Lab 18

Emission Spectra and Atomic Transitions

Continuing Objectives

1. Be able to identify sources of experimental uncertainty in a measurement.

2. Know how to determine experimental uncertainties (multiple measurements of the same quantity, propagation of errors, etc.).

3. Be able to write an experimental result (including correct number of significant digits, uncertainty, units).

4. Be able to make careful measurements to ensure reproducible results.

5. Know how to keep a clear and organized record, including an introduction (with purpose of lab and appropriate laws or equations), apparatus sketch, table of raw data and calculated quantities, and a good conclusion or summary.

Introduction

How can we know that the predictions of quantum mechanics are correct? One way is the analysis of light emitted or absorbed by matter, be it atoms, molecules, or solids. This enterprise is known as *spectroscopy*. In this lab you will use a digital spectrometer that contains an experimental tool of classical physics (similar to the diffraction grating that you saw in the `Interference` lab), a reflection grating, to observe the light emitted by different elements. You will then quantitatively analyze the emission line spectrum from hydrogen atoms. You will find that the emitted wavelengths of these various elements can only be explained using quantum mechanics. At the conclusion of the lab you will have determined a value for the ground-state energy of a hydrogen atom and learned how the spectra you observed are dictated by the rules of quantum mechanics.

Before getting started, some words of caution:

- **The voltage applied to the gas discharge tubes can be dangerous. The high-voltage supplies are designed so that you don't have access to the high-voltage electrodes when the tubes are in place, so never turn on the high voltage without a tube inserted.**
- **Always turn OFF the voltage when removing or inserting tubes. It is also good practice to turn off the voltage when you are not making observations.**
- **Be sure to insert the tubes right-way up. You will know that you are inserting them correctly if the top of the plastic part of the tube has a small dip in the center. This dip should be UP when inserting the tubes.**
- **The gas discharge tubes become very hot after high voltage is applied. Please use caution when handling the tubes and ONLY touch them on the plastic parts.**

The Spectrometer

Figure 18.1 shows the internal diagram for the specific spectrometer we will use today, a Red Tide USB Spectrometer. A fiber optic cable collects the light from an object and connects at point 1, and the light enters the spectrometer at point 2. At point 4 the light is collimated by a mirror towards point 5. At point 5 is a reflection grating. At point 6 a mirror focuses and directs the light towards point 7, which is a light detector that converts the intensity of each color of light of corresponding wavelength to an electronic signal so that the spectrum can be viewed digitally via the Logger *Pro* interface.

We will now practice using the spectrometer and Logger *Pro* interface to observe the spectra of various different elements.

1. Open the Logger *Pro* file "Spectro.cmbl" found in the `PHYS 211_212/212Lab/Emission Spectra` folder on the desktop of your lab PC. You should see an empty graph with "Intensity (rel)" on the y-axis and "Wavelength (nm)" on the x-axis. Make sure the spectrometer is connected to the lab PC by checking the green "Collect" button is active.
2. On your lab bench, you will also find a set of glass and plastic gas discharge tubes and a holder for the tubes that will supply a current to excite and heat

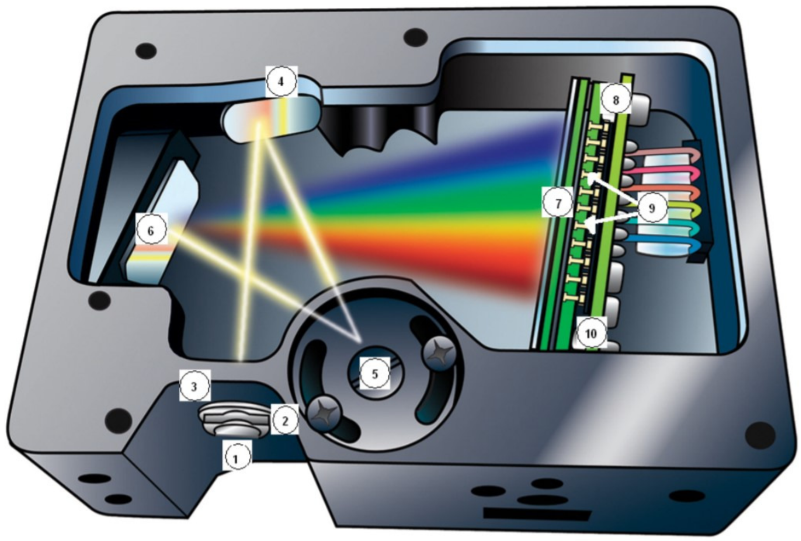


Figure 18.1: Internal diagram of the Red Tide USB spectrometer. [Manual of Red Tide USB650 Spectrometer]

the gas inside. These thin tubes are filled with different, low density gases as indicated by the label on the back of each tube. **Please review the safety precautions stated earlier in the lab before proceeding.**

3. Select the hydrogen tube and place it in the holder, making sure the holder is OFF when you put the tube in. Once it is set, turn on the power using the switch on the back of the holder. What happens? (You might have to give it a second or two for anything to change.) Note your observations and thoughts on what is happening to the hydrogen gas on an atomic and sub-atomic level.

STOP

Discuss your observations and reasoning with your instructor or TA.

4. On your lab bench, there should be a diffraction grating from the `Interference` lab. Look at the hydrogen gas tube through this diffraction grating. Note your observations and sketch what you see. Remember that inside the spectrometer you will use in this lab there is a similar grating. Make a prediction about the graph we expect the spectrometer to produce from the hydrogen gas light.

5. Now find the other side of the fiber optic cable attached to the spectrometer;

this will be the "eye" that observes the light from the gas discharge tubes. Press "Collect" on the Logger *Pro* interface and point the cable end at the discharge tube. Click "Stop" to pause data collection when you feel you have a good emission line spectrum data set. (Think about what you saw using the diffraction grating - how many peaks do you expect?) Compare what you saw with the diffraction grating and what Logger *Pro* displays.

STOP Show your data to your instructor or TA.

6. Now that we have observed the emission line spectrum of hydrogen, let's look at a different element with a different atomic structure: helium. Turn OFF the holder and replace the hydrogen tube with the helium tube. Repeat your observations with the diffraction grating and spectrometer as you did for hydrogen. What do you notice about the spectra of the two elements?

   You should notice that the emission line spectra of hydrogen and helium are noticeably different. If you were to observe another element in the same way, that too would have a different spectrum. In fact, every element has its own unique emission line spectrum. This is a consequence of sub-atomic structure and quantum mechanics.

   Since electrons are permitted to have only certain specific energies when bound to an atom, as dictated by quantum theory, the photons that are produced to make an emission line spectrum will have specific wavelengths. The energies of the emitted photons correspond to differences in energies between energy levels in the atoms. The wavelengths of the emitted photons therefore tell you something about the very small-scale structure of the emitting atoms. You will work more with this in the next part of this lab by analyzing the hydrogen spectrum using quantum theory.

7. Write a mini-conclusion on your observations and findings so far.

Measuring Wavelengths of Hydrogen Emission

Now you can experimentally determine the wavelengths of the emission lines of hydrogen and use this data to determine the hydrogen atom ground state energy, E_1.

1. Put the hydrogen discharge tube back into the holder and obtain a good emission line spectrum on Logger *Pro* . Make sure the emission line peaks are not saturated (they should be sharp at the top, not flat).

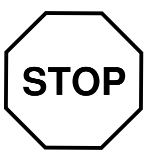
2. Determine the wavelengths of the four emission line peaks from the Logger *Pro* graph and record these values in an Excel sheet. You can get the value of these peaks by rolling the mouse over any peak of the emission line graph and reading the first number in parenthesis at the bottom left of the graph.

3. To determine the uncertainty for your spectral line wavelength measurement, we will make use of the "Full Width at Half Maximum" or **FWHM**. This is a common parameter used in spectral data analysis and is defined as the width of a peak at half the maximum y-axis value of that peak. The FWHM is related to the uncertainty (σ) in the peak value by the following relationship:

$$FWHM = 2\sqrt{2\ln 2}\,\sigma \qquad . \tag{18.1}$$

   Determine uncertainties for your wavelength data by using Excel to calculate them in a new column.
   Hints: To zoom in on a specific peak click and drag over the peak and then click on the + icon on the top menu and adjust the y-range to start at 0 by clicking on the lowest y-tick label. To switch back to the full range use the `A` icon of the menue on the top. To get the width between two points on Logger *Pro* , click and drag between the two points on the graph. The width $\Delta\lambda$ will be listed at the bottom left of the graph.
   Remember to note how you calculated the uncertainty of your wavelength values in your lab notebook.

4. Report your measured wavelengths for each of the four lines.



Show your reported values to your instructor or TA.

Theory

Quantum theory predicts that the energies associated with the various quantum states of hydrogen can be expressed as

$$E_n = \frac{E_1}{n^2} \tag{18.2}$$

where E_1 is the ground state energy, and n is a positive integer. If we take E_1 to be negative, then higher ns correspond to higher (i.e., less negative) energies. As n approaches infinity, the energy of the quantum state goes to zero.

When an excited H-atom makes a transition from a higher energy state n_{upper} to a lower energy state n_{lower} ($n_{\text{lower}} < n_{\text{upper}}$), the atom loses energy. By conservation of energy, this energy shows up as a photon with energy

$$\begin{aligned} E_{\text{photon}} = \Delta E &= E_{\text{upper}} - E_{\text{lower}} \\ &= E_1 \left(\frac{1}{n_{\text{upper}}^2} - \frac{1}{n_{\text{lower}}^2} \right) \end{aligned} \tag{18.3}$$

Since

$$E_{\text{photon}} = \frac{hc}{\lambda}, \tag{18.4}$$

together with Eq. (18.3) we obtain

$$E_{\text{photon}} = \frac{hc}{\lambda} = \Delta E = E_1 \left(\frac{1}{n_{\text{upper}}^2} - \frac{1}{n_{\text{lower}}^2} \right) \tag{18.5}$$

For the spectral lines you are looking at, $n_{\text{lower}} = 2$ and $n_{\text{upper}} = 3$, 4, 5, or 6. The emission lines of hydrogen that lie within the visible range of the electromagnetic spectrum make up what is known as the Balmer series.

Analysis

1. Calculate the energy in eV of the photons emitted at each wavelength you recorded from the Logger *Pro* graph using Eq. (18.4). You can find the value for hc on the inside of the lab manual's back cover, or on the Fundamental Constants PDF on the PHYS 212 Lab Info page.

2. Associate the appropriate pair of numbers $(n_{\text{lower}}, n_{\text{upper}}) = (2,3)$, $(2,4)$, $(2,5)$, or $(2,6)$ with each wavelength. Determine $\Delta E/E_1$ for each of these transitions using Eq. (18.3), that means determine $\left(\frac{1}{n_{\text{upper}}^2} - \frac{1}{n_{\text{lower}}^2} \right)$.

3. Solve Eq. (18.5) for E_1. Use your E_{photon}-values to determine E_1, the ground state energy of the hydrogen atom, for each wavelength. Find the average value of E_1 from your data and its uncertainty (the standard deviation of the mean). Report this result in your lab notebook in the correct form with proper units.

4. You have just measured one of the fundamental properties of the hydrogen atom with your own observations and quantum theory. Compare your calculated value for E_1 including uncertainty to the accepted value for the ground state energy of the hydrogen atom: $E_{\text{ground}} = -13.606$ eV. Is your result consistent?

5. Write a mini-conclusion for this part of the lab. Report your results for the wavelengths of the hydrogen emission lines including uncertainty. Report your calculated value for the ground state energy of the hydrogen atom, E_1, with its uncertainty and whether or not it was consistent with the accepted value.