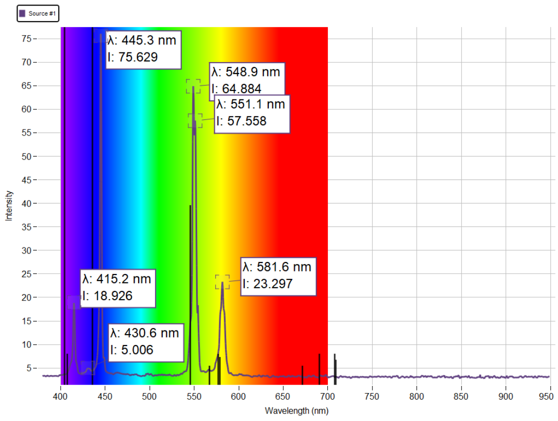


Figure 6: Mercury

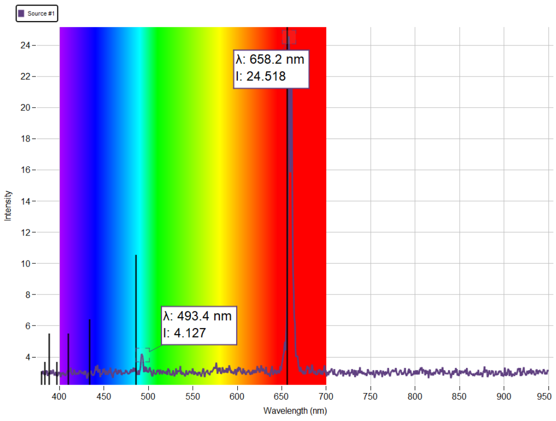


Figure 7: Hydrogen

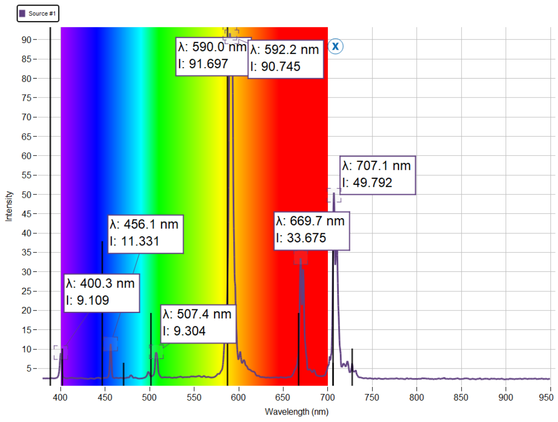


Figure 8: Helium

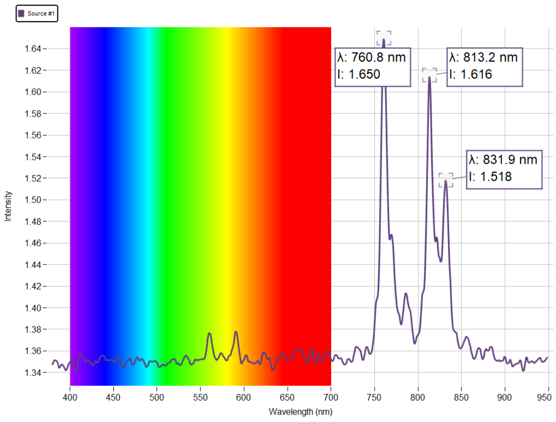


Figure 9: Unknown

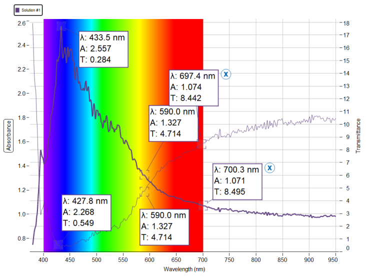


Figure 10: Section 3.5 Red

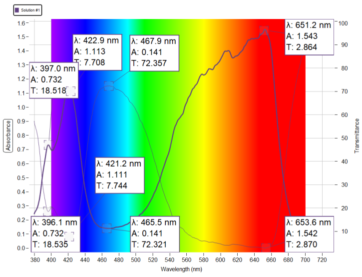


Figure 11: Section 3.5 Blue

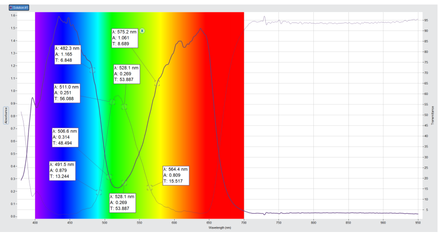


Figure 12: Section 3.5 Green

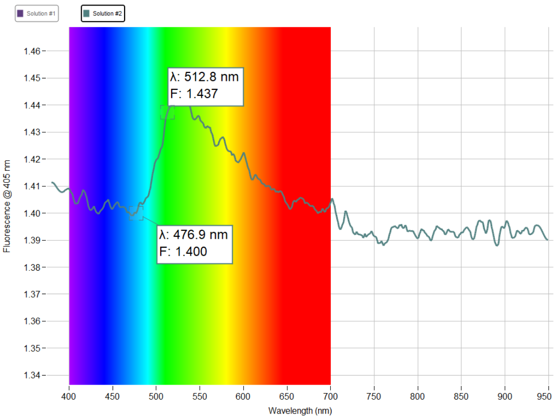


Figure 13: Section 3.6 405nm

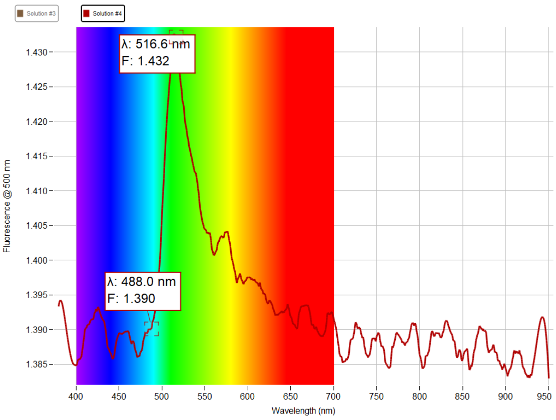


Figure 14: Section 3.6 500nm