

Student Worksheet or Guide

Student Activity Sheet - Worksheet with answers

Quantum Dots Real-World Particles in a Box

Essential Question:

Will all colors of LEDs cause quantum dots to fluoresce? If not, why not?

Objectives: By the end of this activity you should be able to explain:

1. There is a positive linear relation between the energy and frequency of light.
2. Energy is gained and lost by atoms only in certain, discrete amounts.
3. The emission or absorption of light is associated with the transitions of electrons between energy levels.
4. Only certain energy levels and associated electron arrangements are allowed in atoms.

Background Reading:

Quantum mechanics considers matter both as particles and waves. As waves, light can diffract and interfere, and the wave behavior of electrons describes the probability of locating an electron at a particular location. But the emission of electrons when electromagnetic radiation falls on an object, called the **photoelectric effect**, shows that light also behaves like a particle.

The **electromagnetic wave theory** cannot explain the photoelectric effect because according to electromagnetic wave theory, an electric field accelerates and ejects electrons from matter and the strength of the electric field is related to the intensity of the radiation (not to the radiation's frequency). Thus, it follows that electrons in matter would need to absorb energy from a dim light source for a very long time before they gain enough energy to be ejected. But experimentation shows that this does not happen.

The electromagnetic spectrum is a group of radiations. **Radiation** is energy that travels and spreads out as it travels. Different types of radiation include radio, microwave, infrared, visible light, ultraviolet, x-rays, and gamma-rays. Electromagnetic radiation can be described in terms of a stream of photons, which are massless particles each traveling with wave-like properties and moving at the speed of light. Each **photon** contains a certain amount or **quanta** of energy, and all electromagnetic radiation consists of these photons or quanta. The only difference between the various types of electromagnetic radiation is the amount of energy found in the photons.

The electromagnetic spectrum can be expressed in terms of energy, wavelength, or frequency. Each is related to the others in precise mathematical ways. Below is a chart that shows how these are related.

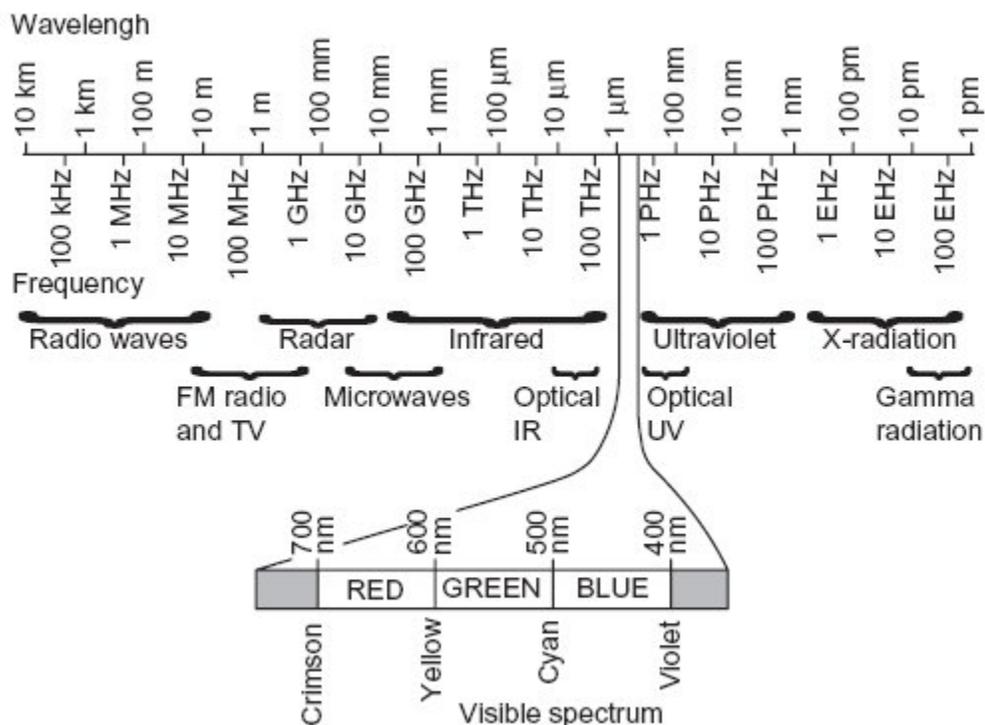


Chart 1

http://content.answers.com/main/content/img/oxford/Oxford_Photo/0198662718.electromagnetic-spectrum.2.jpg

From chart 1 you will notice that the longer the wavelength, the lower the frequency and the lower the energy. So, the shorter the wavelength, the higher the frequency and the greater energy of the photons.

The **visible spectrum** is the portion of the electromagnetic spectrum that is visible to the human eye. A typical human eye will respond to wavelengths from about 380 nm to 750 nm. Colors that can be produced by visible light of a single wavelength are referred to as the pure spectral colors. Although the spectrum is continuous, with no clear boundaries between one color and the next, the ranges shown in chart 2 may be used as an approximation.

The colors of the visible light spectrum^[1]

color	wavelength interval	frequency interval
red	~ 700–635 nm	~ 430–480 THz
orange	~ 635–590 nm	~ 480–510 THz
yellow	~ 590–560 nm	~ 510–540 THz
green	~ 560–490 nm	~ 540–610 THz
blue	~ 490–450 nm	~ 610–670 THz
violet	~ 450–400 nm	~ 670–750 THz

Chart 2

So what causes the photoelectric effect? Electrons are arranged in atoms in regions around the nucleus of only certain allowable energy states called energy levels. The lowest allowable energy

state of an atom is called its **ground state**. In the ground state, the atom does not radiate energy. When energy is added from an outside source (such as visible light radiation), the electron moves to a higher energy level, and can even be emitted from the material if the energy is large enough..

The amount of radiation energy that must be absorbed to cause electrons to move energy levels is called the **threshold frequency**. No matter how intense, radiation with a frequency below the threshold frequency will not cause the ejection of electrons from energy levels. When the incident radiation's frequency is equal to or greater than the threshold frequency, increasing the intensity of the radiation causes an increase in the flow of photoelectrons.

According to Einstein, light and other forms of electromagnetic radiation consist of discrete, quantized bundles of energy, each of which was later called a photon. The energy of a photon depends on its **frequency**. Energy of a photon $E = hf$. The energy of a photon is equal to the product of Planck's constant and the frequency of the photon. E is a unit of energy commonly expressed in electron Volts eV . One electron volt is the energy of an electron accelerated across a potential difference of 1 V. A quantum is the minimum amount of energy that can be gained or lost by an atom.

When the atom is in an excited state due to an absorption of energy, the electron can drop from the higher energy level to a lower energy level. As a result of this transition, the atom emits a photon corresponding to the energy difference between the two levels. Because an atom's electron can move only from one allowable orbit to another, they can emit or absorb only certain amounts of energy. This energy can be given off as photons of light. Since only a certain amount of energy is given off, only a certain frequency of light and therefore color is radiated. This emission of light from a substance after it has absorbed energy is called **fluorescence**.

Quantum dots are small crystals 10-50 times the diameter of an atom which are small semiconductor particles that can contain one electron and one "hole" (the absence of an electron). These electrons and holes act like small particles which can move freely inside the semiconductor, but cannot get out (just like a particle in a box). By carefully observing quantum dots with different sizes, we can see the effect of changing the size of the box on the energy levels of the system.

Quantum dots are **nanoscale** semiconductors whose conducting characteristics are closely related to the size and shape of the individual crystal. Generally, the smaller the size of the crystal, the larger the band gap. The **band gap** is an energy range in a solid where no electron state exists. The band gap generally refers to the energy difference between the top of the valence band and the bottom of the conduction band which is found in insulators and semiconductors. It is the amount of energy required to free an outer shell electron from its orbit about the nucleus to become a charge carrier. As the nanocrystal size decreases, the energy of the first excited state increases, and concurrently, more energy is released when the crystal returns to its resting state. For example, in fluorescent dye applications, this equates to higher frequencies of light emitted after excitation of the dot as the crystal size grows smaller, resulting in a color shift from red to blue in the light emitted. The main advantage in using quantum dots is that because of the high level of control possible over the size of the crystals produced, it is possible to have very precise control over the conductive properties of the material

A variety of applications have been demonstrated for quantum dots and other nanocrystals, including tunable light emitting diodes (LEDs), photovoltaics, single-electron transistors, and fluorescent tags for biological imaging applications.

A **Light Emitting Diode (LED)** is a diode which only allows current (electricity) to flow in one direction and not the other. As electricity is flowing through, they also produce light. In the simplest terms, an LED is made with two different kinds of semiconductor material: one type that has too many free electrons roaming around inside, and another that doesn't have enough. When an electron from the material with too many electrons gets pushed across a thin barrier and gives up its energy in the other material, a photon or particle of light is produced. The color of light depends on a number of factors. A small bandgap that fairly weak electrons can cross gives you infrared or red light, while a large bandgap that needs really strong electron gives you light that has a blue or violet color.

Light Emitting Diodes (LED)

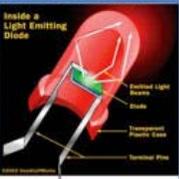
the creation and detection of light by the movement of electrons



What are LED's?
LEDs are tiny light bulbs that are illuminated by the movement of electrons in a semiconductor.

A diode is the simplest semiconductor. A semiconductor is a material with a varying ability to conduct electrical current.

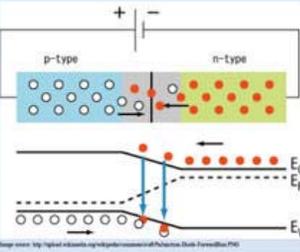
Most semiconductors are made of a poor conductor that has had impurities added to it by a process called doping.



LEDs work because of p-n junction
A semiconductor with extra electrons is called N-type material, since it has extra negatively charged particles.

A semiconductor with extra holes is called P-type material, since it effectively has extra positively-charged particles.

A diode is made of a N-type material bonded to a section of P-type material with electrodes on each end. At the junction free electrons from the N-type material fill holes from the P-type which creates an insulating layer in the middle called the depletion zone.



Source: <http://light-emitting-diodes.org/wiki/p-n-junction> (Public Domain)

Uses of LEDs

- Form numbers on digital clocks
- Transmit information from remote controls
- Jumbo television screens
- Illuminate traffic lights

LEDs can produce or detect light
To get rid of depletion zone you have to get electron moving from the N-type area to the P-type area and the holes moving in the reverse direction.

One way for the electrons to move is to gain enough energy from photons of light to move across the depletion zone. In this case the LED would be able to detect the presence of light.



Source: <http://www.solarpanel.com/technology/solar-panel-diagram>



Another way for the electrons to move would be for the negative end of a battery to be hooked up to the N-type layer and the positive end hooked up to the P-type layer. The free electrons in the N-type material are repelled by the negative electrode and drawn to the positive electrode. In this case the charge creates light.





Procedure:

Part 1

Question: Will a blue LED cause quantum dots to fluoresce?

Write below your answer to the question above.

1. Take out the set of LEDs. Turn LED power on and determine the light that is emitted. List the color on the data chart 1 that follows. Continue with each of the LEDs.
2. Referring to the chart 2 in the Background Section, what would the wavelength of these colors be? Place this information in Data chart 1.

Data Table 1

LED color	Approximate wavelength of light emitted

3. Which one of these would have the least energy? How would you know?

4. Which one of these colors would have the most energy? How would you know?

5. Look at the vials of Cenco quantum dots. These are Indium phosphide quantum dots in solution. The only difference between the vials is that the dots are different sizes.
6. Do they all appear to be the same color? If not, list the colors that they appear.

7. Turn the power on for the blue LED and place under each vial. Write your observations:

8. What causes the containers to fluoresce? _____
Do they all behave the same way? _____
9. List which color(s) of quantum dots fluoresce. _____

Part 2

Question: Will other colors of LEDs cause the vials to fluoresce?

Write below your answer to the question above. _____

1. Take each of the LEDs listed on the chart below and illuminate the bottom of each of the vials. Put an X in the column of each quantum dot that fluoresces.

LED Color	Green Quantum Dot	Yellow Quantum Dot	Orange Quantum Dot	Red Quantum Dot
Yellow				
Orange				
Blue				

White				
Green				

2. Did all colors of LEDs caused the vials to glow? _____
3. What do you think makes the difference? _____

Part 3

What do you think will happen if you use a red or a violet LED to illuminate the vials?
Write your answer to the question above. _____

1. Test your idea and write your conclusions below:

Analysis

1. Based on what you read in the background section, what is the relationship between the color of light and the energy of the radiation?

2. Based on what you read in the background section, what is the relationship between the color of radiated light and the size of the band gap?

3. Based on what you read in the background section, what is the relationship between the size of the quantum dot and the color of radiated light? _____

Conclusion

1. Do your results in data charts 1 and 2 support your answers in questions 1-2 above? Why or why not? _____

2. Based on the data that was collected and your answers to the questions above make a guess as to the size of the particles in the vials List the vial colors from the largest particles to the smallest particles. _____

Resources:

To learn more about nanotechnology and quantum dots, here are some web sites with educational resources:

- www.nnin.org
- www.mirc.gatech.edu/education.php
- www.nano.gov
- http://www.nanooze.org/english/pdfs/nanoozeissue_08.pdf
- http://en.wikipedia.org/wiki/Quantum_dot