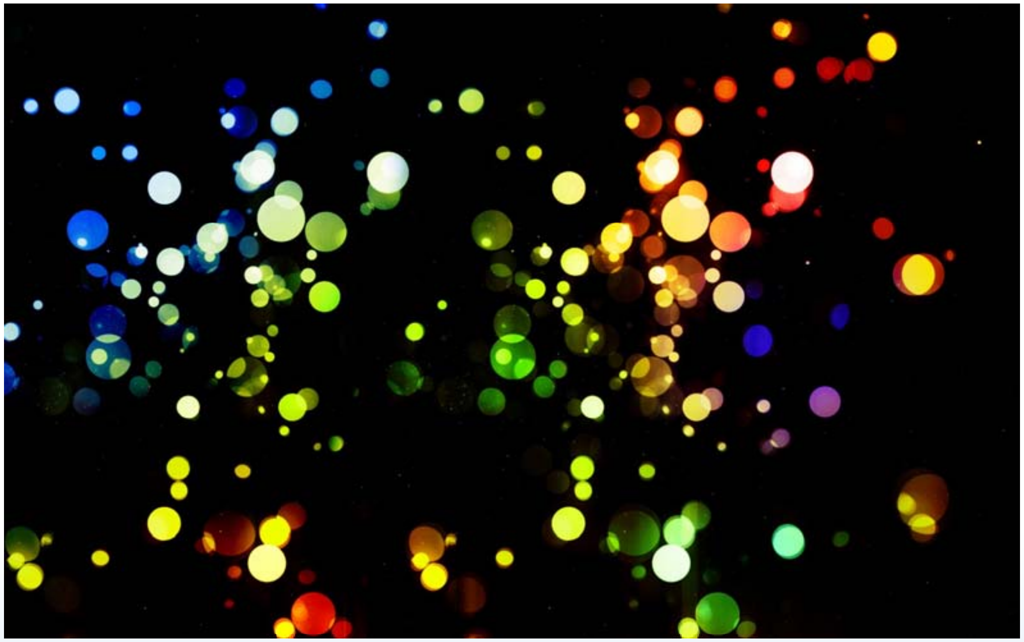


Phys 102 – Lecture 25

The quantum mechanical model of light

Recall last time…

- Problems with classical physics
  - Stability of atoms
  - Atomic spectra
  - Photoelectric effect

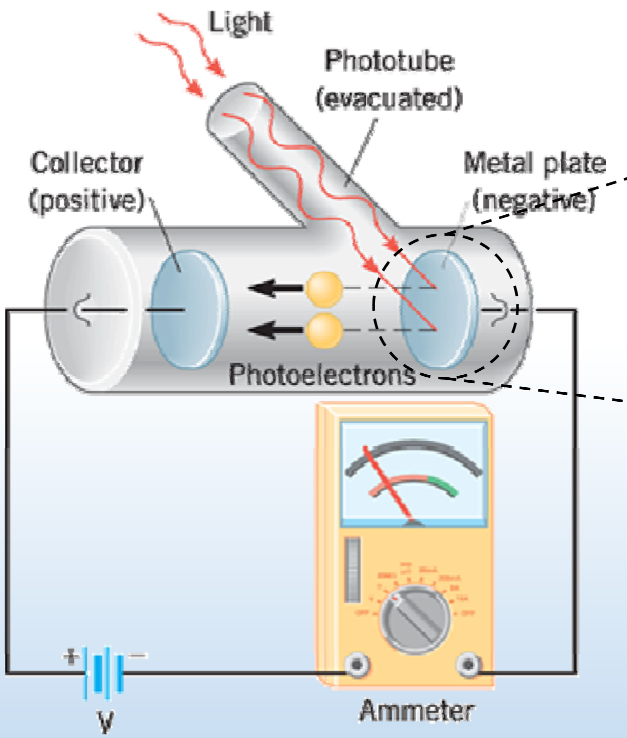
  Today
- Quantum model of the atom
  - Bohr model – only orbits that fit *n* e⁻ λ allowed
  - Angular momentum, energy, radius quantized

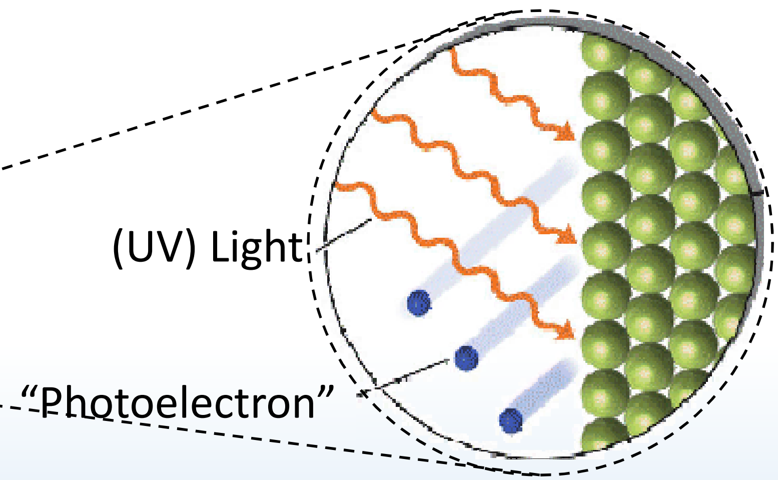
$$L_n = n\hbar \qquad E_n = -13.6\,eV\,\frac{Z^2}{n^2} \qquad r_n = 0.0529\,nm\,\frac{n^2}{Z}$$

- Today: Quantum model of light
  - Einstein's photon model

Photoelectric effect

Light shining on a metal can eject electrons out of atoms





$$K_e = E_{light} - W_0$$

Maximum kinetic energy of electron

Energy of EM wave

Work function of metal

Light must provide enough energy to overcome Coulomb attraction of electron to nuclei: W_0 ("Work function")

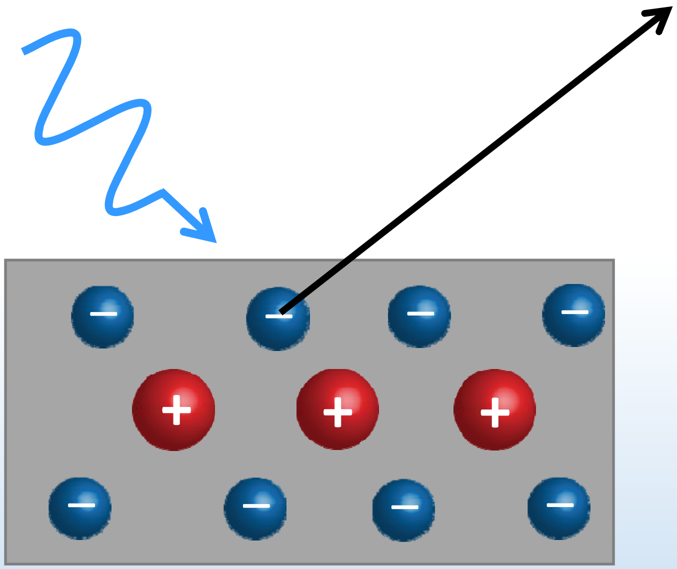
Classical model vs. experiment

$$\boxed{K_e = E_{light} - W_0}$$

Classical prediction

1. Increasing intensity should increase E_{light}, K_e
2. Changing f (or λ) of light should change nothing

$$E_{light} \propto I_{light} = c\bar{u} \propto E_0^2$$



Experimental result

DEMO

1. Increasing intensity results in more e⁻, at *same* K_e
2. Decreasing f (or increasing λ) *decreases* K_e, and below critical value f_0, e⁻ emission stops

Photon Model of Light

Einstein proposed that light comes in discrete packets called *photons,* with energy:

Photon energy

$$\boxed{E_{photon} = hf}$$

Frequency of EM wave

Planck's constant

$$h = 6.626\times10^{-34}\,J\cdot s$$

Ex: energy of a single green photon (λ = 530 nm, in vacuum)

$$f = \frac{c}{\lambda} \qquad E_{photon} = \frac{hc}{\lambda} = \frac{1240\,eV\cdot nm}{530\,nm} = 2.3\,eV$$

Recall Lect. 24

$$hc = 1240\,eV\cdot nm$$

Energy in a beam of green light (ex: laser pointer)

$$E_{light} = N_{photon}E_{photon}$$

ACT: CheckPoint 2.2

A red and blue light emitting diode (LEDs) both output 2.5 mW of light power.

Which one emits more photons/second?

A. Red
B. Blue
C. The same

Photoelectric effect explained

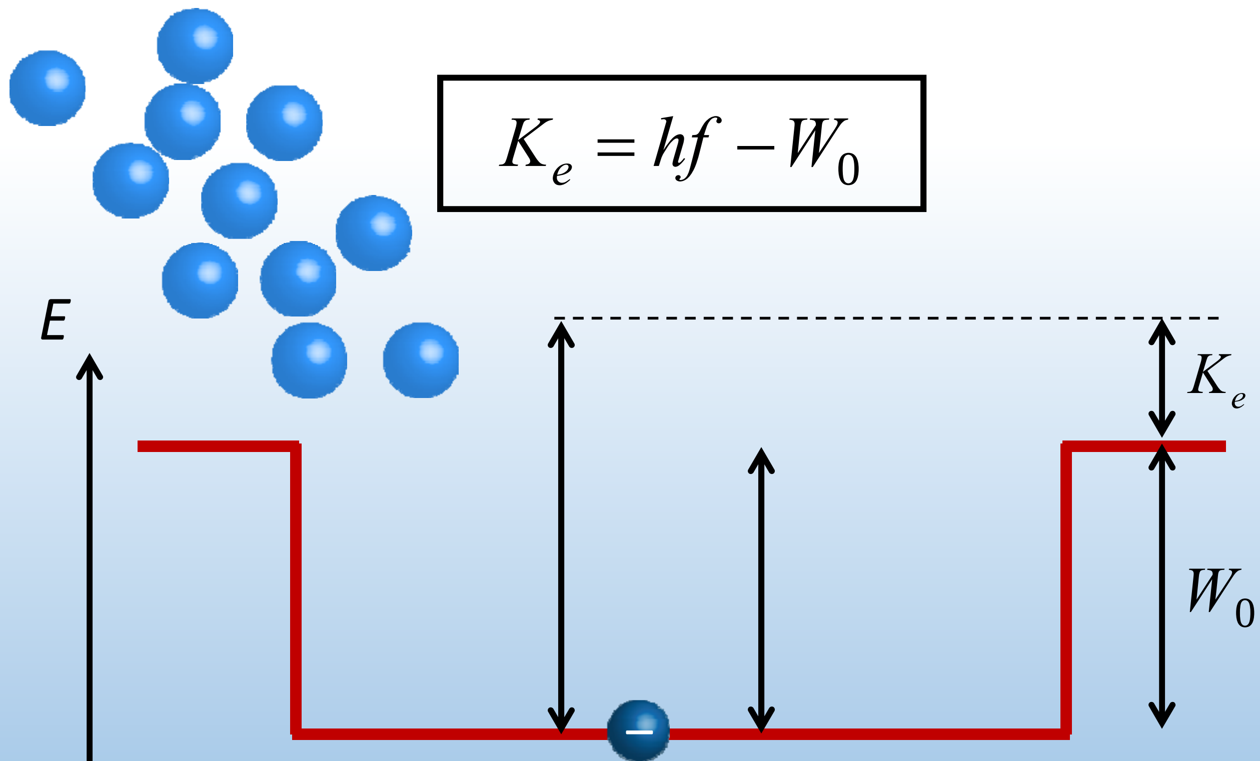
Quantum model

1. Increasing intensity results in *more* photons of the same energy
2. Decreasing f (or increasing λ) decreases photon energy

Experimental result

1. More e^- emitted at *same* K_e
2. Lower K_e and if $hf_{photon} < hf_0 = W_0$ e^- emission stops

$$\boxed{K_e = hf - W_0}$$



ACT: Photoelectric effect

You make a burglar alarm using infrared laser light (λ = 1000 nm) & the photoelectric effect. If the beam hits a metal detector, a current is generated; if blocked the current stops and the alarm is triggered.

Metal 1 – W_0 = 1 eV
Metal 2 – W_0 = 1.5 eV
Metal 3 – W_0 = 2 eV

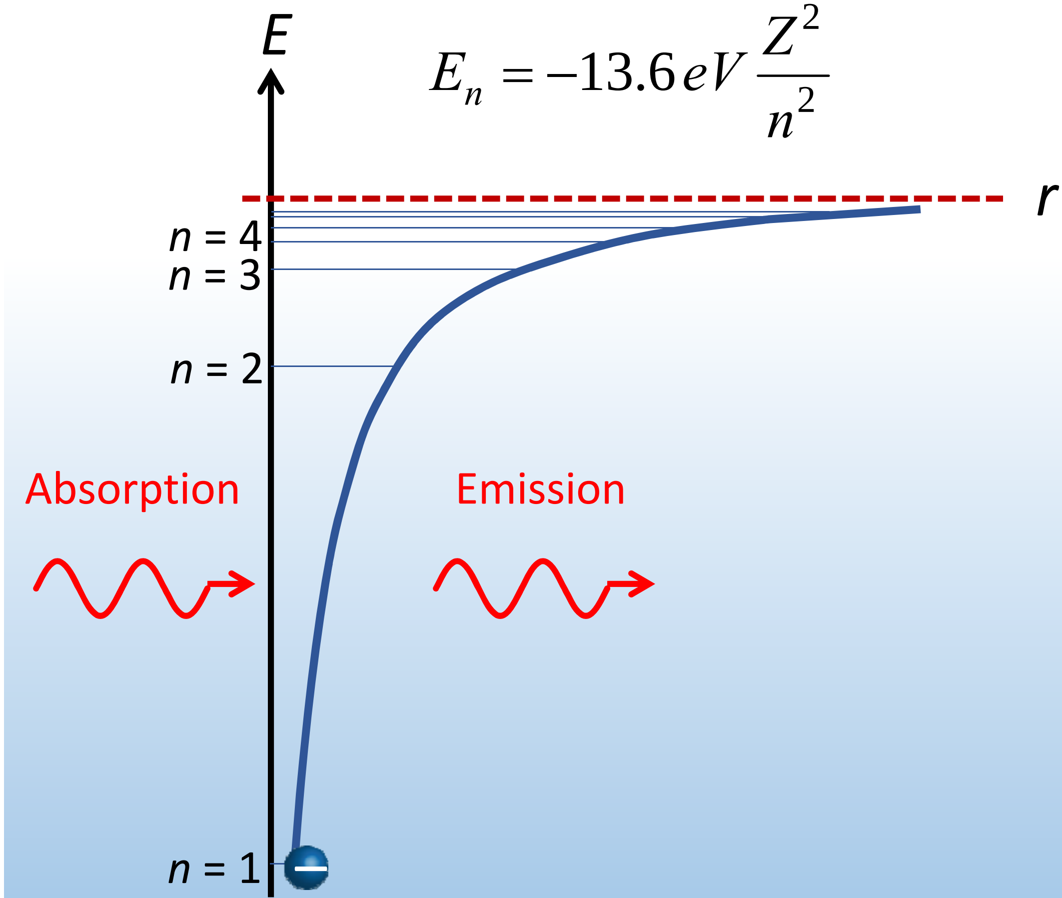
You have a choice of 3 metals. Which will work?

A. 1 and 2
B. 2 and 3
C. 1 only
D. 3 only

Atomic spectra

Electrons in atom are in discrete energy levels

$$E_n = -13.6\,eV\,\frac{Z^2}{n^2}$$



e⁻ can jump from one level to another by absorbing or emitting a photon

Absorption (e⁻ jumps up in energy)

$$E_i + hf = E_f$$

Emission (e⁻ jumps down in energy)

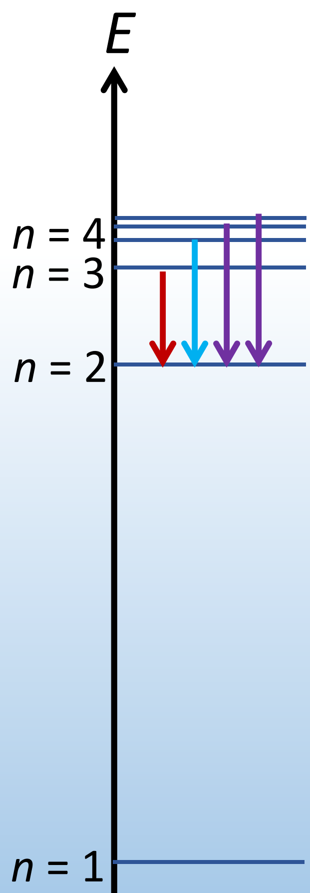
$$E_i = E_f + hf$$

Energy is conserved

$$hf = E_n - E_{n'}$$

Calculation: H spectral lines

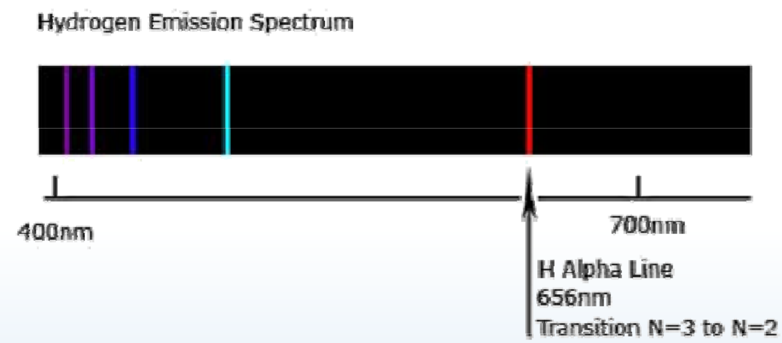
Calculate the wavelength of light emitted by hydrogen electrons as they transition from the n = 3 to n = 2 levels



Emission:

$$hf = E_i - E_f$$

$$\frac{hc}{\lambda} = 13.6eV\,Z^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$



$$\frac{1}{\lambda} = 1.097\times10^{-7}\,m^{-1}\left(\frac{1}{2^2} - \frac{1}{3^2}\right)$$

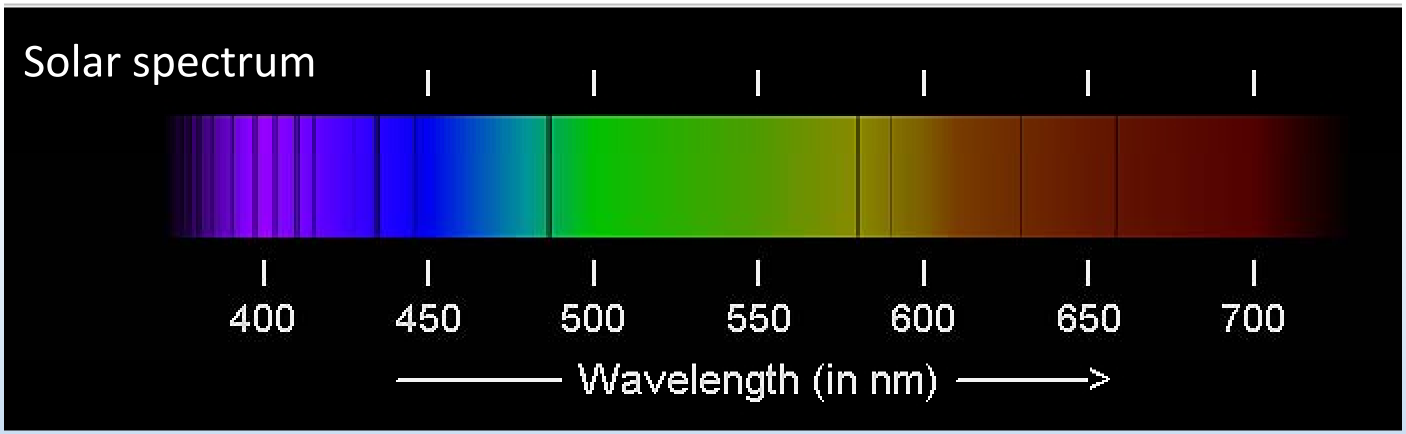
Using $hc = 1240\,eV\cdot nm$

$$\lambda = 6.56\times10^{-7}\,m$$

Transition from n > 3 to n = 2 will generate higher energy/smaller λ photon

Solar spectrum

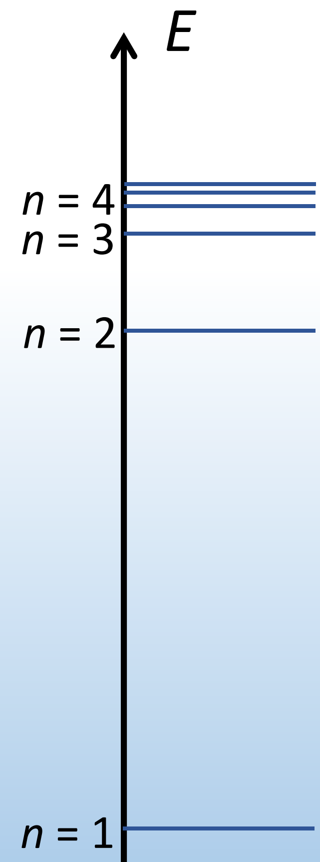
Spectrum from celestial bodies can be used to identify its composition



Sun radiates over large range of λ because it is hot (5800K). Black spectral lines appear because elements inside sun absorb light at those λ.

ACT: CheckPoint 3.1

Electron A falls from energy level n = 2 to n = 1. Electron B falls from energy level n = 3 to energy level n = 1.



Which photon has a longer wavelength?

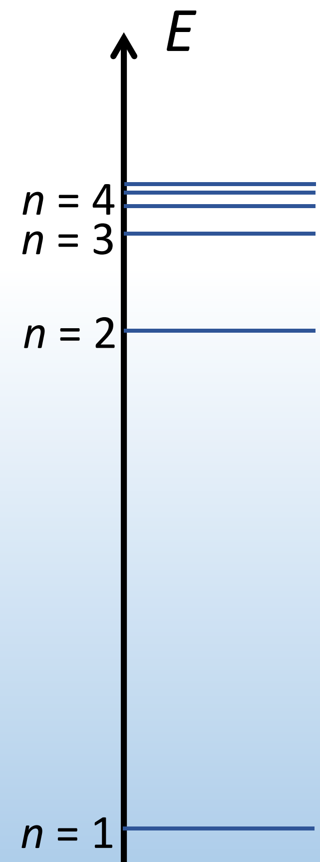
A. Photon A

B. Photon B

C. Both the same

ACT: CheckPoint 3.2

The electrons in a large group of hydrogen atoms are excited to the n = 3 level.



How many spectral lines will be produced?

A. 1

B. 2

C. 3

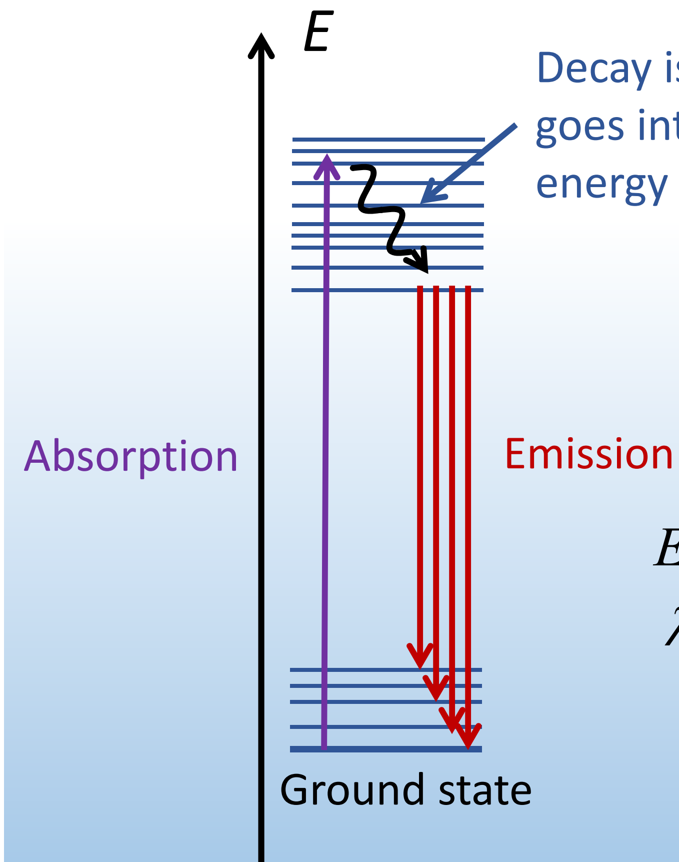
D. 4

E. 5

Fluorescence

Molecules, like atoms, have discrete energy levels. Usually many more, organized in bands

Decay is non-radiative, usually goes into vibrational/rotational energy of molecule



$$E_{emission} > E_{absorption}$$

$$\lambda_{emission} < \lambda_{absorption}$$

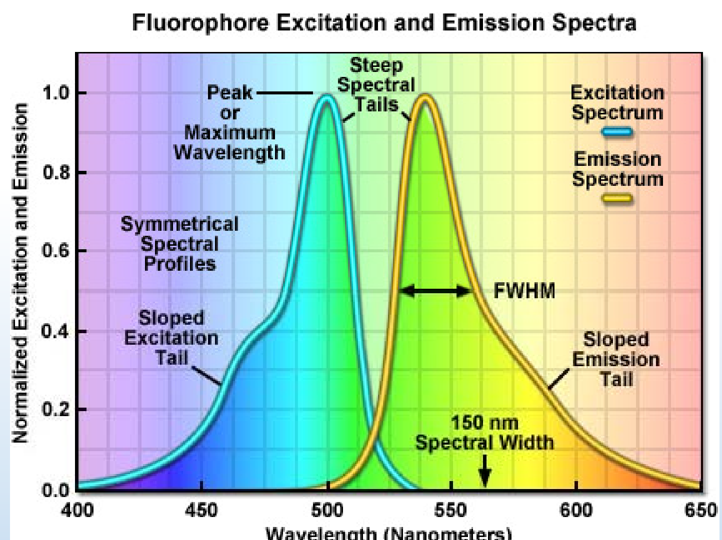


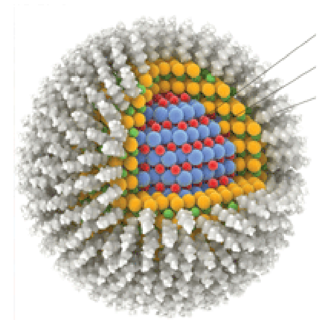
Figure 2

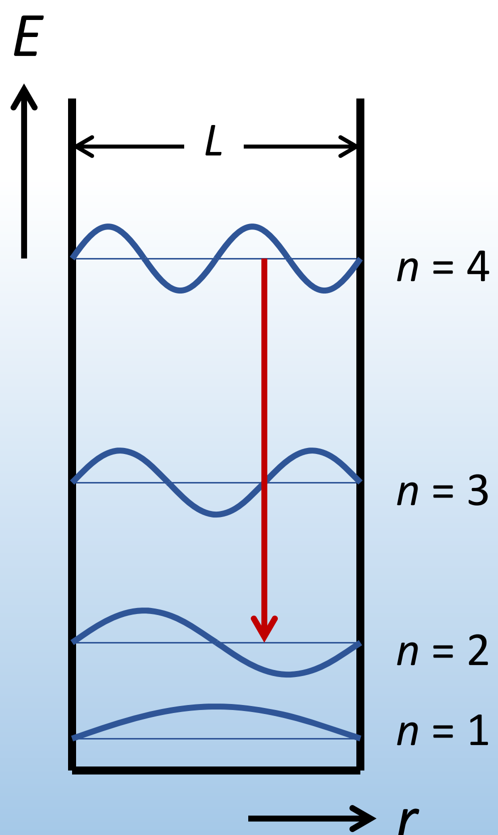
Fluorescent molecules that emit visible light absorb shorter λ (ex: UV)

DEMO

Quantum dots: "electron in a box"

Quantum dots ("Q-dots") are nm-sized particles. Electrons are confined inside nm-sized "box".





Like Bohr model, only e^- λ that fit inside box are allowed:

$$n\frac{\lambda_e}{2} = L \quad n = 1, 2, 3\ldots$$

$$E_{tot} = \frac{1}{2}mv^2 = \frac{p^2}{2m} = \frac{h^2}{2m\lambda_e^2} = \frac{h^2 n^2}{8mL^2}$$

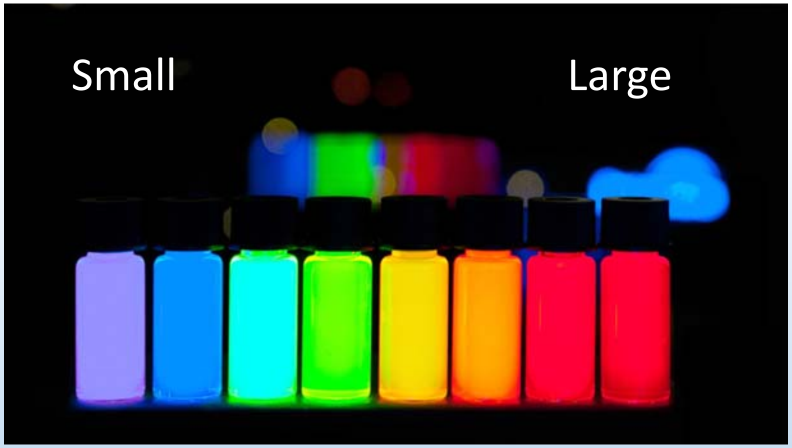
Emitted photon energy depends on Q-dot size:

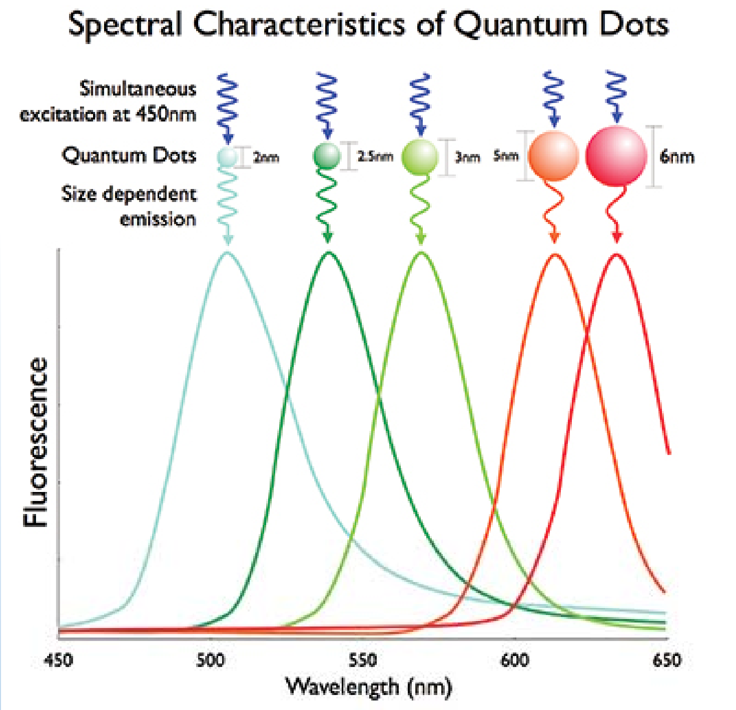
$$hf = E_n - E_{n'} = \frac{h^2}{8mL^2}(n^2 - n'^2)$$

Quantum dot emission

The larger the quantum dot, the longer the emitted photon wavelength

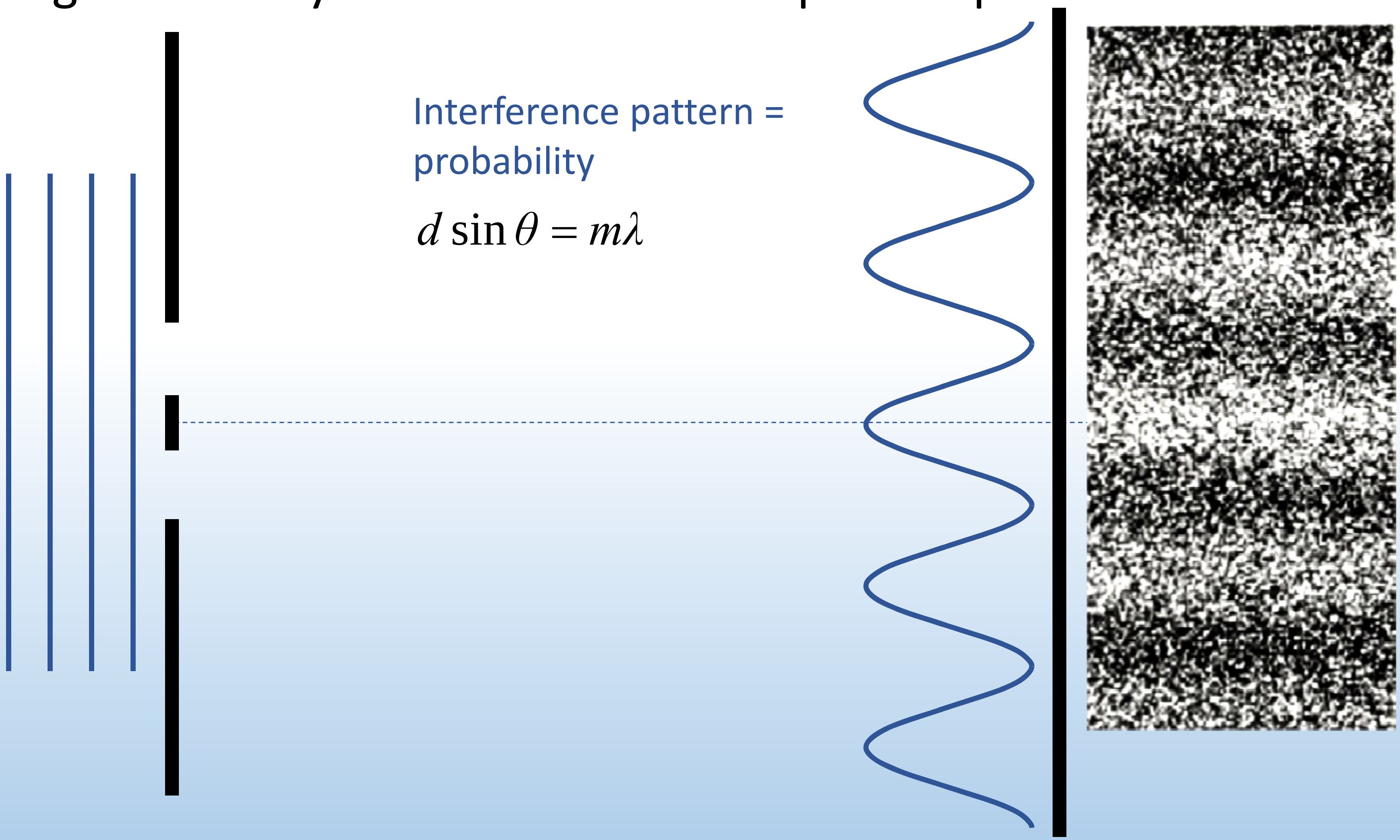
$$hf = E_n - E_{n'} = \frac{h^2}{8mL^2}(n^2 - n'^2)$$





Young's double slit revisited

Light intensity is reduced until *one* photon passes at a time



ACT: Photons & electrons

A free photon and an electron have the same energy of 1 eV.

Therefore they must have the same wavelength.

A. True

B. False

Summary of today's lecture

- Quantum model of light
  - Light comes in discrete packets of energy $E_{photon} = hf = \frac{hc}{\lambda}$
  - Light intensity is related to number of photons, not photon energy
- Spectral lines
  - Transitions between energy levels $hf = E_n - E_{n'}$
- Wave-particle duality
  - Waves behave like particles (photons)
  - Particles behave like waves (electrons)