Your questions/comments

PICK UP A DIFFRACTION GRATING AS YOU ENTER!
Exam 3 tomorrow!

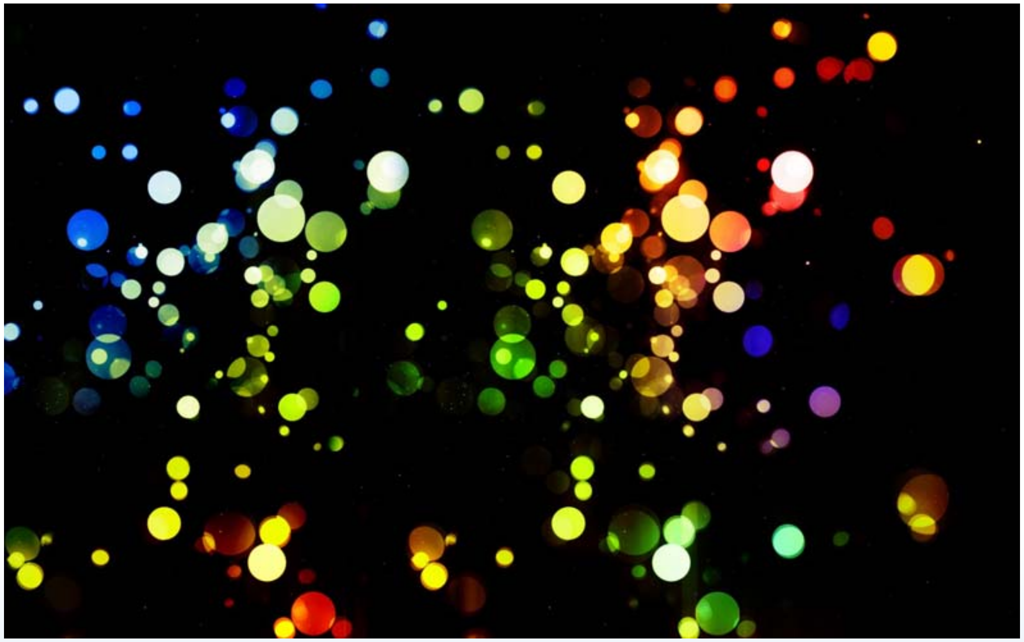
“No amount of energy will make me worry about this material until after the test tomorrow.”

“AIN'T NOBODY GOT TIME FOR THIS….EXAM”

“Studying for the test!!!!”

“Please don't hate me . . .I guessed on everything :(Exam 3>>>>>>>>>>> everything else”

“MCB 244 trumps Physics :(“



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

  $\lambda = h/p$

  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

ACT: Quick review

Z =

Consider an atom with a nuclear charge of +2e with a single electron orbiting, in its ground state (n = 1), i.e. He^+.

How much energy is required to ionize the atom totally?

A. 13.6 eV

B. 2 × 13.6 eV

C. 4 × 13.6 eV

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

Energy measured relative to free electron (E = 0)

Atomic units

At atomic scales, Joules, meters, kg, etc. are not convenient units

"Electron Volt" – energy gained by charge +1e when accelerated by 1 Volt: $U = qV$

1e = 1.6×10^{-19} C, so 1 eV = 1.6×10^{-19} J

Planck constant: $h = 6.626 \times 10^{-34}$ J·s
Speed of light: $c = 3 \times 10^{8}$ m/s

$$hc \approx 2\times10^{25}\,\mathrm{J\cdot m} = \underline{\underline{\underline{1240\,\mathrm{eV\cdot nm}}}}$$

Electron mass: $m = 9.1 \times 10^{-31}$ kg

$$mc^2 = 8.2\times10^{-13}\,J = \underline{\underline{511{,}000\,\mathrm{eV}}}$$

Since $U = \dfrac{ke^2}{r}$, ke^2 has units of eV·nm like hc

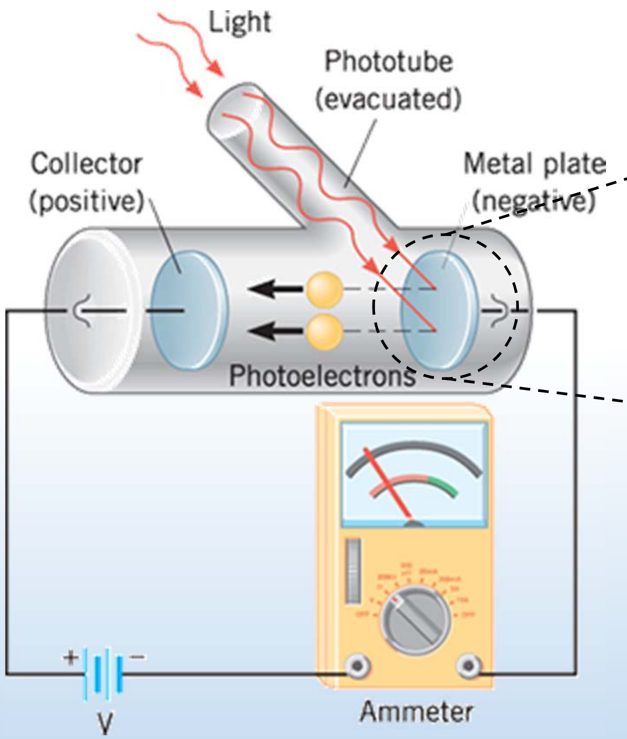
$$ke^2 \approx 1.44\,\mathrm{eV\cdot nm}$$

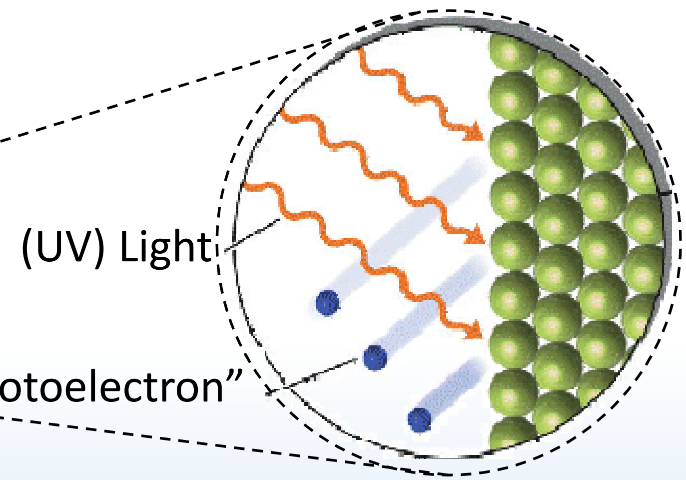
$$\frac{ke^2}{\hbar c} = 2\pi\frac{ke^2}{hc} \approx \frac{1}{137}$$

"Fine structure constant" (dimensionless)

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

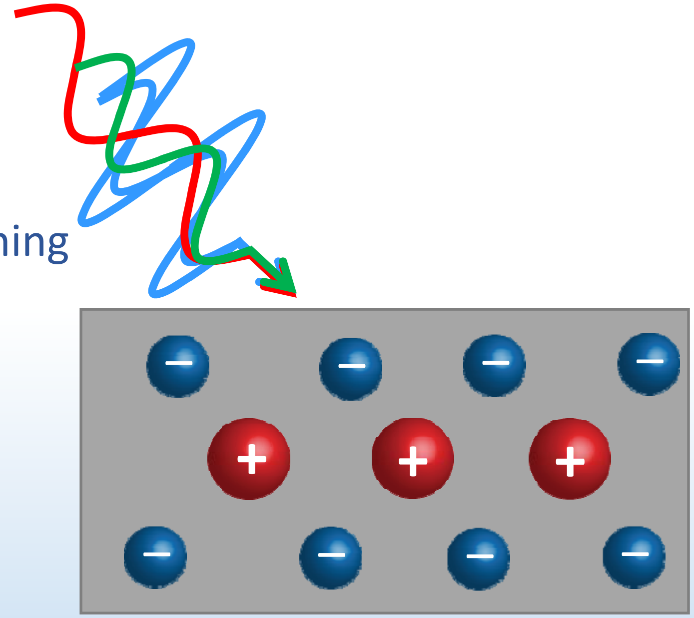
Work function of metal

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

Binding energy

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)

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

CheckPoint 2.1: Higher/lower λ = lower/higher *E*

ACT: CheckPoint 2.2

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

Red = 650 nm & blue = 490nm

ROYGBIV

Which one emits more photons/second?

32% A. Red

49% B. Blue

19% C. The same

$$P = \frac{\Delta E_{light}}{\Delta t} = \frac{\Delta N}{\Delta t} E_{photon}$$

Energy per photon

Number of photons per second

Red light has less energy/photon so if they both have the same total power, red has to have more photons/time!

Photoelectric effect explained

Quantum model

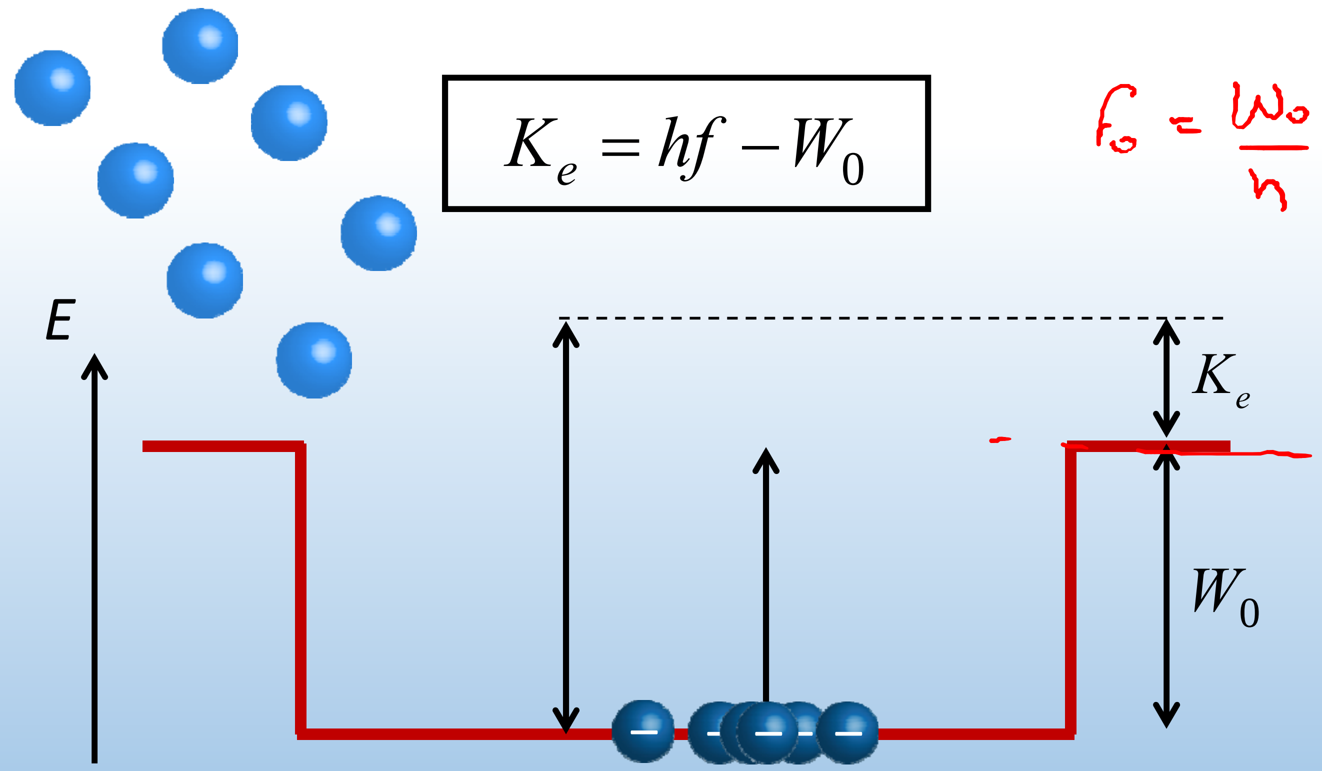
1. Increasing intensity results in *more* photons of the same energy
2. Decreasing f (or increasing λ) decreases photon energy

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

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

$$f_0 = \frac{W_0}{h}$$



free electron
$E = 0$

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

We need:

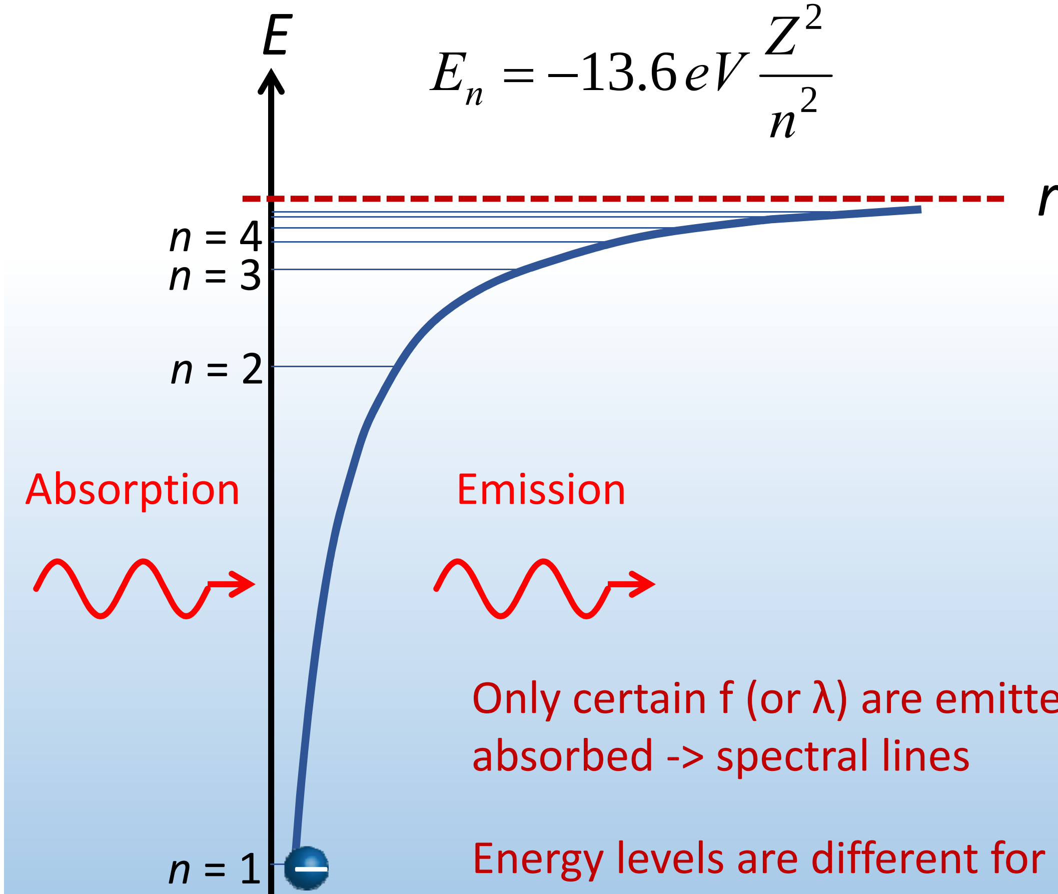
$$K_e = hf - W_0 > 0$$

$$E_{photon} = hf = \frac{hc}{\lambda} = \frac{1240\, eV \cdot nm}{1000\, nm} = 1.24\, eV$$

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

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

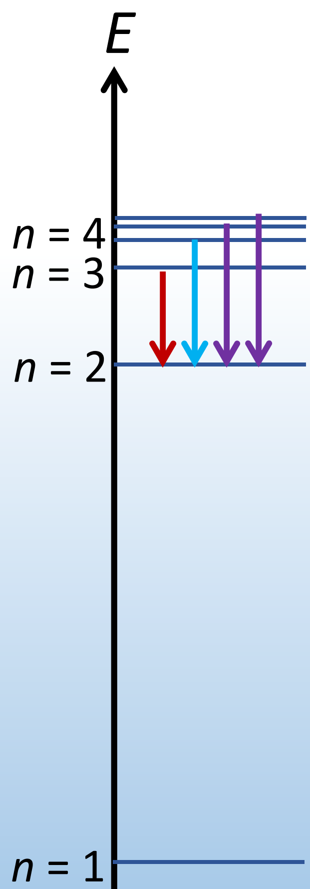
Only certain f (or λ) are emitted or absorbed -> spectral lines

Energy levels are different for elements, so spectra are different

DEMO

Calculation: H spectral lines

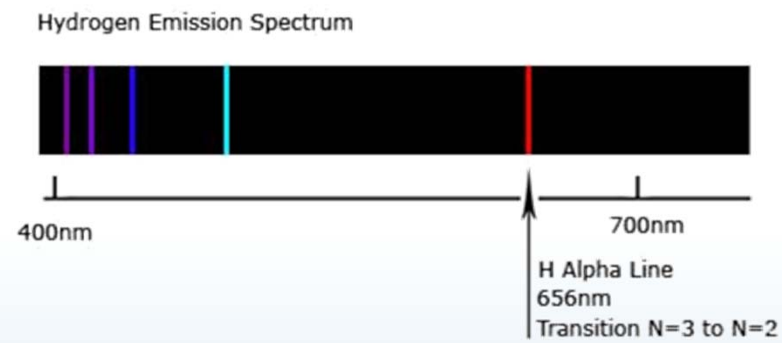
Calculate the wavelength of light emitted by hydrogen electrons as they transition from the n = 3 to n = 2 levels



Emission:

$$hf = E_i - E_f$$

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



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

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

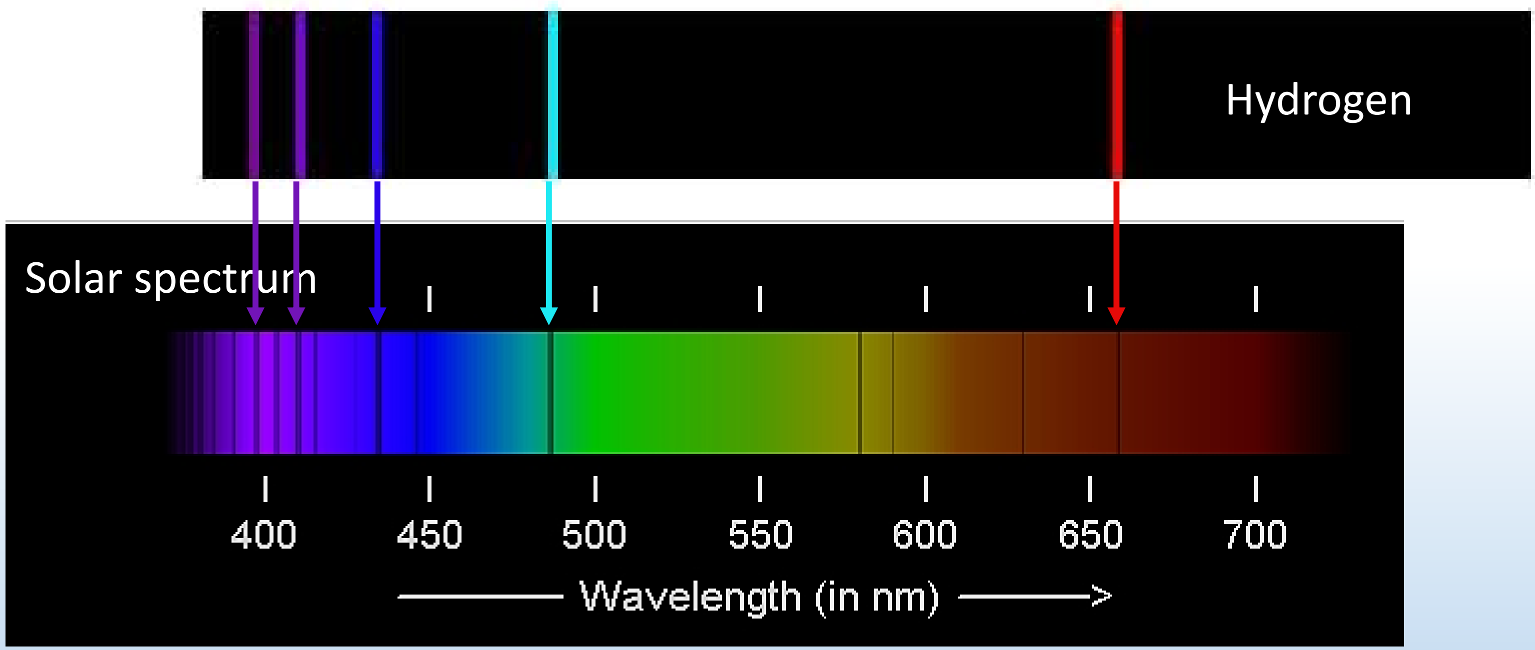
Using $hc = 1240\, eV \cdot nm$

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

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?

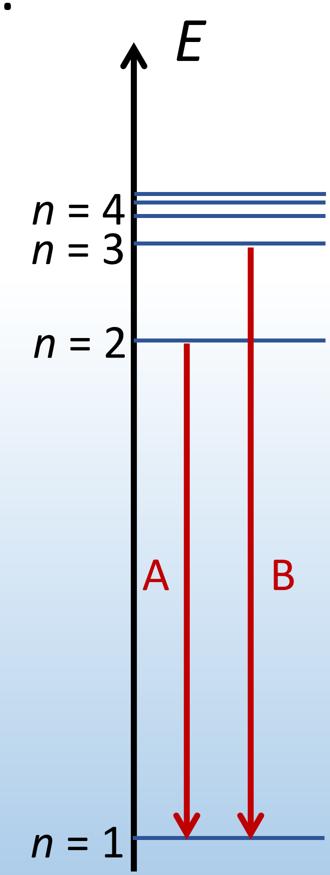
50% A. Photon A

36% B. Photon B

14% C. Both the same

$$E_{photon} = hf = \frac{hc}{\lambda}$$

So, $E_A < E_B$ and $\lambda_A > \lambda_B$



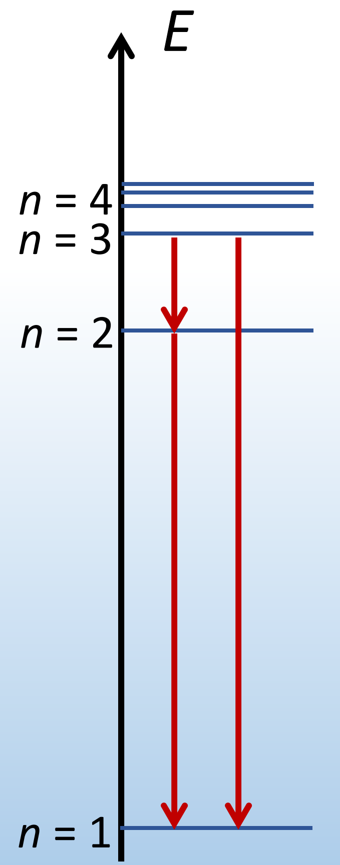
ACT: CheckPoint 3.2

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

How many spectral lines will be produced?

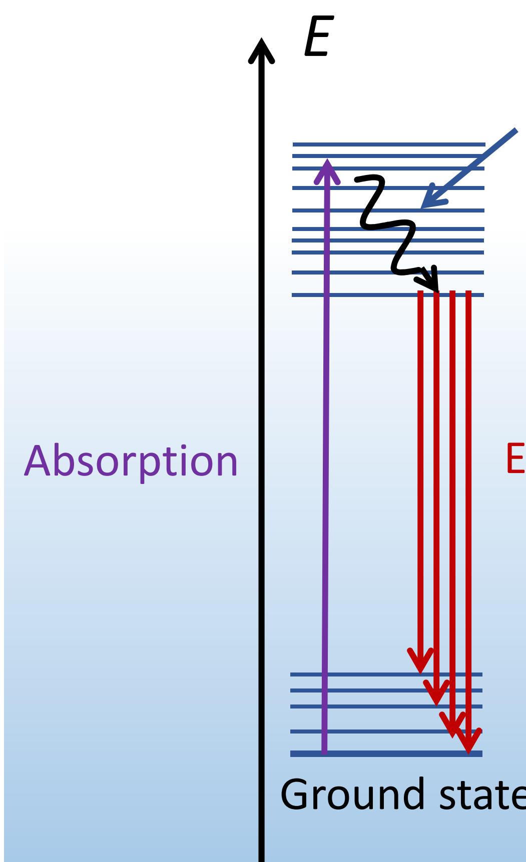
8%	A. 1
30%	B. 2
47%	C. 3
11%	D. 4
4%	E. 5

Notice that n = 3 e^- could first decay to n = 2, then to n = 1



Fluorescence

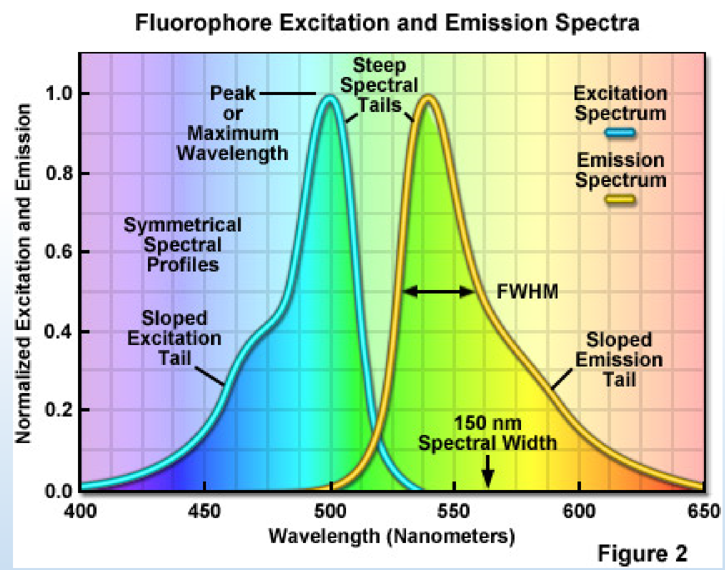
Molecules, like atoms, have discrete energy levels. Usually many more, and organized in *bands*



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

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

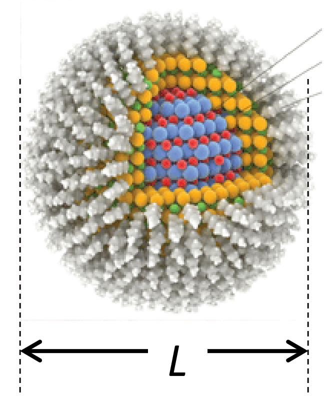
DEMO

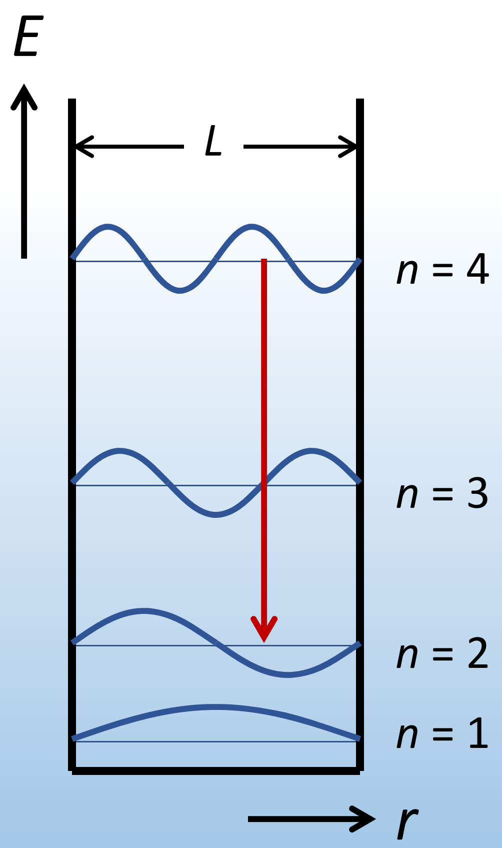


Fluorescent molecules that emit visible light absorb shorter λ (ex: UV)

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:

$\lambda = h/p$

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

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

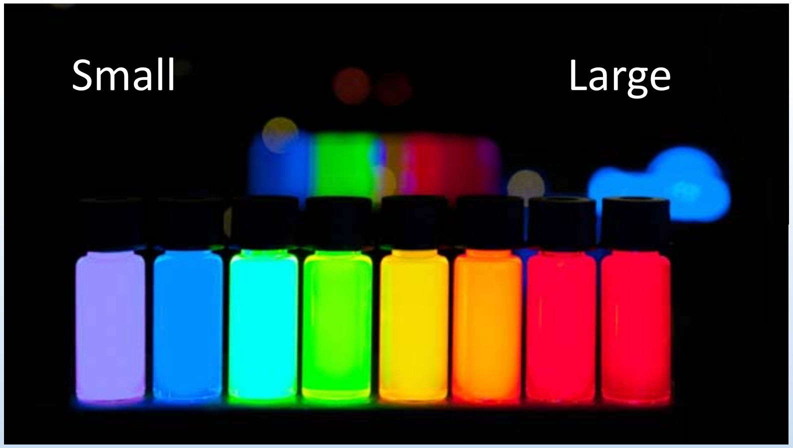
Emitted photon energy depends on Q-dot size:

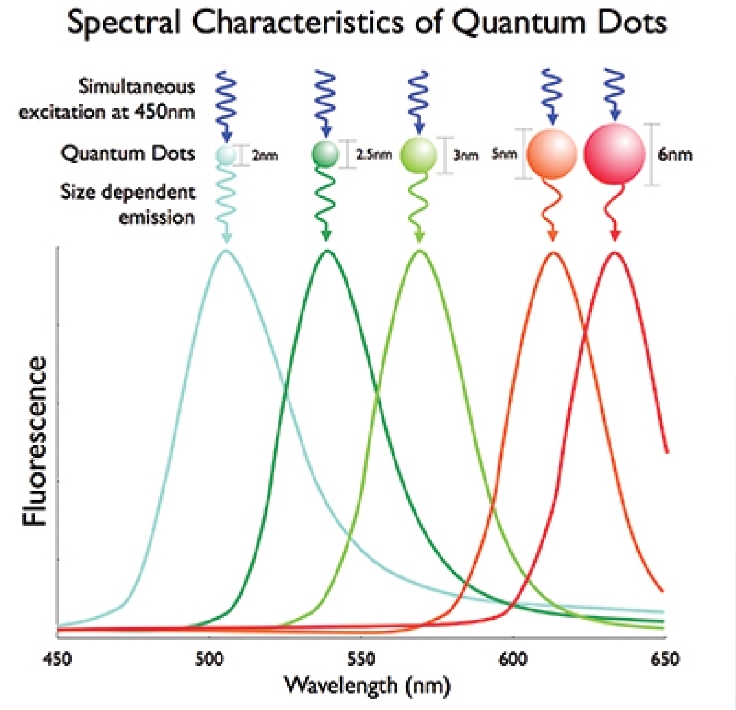
$$hf = E_n - E_{n'} = \frac{h^2}{8mL^2}(n^2 - n'^2)$$

Quantum dot emission

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

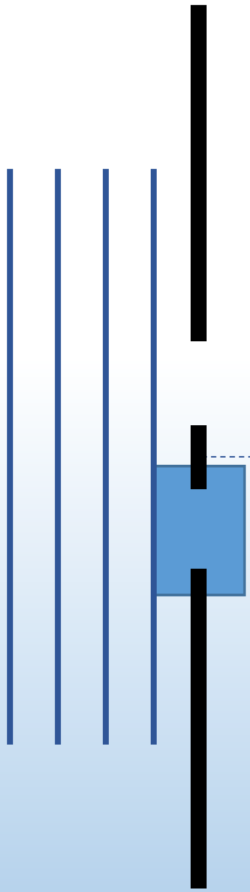
$$hf = \frac{hc}{\lambda} = E_n - E_{n'} = \frac{h^2}{8mL^2}(n^2 - n'^2)$$





Young's double slit revisited

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



Interference pattern = probability

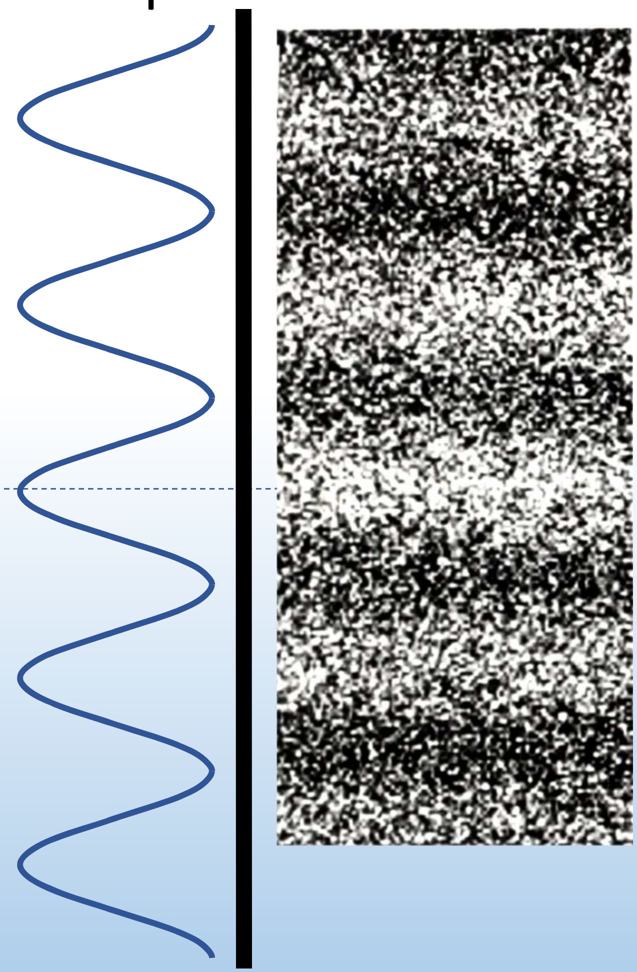
$$d \sin\theta = m\lambda$$

Wait! Is light a wave or a particle?

Both!

What if we measure which slit the photon passes through?

Interference disappears!



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

$$E_{photon} = hf = \frac{hc}{\lambda_{photon}} \qquad \lambda_{photon} = \frac{hc}{E_{photon}}$$

$$= \frac{1240\, eV \cdot nm}{1 eV} = 1240\, nm$$

$$E_{elec} = \frac{p^2}{2m} = \frac{h^2}{2m\lambda_{elec}^2} \qquad \lambda_{elec} = \frac{hc}{\sqrt{2mc^2 E_{elec}}}$$

$$= \frac{1240\, eV \cdot nm}{\sqrt{511{,}000\, eV \cdot 1 eV}} = 1.23\, nm$$

Notice BIG difference!

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)