Lab 9: Hydrogen Gas and Quantum Dots Spectra

(Experiments partially based on CENCO Quantum Dots Experiment Guide)

In this experiment we will obtain the emission spectra of hydrogen and identify the corresponding electron transitions. We will also obtain the spectra of quantum dots in solutions. The spectra will allow us to determine the sizes of the quantum dots and find their relationship with emitted wavelengths.

Equipment

Power supply
Red Tide spectrometer (specs and information in the Appendix)
Hydrogen lamp with power supply (Model STPS-1)
Quantum Dots (four vials in the casing; Cenco)
Light Emitting Diode (LED)
Breadboard; two 1000-Ω resistors
6 alligator clips; ammeter; voltmeter

Theory

The electromagnetic spectrum of the hydrogen atom can be explained by Bohr's theory. According to the theory, a photon is emitted from the hydrogen atom when the electron makes a transition from a higher (n_i) to a lower (n_f) energy level. The photon's wavelength is related to the energy difference between the two levels, ΔE, as:

$$\lambda = \frac{hc}{\Delta E}$$

where c is the speed of light in vacuum and h Planck's constant.

From the previous equation, ΔE can be obtained directly in electronvolts (eV) from:

$$\Delta E \text{ (in eV)} = \frac{1240 \text{ nm} \cdot \text{eV}}{\lambda \text{ (in nm)}}$$

The relationship between ΔE and the quantum numbers n_i and n_f is:

$$\Delta E = E_i - E_f = (-13.6 \text{ eV}) \cdot \left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right)$$

In this lab, we will observe the visible (Balmer) spectral lines, for which $n_f = 2$.

Procedure

Part I - Hydrogen Spectrum

Caution: The power supply provides high voltage of 5000 V, which is a lethal voltage. Do not touch the socket with the power on. When replacing the spectrum tube, remove the AC plug from the wall socket and place the power switch to the OFF position. The tube life is extended if operation is cyclic (30 seconds ON and 30 seconds OFF, etc.).

1. With the power cord disconnected from an electrical outlet, set up the hydrogen lamp on the high voltage power supply. Connect the Red Tide spectrometer to a PC USB port using the appropriate cable. Start the Overture software.
2. Turn off the lights in the room (first check if this is all right with everyone). Turn on the high voltage power supply and collect the light emitted by the lamp by positioning the spectrometer's entrance next to it or using a fiber optic cable, if available.
3. Optimize the time exposure and number of scans to obtain a clear spectrum with well-defined peaks. The left mouse button allows you to display the wavelength and intensity of a peak. In Table 1, record the peak positions (wavelengths). Calculate the energy difference, ΔE, between the two states that gives rise to each line and identify the initial state (n_i) for each line. Notice that $n_f = 2$.

Table 1

λ (nm)	ΔE (eV)	$n_i \rightarrow n_f$
		$\rightarrow 2$
		$\rightarrow 2$
		$\rightarrow 2$

Part II - Quantum Dots Spectra

When a photon is absorbed by a semiconductor an electron from the valence band can transition into the conduction band. As a result, a positively charged hole is left in the valence band. The electron and the hole are attracted by Coulomb force and form a bound state. This bound state, called an exciton, is an electrically neutral quasiparticle. Fig. 1 illustrates an exciton, the valence and conduction bands of a semiconductor and the band gap between them.

The exciton is a hydrogen-like particle, where the nucleus is substituted by the positively charged hole and the electron's mass by the reduced mass. Due to the screening by other electrons and the reduced mass, the exciton's binding energy is much smaller than that of a hydrogen atom.

When a semiconductor is smaller than the Bohr radius of its exciton, the exciton exhibits quantum confinement effects, much like a particle in a box in which the energy states depend inversely on the size of the box (L):

$$E_{box} = \frac{\hbar^2\pi^2}{2mL^2}$$

By changing the size of the box, the energy states of the particle can be varied, and so can the wavelengths that correspond to transitions between these energy states.

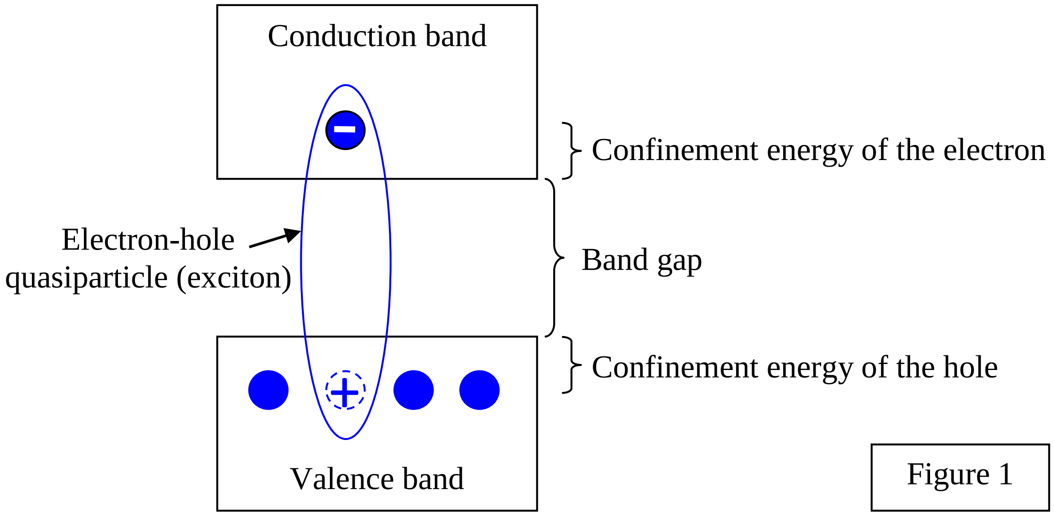


Figure 1

Quantum dots are semiconductors whose excitons are confined in three dimensions. The exciton moves freely inside the quantum dot, but an infinite potential at the boundaries keeps it from leaving it. A quantum dot is a more complicated system than an idealized particle in an infinite potential box. Thus, some adjustments have to be made to the particle-in-a-box model as applied to quantum dots. First, the dot is a three dimensional sphere and not a box. Second, there are actually two types of particles in each quantum dot: electrons and holes. Finally, the “box” is not empty but filled with a semiconductor.

When the electron recombines with the hole, a photon is emitted. As can be seen from Fig. 1, the energy of the emitted photon, in the simplified model, can be represented as:

$$E = E_g + \frac{\hbar^2\pi^2}{2m_e r^2} + \frac{\hbar^2\pi^2}{2m_h r^2} \qquad \text{Eq. 1}$$

where:

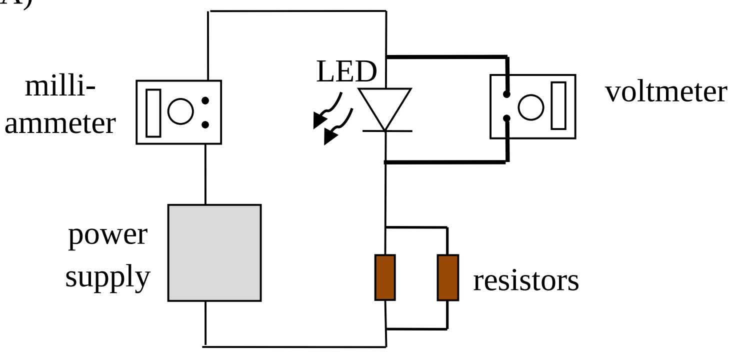
- E_g = band gap energy
- r = radius of the quantum dot
- m_e = electron mass
- m_h = hole mass

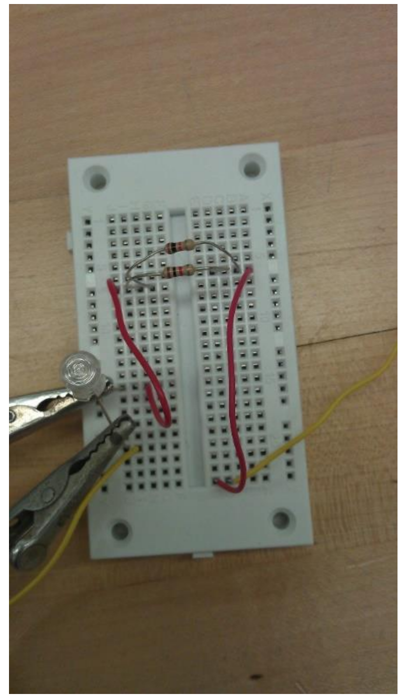
In the derivation of Eq. 1, we used de Broglie relationship $p = h/\lambda$ and $r = \lambda/2$ for the ground energy state. In this experiment the following values will be used: $E_g = 2.15\text{x}10^{-19}$ J, $m_e = 7.29\text{x}10^{-32}$ kg and $m_h = 5.47\text{x}10^{-31}$ kg.

As can be seen from Eq. 1, the energy of the emitted photon is inversely proportional to the square of the radius of the dot. Therefore, quantum dots of the same material but different sizes will emit light of different colors. Larger dots will emit lower energy ("redder") light, while smaller dots will emit higher energy ("bluer") light.

The samples we will use are quantum dots placed in solutions and sealed in four vials. The diameters of the quantum dots vary between 1 – 10 nm. To obtain emitted spectra of the quantum dots we will excite the samples with a light emitting diode (LED). Different vials will emit different wavelengths, which will depend on the size of the quantum dots in the solutions. Measurements of the emitted wavelengths with a spectrometer allow us to find the actual size of the quantum dots. The experimental setup is shown in Fig. 2.

A)





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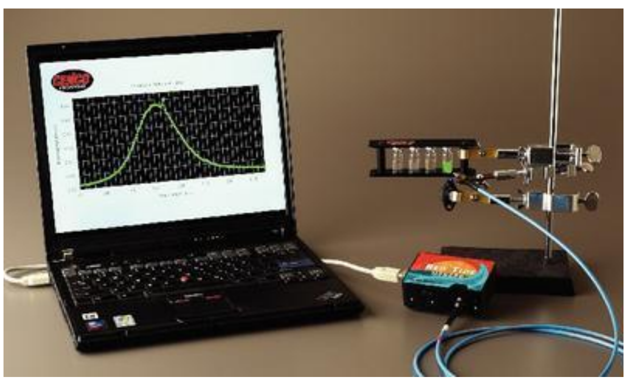

C)

Figure 2

Procedure

4. Build the circuit shown in Fig. 2 for the LED on a breadboard (described in Appendix I). The voltage supplied to the LED should **not exceed 4 V** and the current through it should be limited to **less than 20 mA**. The long lead of the LED is the anode (+). Use the resistance of about 500 Ω, obtained by connecting two 1000 Ω resistors in parallel. To protect the LED add an ammeter in series with the rest of the circuit and a voltmeter in parallel with the LED.

5. Set the aluminum rack with the vials in the provided holder. Set up the spectrometer probe so it is held stationary and pointed at the solution in a vial (see Fig. 2 and Fig. 3).

6. The light source (LED) needs to be illuminating a vial, while being perpendicular to the spectrometer probe (see Fig. 3). Turn off the lights in the room (first check if this is all right with everyone else).

7. Vary the voltage of the power supply until the current through the LED is about 15 mA with the voltage across the LED not exceeding 4 V.

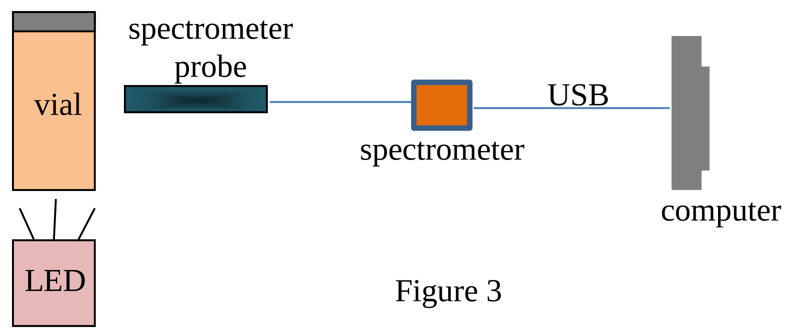

Figure 3

8. Optimize the setup, time exposure and number of scans to obtain a clear spectrum with a well-defined peak.

9. In Table 2, record the peak wavelength. For broad peaks it is sometimes better to find the wavelengths of the half-maximum intensity points and average the wavelengths to obtain the peak wavelength. Use Eq. 1 to calculate the radius of the quantum dots in the vial.

Table 2

Vial	λ (nm)	r (nm) (from Eq. 1)

10. Repeat this procedure for the other vials.

11. Plot the emitted wavelength versus the quantum dot radius. What relationship do you observe? Does this agree with Eq. 1?

Appendix I
Breadboard

A breadboard (Fig. A1) is made of a plastic board with metal clips positioned under the perforations. A breadboard is used to make temporary electric circuits without soldering.

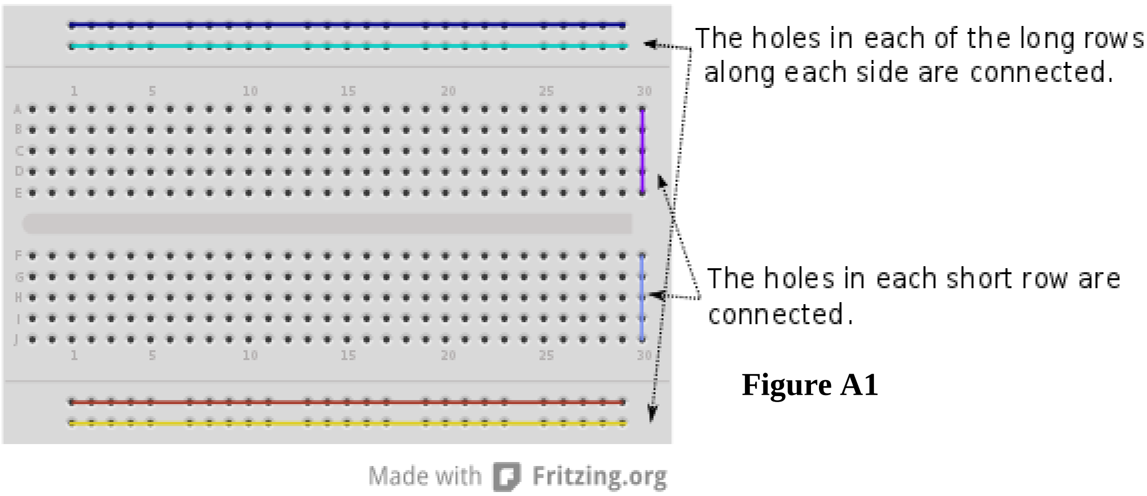

Figure A1

The top and bottom rows that run along the longer sides of the breadboard are used to deliver power to the electronic components. Usually the + column is marked in red, while the column for ground is marked in blue or black. The other holes are linked vertically in groups of five with no links to other holes. Short (jump) wires are used to make connections between different circuit components.

Appendix II
Red Tide Spectrometer

The Ocean Optics Red Tide spectrometer is a compact unit that contains a grating, a CCD camera and associated optics. The 25 μm slit allows for direct input of the light signal. As an alternative a fiber optic can be easily coupled to the unit for signal collection. An EEPROM memory chip in the spectrometer contains wavelength calibration coefficients, linearity coefficients, and a serial number unique to each individual spectrometer. The Spectra Site software (Overture) application reads these values directly from the spectrometer, enabling the ability to “hot-swap” spectrometers between computers without entering the spectrometer coefficients manually on each computer

The inner workings of the spectrometer are shown in Fig. A2. The labels are:

1. SMA 905 Connector Secures the input fiber to the spectrometer. Light from the input fiber enters the optical bench through this connector.
2. Slit: A dark piece of material containing a rectangular aperture, which is mounted directly behind the SMA Connector. The size of the aperture (from 5 μm to 200 μm) regulates the amount of light that enters the optical bench and controls spectral resolution. You can also use the Red Tide without a Slit. In this configuration, the diameter of the fiber connected to the Red Tide determines the size of the entrance aperture.

3. Filter: Restricts optical radiation to pre-determined wavelength regions. Light passes through the Filter before entering the optical bench. Both bandpass and longpass filters are available to restrict radiation to certain wavelength regions.

Figure A2

1. Collimating Mirror Focuses light entering the optical bench towards the Grating of the spectrometer. Light enters the spectrometer, passes through the SMA Connector, Slit, and Filter, and then reflects off the Collimating Mirror onto the Grating.
2. Grating Diffracts light from the Collimating Mirror and directs the diffracted light onto the Focusing Mirror.

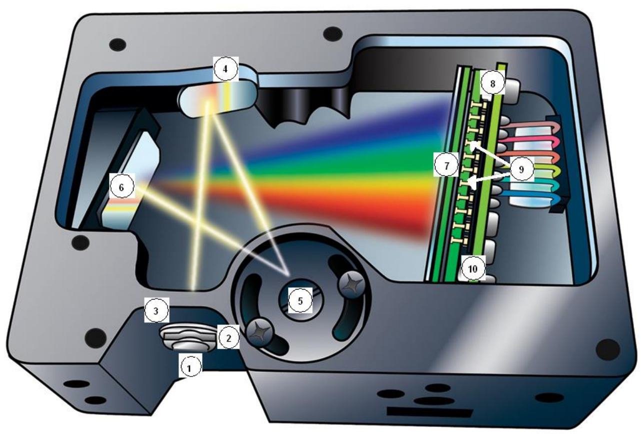

Figure A3

3. Focusing Mirror. Receives light reflected from the Grating and focuses first-order spectra onto the detector plane.
4. L4 Detector Collection Lens An optional component that attaches to the Detector to increase light-collection efficiency. It focuses light from a tall slit onto the shorter Detector elements. The L4 Detector Collection Lens should be used with large diameter slits or in applications with low light levels. It also improves efficiency by reducing the effects of stray light.
5. Detector (UV or VIS) Collects the light received from the Focusing Mirror or L4 Detector Collection Lens and converts the optical signal to a digital signal. Each pixel on the Detector responds to the wavelength of light that strikes it, creating a digital response. The spectrometer then transmits the digital signal to the SpectraSuite application.