Quantum Dotting the "i" of Inquiry: A Guided Inquiry Approach to Teaching Nanotechnology

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When illuminating four "mystery" vials of nanoparticle solution with a 405-nm light emitting diode (LED), four distinct colors related to the peak wavelength of fluorescent emission can be observed.[1] This phenomenon perplexes high school physics students and leads to the subsequent exploratory question, "Why are the four vials emitting a different color light if they all contain the same material and are illuminated with the same light source?" That question gives students the opportunity to collect and analyze data, which leads to the development of the inherent scientific concept that the color of the emitted light depends on the size of the material (quantum dot) suspended in solution.

In recent years, the emerging cross-curricular field of nanotechnology has led to the realization that material properties change dramatically because quantum effects arise from the confinement of electrons and "holes" in the material (a hole is the absence of an electron, i.e., the hole behaves as though it were a positively charged particle).[2] This quantum effect has been observed in semiconductor nanostructures due to confinement in one dimension (quantum wells), two dimensions (quantum wires), and three dimensions (quantum dots).[3] The effect is particularly strong in quantum dots where smaller dots will have a different emission color than larger dots when they are illuminated. In other words, size matters—the same material will emit different colors of light when there is a change in dimension at the nanometer scale.[2] The following guided inquiry[4] lesson provides high school physics students the opportunity to experience cutting-edge nanotechnology in the classroom by exploring, developing, and applying the inherent scientific concept.

Exploration

In order to answer the exploratory question, the following materials are required: an Ocean Optics spectrometer (Item# 1752-65) and related software (Item# 1752-67), a 400-µm optical fiber (Item# 1752-64), a CENCO Quantum Particle in a Box kit (Item# 1751-18), a 405-nm LED (Item# 1755-43), and a laptop computer (a laptop computer is recommended but a personal computer would be adequate), as shown in Fig. 1. The total cost, not including a computer, to implement the investigation is approximately $1500. The majority of the cost is attributed to the spectrometer ($999). Several options are available to help alleviate the proposed financial encumbrance.[5,6]

Students collect experimental data by illuminating each of the vials of quantum dot solution with the 405-nm LED. As each vial is illuminated, the fluorescent emission spectrum is collected by a fiber-coupled portable spectrometer in conjunction with a laptop computer. Students save the emission spectrum for each solution, note the color of emission, and determine the peak emission wavelength. Typical quantum dot fluorescent emission spectra for the experiment are displayed in Fig. 2.

Students realize that the emitted color corresponds to a particular wavelength; however, students lack essential information required to answer their exploratory question. Prior to student involvement in the lesson, the radius of each quantum dot material suspended in solution was characterized by transmission electron microscopy (TEM) at the Samuel Roberts Noble Electron Microscopy Laboratory at the University of Oklahoma (see Table I). A micrograph for each quantum dot

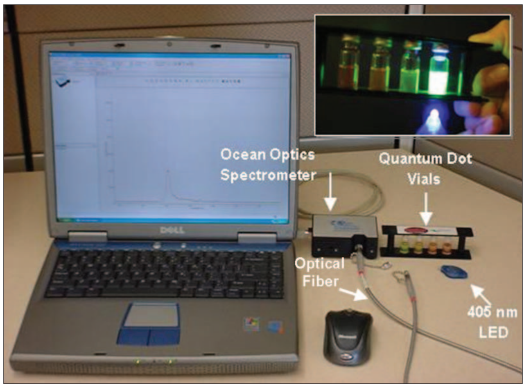

Fig. 1. Experimental setup: Ocean Optics UV-Vis portable spectrometer, optical fiber, quantum dots, 405-nm LED, and a laptop computer.

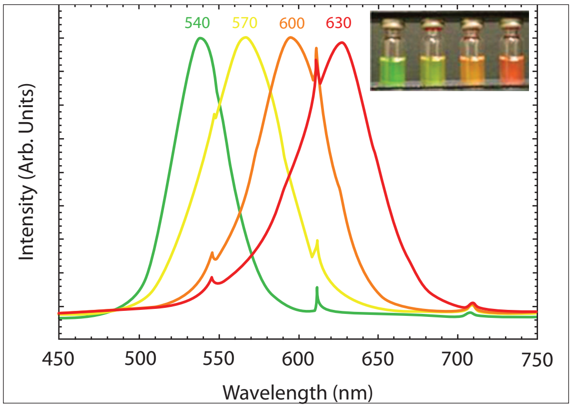

Fig. 2. Specific emission wavelength for each quantum dot vial of solution.

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Table I. TEM data for each quantum dot in solution.

Vial Color	Radius (nm)
Green	~2.3
Yellow	~2.5
Orange	~2.7
Red	~2.9

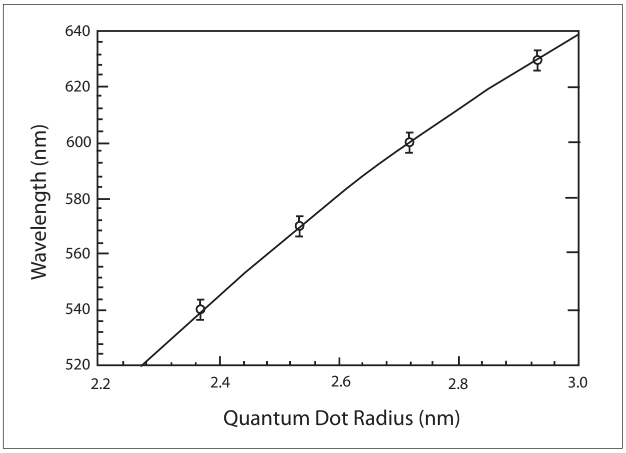

Fig. 3. Graphical representation showing the relationship between the emission wavelength and quantum dot radius.

was distributed to students so they could measure the radius of each quantum dot and gain an appreciation of the dimensionality.[7] Students later visit the TEM laboratory, where the micrographs were developed, to enhance further their understanding of the nanoscale.

Given only the collected data, the radii of the quantum dots (as determined from the micrographs), the material parameter constants, and Eq. (1), students are asked to calculate the energy and emission wavelength of the quantum dots that experimentally showed red fluorescent emission.

$$E = \frac{\hbar^2 n^2 \pi^2}{2m_\mathrm{e} R^2} + \frac{\hbar^2 n^2 \pi^2}{2m_\mathrm{h} R^2} + E_\mathrm{g} = \frac{hc}{\lambda}. \tag{1}$$

An example calculation was given for the quantum dot solution emitting in the green portion of the electromagnetic spectrum where $\hbar$ is Planck's constant (1.05459×10^{-34} J·s), n is the quantized energy level (1), m_e is the effective mass of an electron (7.29×10^{-32} kg), m_h is the effective mass of a hole (5.47×10^{-31} kg), R is the radius of the quantum dot (2.36×10^{-9} nm), E_g is the energy gap of the quantum dot material (2.15×10^{-19} J), hc = 1240 eV·nm, and λ is the wavelength (nm). Students are asked to find the percent error between the previously measured wavelengths versus the calculated wavelengths and comment on these differences, if any.

Concept development

Data collection up to this point in the lesson was driven by the question, "Why are the four vials emitting a different color light if they all contain the same material and are illuminated with the same light source?" Students are motivated to analyze the emission spectrum for each solution, the color of emission, the peak emission wavelength, the calculated emission wavelengths and energies, and the TEM micrographs. They are asked to construct a graphical representation (as seen in Fig. 3) of the emission wavelength (and corresponding color) versus quantum dot radius. (Due to the nature of the equipment and materials used in this investigation, significant error bars on the vertical scale would be smaller than the symbols.) By having students graph these data, they are able to observe a visual representation of the collected data and to answer their exploratory question. Students excitedly state that the reason why each vial emitted a different color was dependent on the size of the quantum dot suspended in each solution. In other words, as the size of the quantum dot increases, the emission energy decreases, thus resulting in a longer emission wavelength. Students realize that a variety of colors can be emitted from a single material simply by changing the size of the quantum dot.

Concept application

After students determine that the color of the emitted light is dependent on the radius of the quantum dot, they are then challenged to determine the actual semiconductor quantum dot material solution contained within the four vials. Four different sets of material parameters for common quantum dots (i.e. GaAs, CdTe, InAs, and InP) are provided in Table II for comparison to the already extracted experimental data and the calculated data.

A Microsoft Excel spreadsheet was created in order to establish which quantum dot material (out of the four choices given in Table II) is present in the four vials.[8] This task is completed by comparative analysis of the experimental data collected with the calculated values for each material. Students recognize that InP (indium phosphide) closely matches the experimental data, leading to the conclusion that a specific size of InP quantum dot is present in each vial.

Students are asked to apply the conceptual understanding developed about the fluorescent emission of quantum dots by determining the radius of dot required to design a ZnO (zinc oxide) light emitter at a peak emission wavelength of 350 nm. While this may seem like quite an endeavor, it is actually very straightforward using the tool set developed by performing the previous portions of the lesson. The material parameters required to design a ZnO light emitter are provided (see Table III). Using the previously developed Microsoft Excel spreadsheet, only a very slight modification is required to perform an immediate calculation over a large range of quantum dot radii. It is revealed that within a matter of minutes, a 2.8-nm radius ZnO quantum dot would give the desired emission wavelength of 350 nm.

Students' interest in quantum dots and nanotechnology may be piqued because of their experiences with this lesson.

Table II. Material parameters provided to determine the quantum dot material. E_g is the band gap of the material in electron volts (eV), m_e/m_0 is the effective mass of the electron with respect to the free electron mass, and m_h/m_0 is the effective mass of the hole with respect to the free electron mass. It should be noted that the band gap (E_g), electron effective mass (m_e), and the hole effective mass (m_h) are dually material- and temperature-dependent.

Material	E_g (eV)	m_e/m_0	m_h/m_0
GaAs	1.520	0.067	0.539
CdTe	1.475	0.096	0.599
InAs	0.354	0.027	0.400
InP	1.340	0.080	0.600

As a culminating activity, students are permitted to access the Internet to determine other applications of quantum dots in the scientific and social community. A few real-world applications include white LED fabrication, optical switches, logic gates, biosensing equipment, and other medical devices. When students make the realization that the scientific content they are constructing in the physics classroom has diverse applications beyond traditional schooling, they will gain an appreciation for advancements in science and technology and its relevance in society. It is because of these interdisciplinary influences that nanotechnology should be included in high school physics curricula where there are a dearth of modern physics investigations and associated real-world applications.

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7. Please contact the lead author for a copy of the TEM micrographs.
8. Please visit eip.k20center.org/summer-engineering-academy/2008-sea for the teacher version and student version of the Excel spreadsheet.

Table III. Material parameters provided to design a ZnO quantum dot light emitter at 350 nm.

ZnO Parameters and Constants	
n	1
π	3.14
E_g	3.28 eV
m_e/m_0	0.24
m_h/m_0	0.78
$\hbar$	1.054×10^{-34} J·s
m_0	9.11×10^{-31} kg
Radius (nm)	**TBD**

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