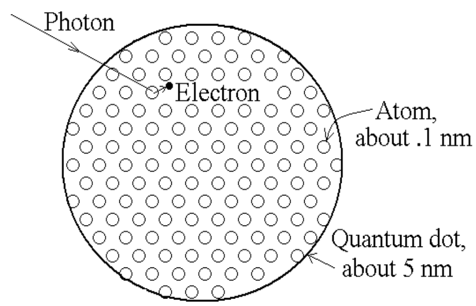
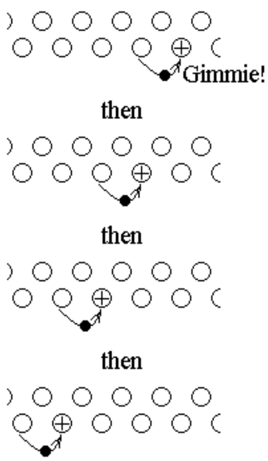
Experiment 8: A Particle in a Box

You will observe the wavelength of light emitted from a system similar to a square well, and compare it to what is predicted by theory. You have four glass vials. In them, suspended in liquid, are many "quantum dots;" spherical semiconductor particles just a few nanometers across. Each vial contains dots of a different size. An electron is free to move in such a dot but can go no further than the surface, just as an electron in the one dimensional well from class is free to move between x = 0 and x = L but no further. The energy levels in the dot are described by essentially the same formula as for the one dimensional well, and this is used to calculate a theoretical wavelength for each vial. To observe the wavelengths, the dots are excited by light from an LED. As they re-emit the energy, the light is observed with a spectroscope.

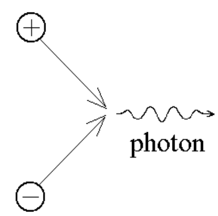
<u>Details:</u>

Light hits an atom, knocking an electron off it. Once out of the atom, the electron is free to move around the material, like a conduction electron in a metal. →





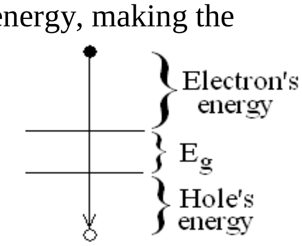
← The positive ion which the electron left behind steals a neighbor's electron to become neutral again. The neighbor atom then steals another electron from another neighbor. As this process continues, the overall effect is that a unit of positive charge is also free to move around in the material. For all practical purposes, it can be thought of as a positive particle called a "hole." So, we actually have two "particles in a box;" an electron and a hole. When they eventually wander into each other, they recombine and give off light. →



While moving around in the dot, these particles are confined to the region $0 \le r \le R$ just as a particle in a one dimensional well is confined to $0 \le x \le L$. Thinking of the electron and hole as waves, only certain wavelengths can have a node at the center and surface of the dot, so only certain energies are possible. Therefore, there are energy levels.

Energy gap: E_g is the difference between the most energy a hole can have and the least an electron can have, in a large piece of the material. The gap exists because a certain minimum energy (from the incoming light) is needed to knock the electron free and create the hole.

In a small piece of the material, an electron or hole also has a zero-point energy, making the minimum energy difference between them more than E_g. The light coming from the vials is emitted by electrons recombining with holes. The energy per photon is the electron's initial energy plus the hole's initial energy plus E_g, as shown. To find the energy of the electron and the energy of the hole, use the expression for a one dimensional well, using the dot's radius for L. Values for the radii and E_g are given later.

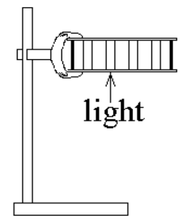


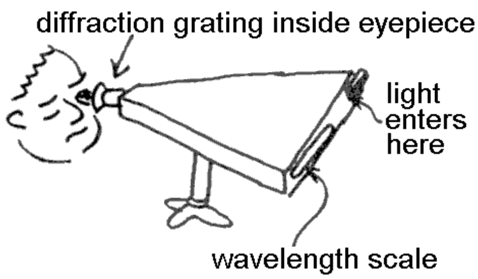
Procedure:

Do not attempt to open the vials. You would ruin them, and could poison yourself.

The spectroscope is simpler but somewhat less accurate than last week's. The grating is mounted in a metal case. Light enters through a slit, and then the grating bends different colors into different directions, making them appear in front of different points on a wavelength scale.

1. Mount the vials on a ring stand at the height of the spectrometer. If you want a second ring stand for the LED light source just ask, but it might be easier to just have someone hold it. It should shoot light into the bottom of a vial.





2. Line up the spectroscope's slit with this vial, adjusting height as necessary. Check that the slit isn't all the way shut. Put the slit an inch or less from the vial.

3. Turn on the LED. While looking in the spectroscope, slowly turn it one way or the other until you see a smear of color. Record the wavelength where this is brightest. The scale is in nanometers. Leaving the overhead lights on will illuminate the wavelength scale, but may add some background features to the spectrum which you should ignore. Estimate an uncertainty such that you are certain the brightest part of the smear is somewhere in the range.

4. Repeat for all four vials.

The information that comes with these kits does not say why there is a broad range of wavelengths rather than a sharp line, such as you saw from hydrogen. Perhaps it is a thermal effect, and the spectral "line" would get narrower if the quantum dots were cooled. This information is also vague about what semiconductor the dots are made of. The hazardous materials sheets mention zinc sulfide and indium phosphate. Whatever the material is, it is the same in all four vials. The color difference comes from different particle sizes, not different compositions.

Calculations:

The particle radii are: Green vial: 2.367 nm. Yellow: 2.534 nm. Orange: 2.718 nm. Red: 2.925 nm. As mentioned earlier, these correspond to "L" for a one dimensional well.

Because of how it interacts with the surrounding material, an electron behaves less sluggishly than in a vacuum. This gives it an effective mass different from its true mass. Likewise, a hole has an effective mass which is not zero. For this material, $m_e = 7.29 \times 10^{-32}$ kg and $m_h = 5.47 \times 10^{-31}$ kg.

For this material, $E_g = 2.15 \times 10^{-19}$ J

As explained earlier, the total energy given off by an electron combining with a hole is the electron's ground state energy plus the hole's ground state energy plus the gap energy. Calculate each wavelength from this, and comment whether it agrees with what you saw.

Vial color:	Peak wavelength:
Green	____________ ± ____________ nm
Yellow	____________ ± ____________ nm
Orange	____________ ± ____________ nm
Red	____________ ± ____________ nm

Calculate theoretical wavelengths: