PHYS-201   LAB-03

Bohr's Model and Emission Spectra of Hydrogen and Helium

1. Objective

The objective of this experiment is to study the emission spectrum of hydrogen and to understand its origin in terms of the energy levels of the hydrogen atom and the energy changes which are associated with electronic transitions from one level to another as described by Bohr's model. We will also study the spectrum of He gas by modeling singly ionized helium atom as a hydrogenic system.

2. Theory: Bohr's Model

The planetary model for the hydrogen atom that explained the emission spectrum of the hydrogen gas was proposed by Bohr, who made the following assumptions.

[1] The electron in a hydrogen atom travels around the nucleus in a circular orbit.

[2] Only some orbits with certain energies are allowed. In other words, the orbits are quantized. This is an *ad hoc* hypothesis and is equivalent to asserting that the angular momentum of the electron is quantized – it is an integral multiple of some constant. More precisely, the angular momentum in the nth orbit, $L_n = mv_n r_n = nh/2\pi$, where m is the mass of the electron, v_n and r_n are , respectively, the speed and the radius of the electron in the nth orbit, and h is the Planck's constant. In the Bohr model, n is also known as the principal quantum number.

[3] Light is absorbed when an electron jumps to a higher energy orbit and emitted when an electron falls into a lower energy orbit. The energy of the light emitted or absorbed equals the difference between the energies of the orbits involved in the transition.

 Notice that an electron in a circular orbit is accelerating and, according to classical mechanics, will lose energy by radiation and would spiral down and eventually fall into the nucleus. Bohr knew this but, since atoms are stable, he also recognized that it was

impossible to explain the spectrum of the hydrogen atom within the limits of classical physics. Thus he made an intellectually daring hypothesis that one or more of the principles from classical physics might not be valid on the atomic scale.

2.1 Derivation of Energy Levels of the Hydrogen Atom.

For an electron in a circular orbit around a proton, application of Newton's second law,

$F = ma$, where F is the Coulomb force between the nucleus (proton) and the electron, gives

$$\frac{ke^2}{r_n^2} = \frac{mv_n^2}{r_n}, \text{ where } k = 1/4\pi\varepsilon_0 = 8.988x10^9 \text{ N.m}^2/C^2.$$

Combining it with the quantization condition, $L_n = mv_n r_n = nh/2\pi$, one can write

$$r_n = \varepsilon_0 n^2 h^2/\pi m e^2, \qquad \qquad ...[1]$$

$$v_n = e^2/2\varepsilon_0 nh \qquad \qquad ...[2]$$

for $n = 1$, $r_1 = a_0 = \varepsilon_0 h^2/\pi m e^2 = 5.29x10^{-11}m$ is known as the Bohr radius. Thus eq.[1] can be expressed as $r_1 = n^2 a_0$.

The total energy of the electron, $E_n = K_n + U_n$, where $K_n = 1/2 mv_n^2$ and

$$U_n = -\frac{ke^2}{r_n} = -\frac{me^4}{4\varepsilon_0^2 n^2 h^2} \text{ are, respectively, the kinetic and potential energy terms.}$$

Thus, $E_n = K_n + U_n = -\dfrac{me^4}{8\varepsilon_0^2 n^2 h^2} = -\dfrac{ke^2}{2a_0}\left(\dfrac{1}{n^2}\right) \qquad ...[3]$

[Note: Eq. [3] is sometimes also expressed as $E_n = -13.6eV/n^2$]

The energy released when an electron jumps from state n_2 to n_1 is given by

$$\Delta E = h\nu = hc/\lambda = \frac{me^4}{8\varepsilon_0^2 h^2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \qquad ...[4]$$

Or $\quad \dfrac{1}{\lambda} = R\left(\dfrac{1}{n_1^2} - \dfrac{1}{n_2^2}\right) \qquad \qquad ...[5]$

Where $R = \dfrac{me^4}{8\varepsilon_0^2 h^3 c} = 1.0973732 \times 10^7\, m^{-1}$ is known as the Rydberg constant.

The group of transitions for which $n_1=1$ and $n_2 = 2,3,4,5\ldots$ is known as the Lyman series. Similarly, transitions for which $n_1=2$ and $n_2 = 3,4,5,6\ldots$ form the Balmer series and Paschen series contains emission lines for which $n_1=3$ and $n_2 = 4,5,6,7\ldots$ For hydrogen, emission lines in the Lyman series fall in the ultraviolet region of the light(electromagnetic) spectrum, while the Paschen series lines lie in the infrared region. In the present experiment we will be interested in investigating spectral lines of the Balmer series.
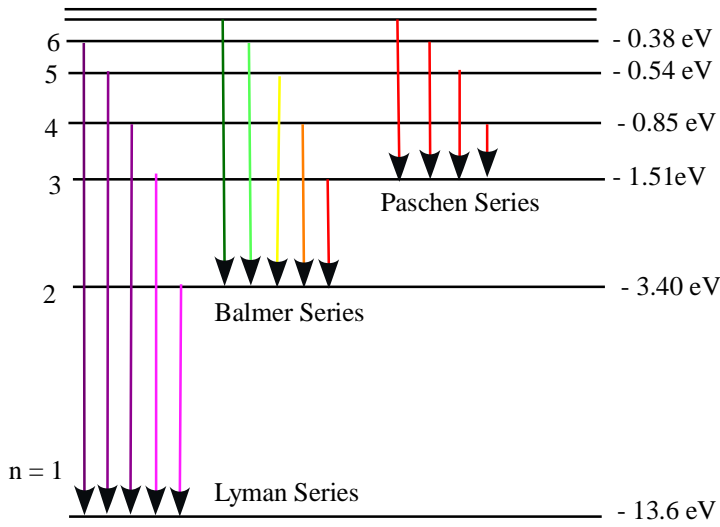
ENERGY LEVEL DIAGRAM FOR HYDROGEN

2.2 Energy Levels of the Helium Atom.

A singly ionized He atom can be treated in the same Bohr framework as an *H* atom simply by assigning a charge *Z = 2e* to the *He* nucleus. This amounts to rewriting the energy level expression for helium as

$E_n = 4*[-13.6eV/n^2] = -54.4eV/n^2$ ...[6]

and rewriting eq.*[5]* as

$$\frac{1}{\lambda} = 4R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \qquad ...[7]$$

It should be emphasized that eq.*[6]* models a singly ionized helium atom and not a neutral helium atom. Therefore, every line that you observe in the helium spectrum can not be described by eq. *[7]*. According to *[6]*, the energy required to remove the second electron from the He$^+$ is 54.4*eV* as experimentally observed. To remove the first electron from the neutral helium atom is 24.6*eV* and this is certainly not consistent with eq.*[6]* Other simplifying assumptions of Bohr model will also cause differences between the the theoretically predicted and the experimentally observed and spectra. These assumptions are that all orbits are circular and that the nucleus remains stationary as the electron revolves around it. To accurately predict the observed He spectra, a more sophisticated quantum mechanical model is required.

3. Experimental Details

3.1 Apparatus

One hydrogen and one helium discharge tube with a discharge tube power supply

An Ocean Optics spectrometer (Model USB4000-UV-VIS) with associated fiber cable(s).

3.2 General Precautions.

Once operating, the discharge tubes can get very hot and should not be touched. Once the power supply has been shut off, wait at least 10 minutes to remove the tube from the power supply sockets. Use a paper towel to hold the tube.

The optical fiber cable should not be bent sharply as this can cause cracks in the fiber. Never touch the free end of the fiber cable with your fingers as this can leave residue on the fiber tip or scratch the fiber tip surface and degrade the performance of the fiber cable. When not in use, cover the cable tip with the protective cap.

3.3 Experimental Procedure

A. Introduction

This is an easy experiment to carry out. The gas (H or He) atoms are excited by creating an electrical discharge between two electrodes surrounded by gas in a glass tube. The emitted light is passed through a spectrometer. There are two essential parts of a spectrometer: a diffraction grating and an array of detectors as shown

SCHEMATIC DIAGRAM OF A SPECTROMETER
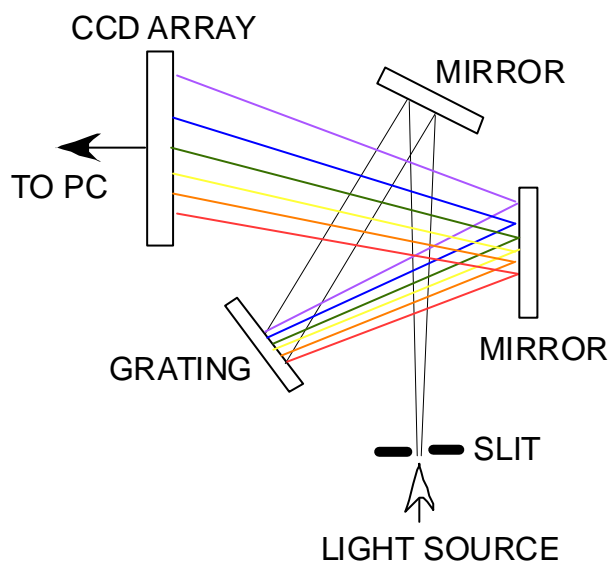
below. A diffraction grating separates the different wavelengths in a beam of light with longer wavelengths being diffracted at a larger angle than the shorter wavelengths. You can view this effect by holding a DVD nearly horizontally at arms length in a well lit room (see picture below). A DVD has 625 *lines*/*mm* and is an excellent example of a diffraction grating. Once the light from the discharge tube is diffracted, it is allowed to fall on a closely spaced array of detectors. Since the angle of diffraction depends on the wavelength of the light, the position of the detectors in the array can be calibrated in terms of the wavelengths of the input beam.

B. Experimental Setup and Data Collection

Plug in the power supply but leave the power supply switch in the 'off' position. Insert the

hydrogen tube between the spring loaded sockets. Turn the power supply switch to 'on' position.

Plug in the spectrometer to one of the USB ports of your computer. Insert one end of the fiber cable into the input port of the spectrometer. Click on the SpectraSuite icon to launch the spectrum analysis program. Remove the protective cap from the other end of the fiber cable, and position it about two inches away from the discharge tube using the clamp provided. You should be able to see some peaks on the screen. On the top left hand side of the screen adjust the acquisition time to 50msec. (Note: increasing the acquisition time increases the spectral intensity while decreasing it lowers the intensity). By adjusting the position of the input fiber end with respect to the discharge tube you should be able to obtain a spectrum such that its highest peak intensity is between 50,000 to 60,000 counts. For hydrogen, these peaks are the emission lines of the Balmer series.

C. Data Analysis

C.1 How to record the spectrum.

After you have the desired spectrum, simply click on the [💾] icon in the toolbar above the graph. A window will pop up to continue the saving procedure.
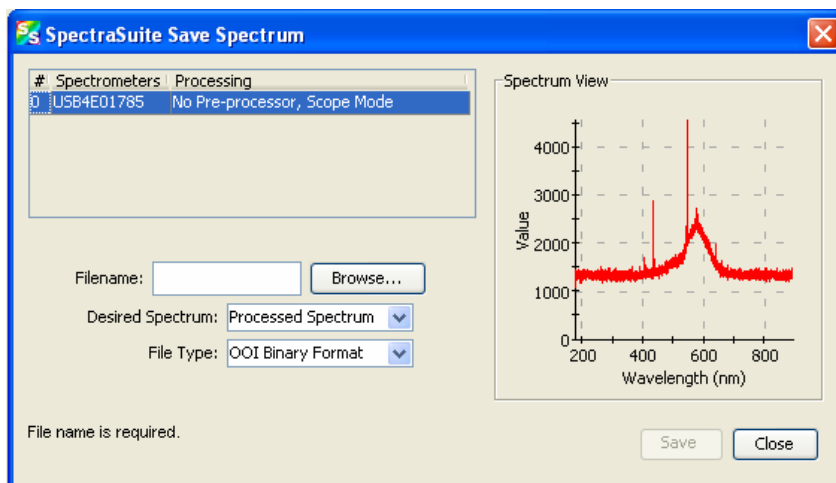

Click on "Browse" and specify where you would like to save the data and give the graph a file name. You will not see the *save* button yet. Click on the device that recorded the data to finally save the file. (In this case, there is only one device in the window, as shown below)
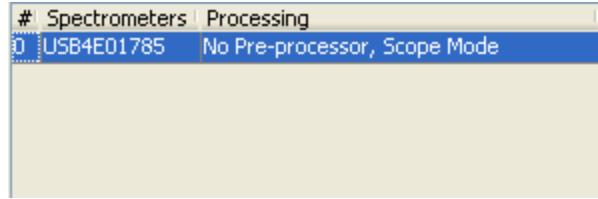
C.2 Reading the spectral wavelengths.

In SpectraSuite, go to [File > Open > Load Processed Spectrum] to open the graph (intensity vs. wavelength plot) (Look for the file you have saved in the specified directory and double-click to open.

On the left, you will see a new item in Data Sources with the name of your graph.
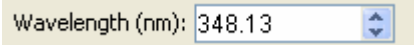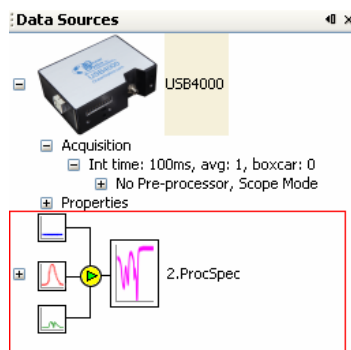

Right-click on the new item (your graph) and click on "Show as overlay". When a window pops up, click on *load*. Another window will pop up asking where to save the file.
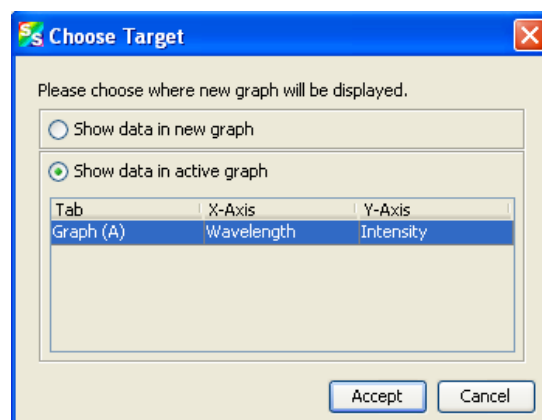
Check "Show data in new graph" and click on *Accept*. (If you want to view multiple spectra on a single graph to compare, then check "Show data in active graph" and click

on a graph to overlay different plots. [**At this point TURN THE POWER SUPPLY OFF.** This will allow the tube to cool down and allow you to replace the hydrogen tube with a helium discharge tube for the next part of the experiment. Wait at least ten minutes after the power supply is switched off before you attempt to remove the hydrogen tube from mounting sockets.]

To read the data, you can click anywhere on the graph and a vertical cursor line should appear. To accurately read the data, read the window at the bottom of the plot. To adjust the position of the cursor line, simply click on the UP arrow or DOWN arrow to move to a different spectral peak. Enter the wavelengths of the various peaks in the Data Table-I.

Replace the hydrogen tube with a helium tube, and repeat the above steps to the emission spectrum of helium. Enter the wavelength data in the appropriate table.