Quantum Dots
Rochester Institute of Technology

PHYS-316 Advanced Lab*

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Goals

In this experiment, you will shine an near-UV LED on a vial of semiconductor nano-crystals (quantum dots), and observe the flourescence spectrum. The incident photons excite electrons to the conduction band, leaving behind a hole in the valence band, and are constrained spatially to the volume of the dot in a quantum well. The electron-hole pair de-excites by emitting a photon and returning to the ground state. The photon energy released is related to the energy of the 'exciton' (an electron plus hole pair) in the quantum dot. You will calculate the range of diameters of each of the quantum dot samples based on the range of wavelengths emitted by each sample.

Introduction and Setup

In Modern Physics lecture, you study the problem of a particle trapped in an infinite potential well. This may have seemed like a pretty unrealistic problem, but a quantum dot is a realization of that model.

A quantum dot is a nano-scale bit of material. If an electron is 'free' within this material, it is not completely free (as it would be in a bulk chunk of metal, for example). In particular, the electron cannot travel beyond the edge of the material; it cannot fall out into the surrounding medium. The electron is caught in a potential well that is effectively infinite at the edges of the dot.

Theory

Please complete the PreLab, where you will consider and construct several theoretical models describing the energy of the exciton, and the wavelength of the emitted photon.

Experiment

You will collect quantitative data that describes the distribution of wavelengths emitted from the excited quantum dots in solution. This will be a collective effort from everyone in the

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lab section, along with your lab instructor. Each student will share the data and analyze it as an independent effort but with group input and instructor guidance.

There are multiple vials, each containing quantum dots of a narrow range of sizes. Learn to operate (or refresh yourself) the OceanOptics digital spectrometer. Illuminate a vial with the near-UV LED and observe the emitted light by eye. Use the software to collect a raw data file and a screenshot for each of the different vials.

Qualitatively, which of the vials is showing the highest energy emission? Which of the vials has the smallest particles? What physical principal allows you to predict these answers without taking any data?

Analysis

You must download the JupyterNotebook from myCourses, called Lab1_QuantumDots_Spring2215 provided for this course. You may choose to develop your JupyterNotebook remotely on the provided JupyterHub server, or edit the code locally on your machine (either as a Jupyter-Notebook or as a Python script). This will allow you to work on your experiments from any internet-connected machine, but you should also regularly back up copies of all of your work! See details on myCourses.

For your analysis of our Cadmium Selenide (CdSe) quantum dots, please use a bulk band gap energy of $E_g = 1.74$ eV, and effective masses $m_e^* = 0.13m_e$ and $m_h^* = 0.45m_e$ for CdSe.

Emission Spectral Shape Model

Explore two different peak-like models built into Lmfit (Gaussian and Skewed Voigt) and vary your fit ranges until you find a good-quality fit. Justify the quality of your fit by interpreting the value of χ^2 and the corresponding p-value. Show that the model you settle on is superior to the other(s) you try. Does one model fit all of the samples well? This is preferable to simply picking the model that best fits each sample separately, as it would seem to give some physical justification for your choice of model.

Summarize (in table form) the peak wavelength (with uncertainty) and a sensible measure of the variation in wavelengths (with uncertainty) for each sample. Note that the fit parameter 'center' in your best-fit model may not represent the peak wavelength!

Do all samples have the same overall photon rate (intensity of emission)? If not, what factor(s) do you believe could be causing differences?

The variation of emitted wavelengths is almost exclusively due to the variations in dot size due to the manufacturing process. If the manufacturer could produce identical quantum dots, these emitted spectra would be very narrow, spread out slightly by the resolution of the detector equipment.

Dot Size Model

Plot the peak wavelength (with appropriate error bars) versus the dot diameter given by the manufacturer. Define five functions (your physical models for the relationship between emitted photon wavelength and dot size) based on your PreLab work that we will compare to your plotted data using chi-square. Note that this is not a fitting procedure - you are simply comparing model predictions to your data. Demonstrate by χ^2 comparison that your chosen model is superior to the others.

Using a sensible measure for the variation in wavelengths, determine the variation in dot diameters for each sample. Do all samples have the same variation?

Follow-up Questions

1. What other factor(s), in addition to size variations, might cause the variation in emitted wavelengths?

2. Determine if we could ever observe $n = 2$ to $n = 0$ photon emissions in this experiment, given our measured LED wavelength. Show your calculations!

Bonus*

Notice from the manufacturer's specs that the peak wavelength in the absorption spectrum (from a driving LED) is shifted with respect to the peak emission wavelength. In other words, the initial exciton state is higher in energy, and loses a small energy by other interactions in the quantum dot prior to recombination. This is known as Stokes shift. Do a literature search and talk to your instructor to see if you can quantify the dependence of the Stokes shift on the size of the quantum dots. You may find a plot digitizer such as https://apps.automeris.io/wpd/ to be useful.

*Throughout this course, bonus credit can be earned by exploring aspects of each experiment more deeply than is indicated by the lab handout, and/or exploring related issues that are not mentioned in the handout. You can always discuss such things with your lab instructor, provided that you have fully completed the required aspects of the experiment to the best of your ability. By the end of the semester, you will apply this level of exploration to one experiment you have completed, to refine your understanding of the physics and analysis.