Your questions/comments

PICK UP A DIFFRACTION GRATING AS YOU ENTER!

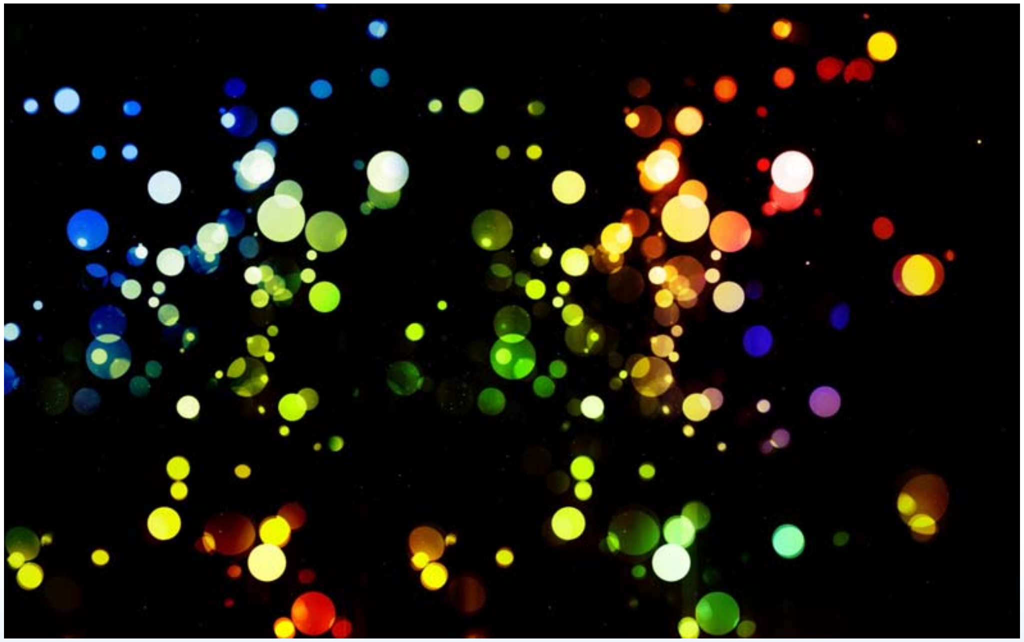
“SOOOOOO COOOOOOOOL! Like seriously!”

“Does the amount of time a light source is displayed on a metal surface change the threshold? For instance if a light isn't of high enough frequency to expel electrons after 1 minute of exposure will changing the length of exposure to 10 minutes make a difference?.”

“Frequency is still a property of waves. How is the "particle view" of light influenced by frequency?”

“I just quant...um..seem to figure this stuff out”

“I don't understand the concept of how many spectra lines will be produced when the electron is excited to a different state.”



Phys 102 – Lecture 25

The quantum mechanical model of light

Recall last time…

- Problems with classical physics

  Stability of atoms

  Atomic spectra } Today

  Photoelectric effect } Today

- Quantum model of the atom particles are waves

  Bohr model – only orbits that fit n e^- λ allowed

  Angular momentum, energy, radius quantized Quantum #

$$L_n = n\hbar \qquad E_n = -\frac{Z^2}{n^2}\times 13.6\,\text{eV} \qquad r_n = \frac{n^2}{Z}\times 0.0529\,\text{nm} \qquad n = 1, 2, 3\ldots$$

- Today: Quantum model of light

  Einstein's photon model Nobel 1921

ACT: Quick review

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

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

Z = 2 (nuclear charge)
n = 1 (ground state)
Energy measured relative to free electron (E = 0)

Recall: 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

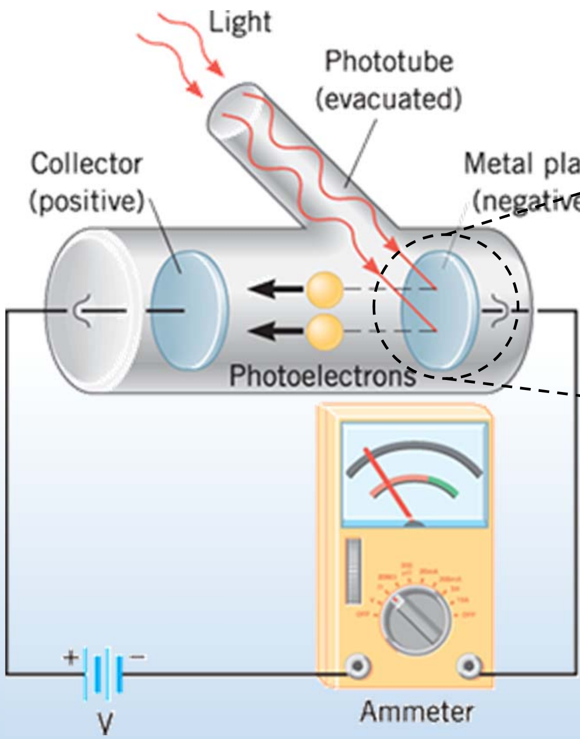
$$hc \approx 2\times10^{-25}\,\mathrm{J\cdot m} = 1240\,\mathrm{eV\cdot nm}$$

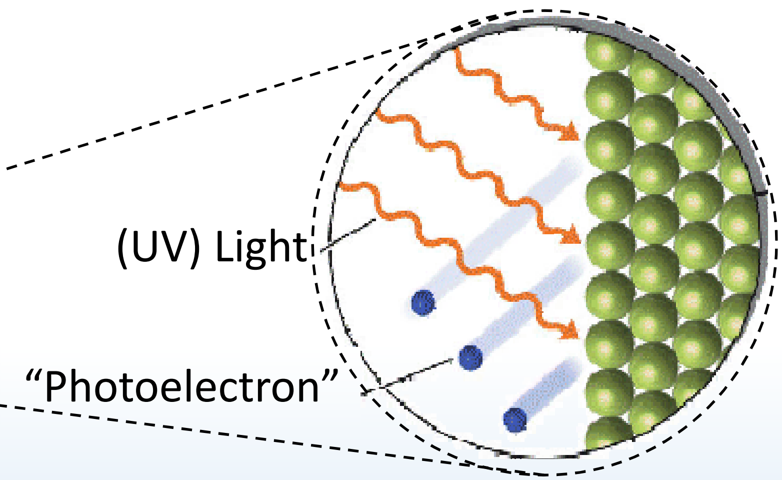
Electron mass: $m = 9.1 \times 10^{-31}$ kg

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

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

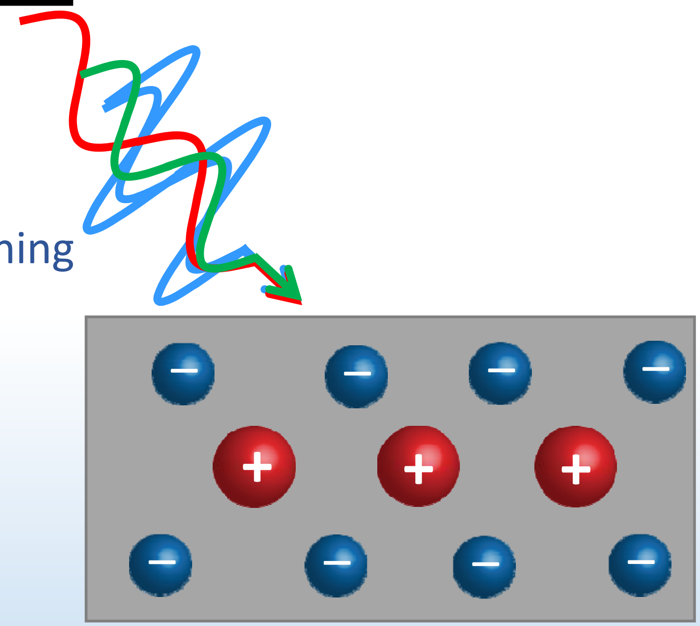
$$K_e = E_{light} - W_0$$

Classical prediction

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

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

$$f = \frac{c}{\lambda}$$



Experimental result

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

DEMO

Photon Model of Light

"particles of unit"

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

Photon energy → $$E_{photon} = hf$$ ← Frequency of EM wave

↑ Planck's constant

$$h = 6.626 \times 10^{-34}\, J \cdot s$$

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

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

$$hc = 1240\,\mathrm{eV \cdot nm}$$

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?

31% A. Red

42% B. Blue

27% 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

$E_{ph} = \frac{hc}{\lambda}$

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

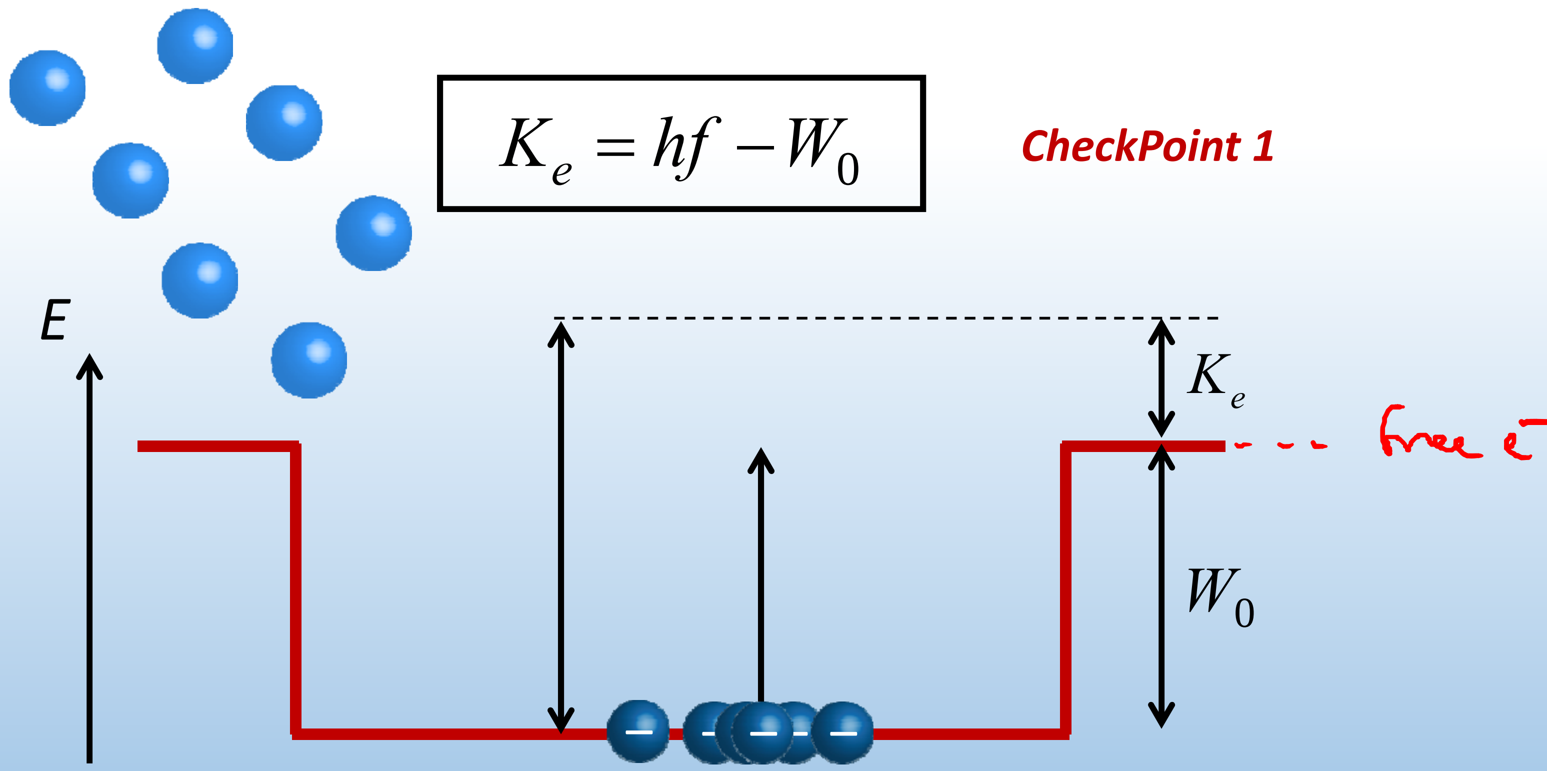
1. Increasing intensity results in *more* photons of the same energy
2. Decreasing f (or increasing λ) decreases photon energy

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

$$K_e = hf - W_0$$

CheckPoint 1



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:

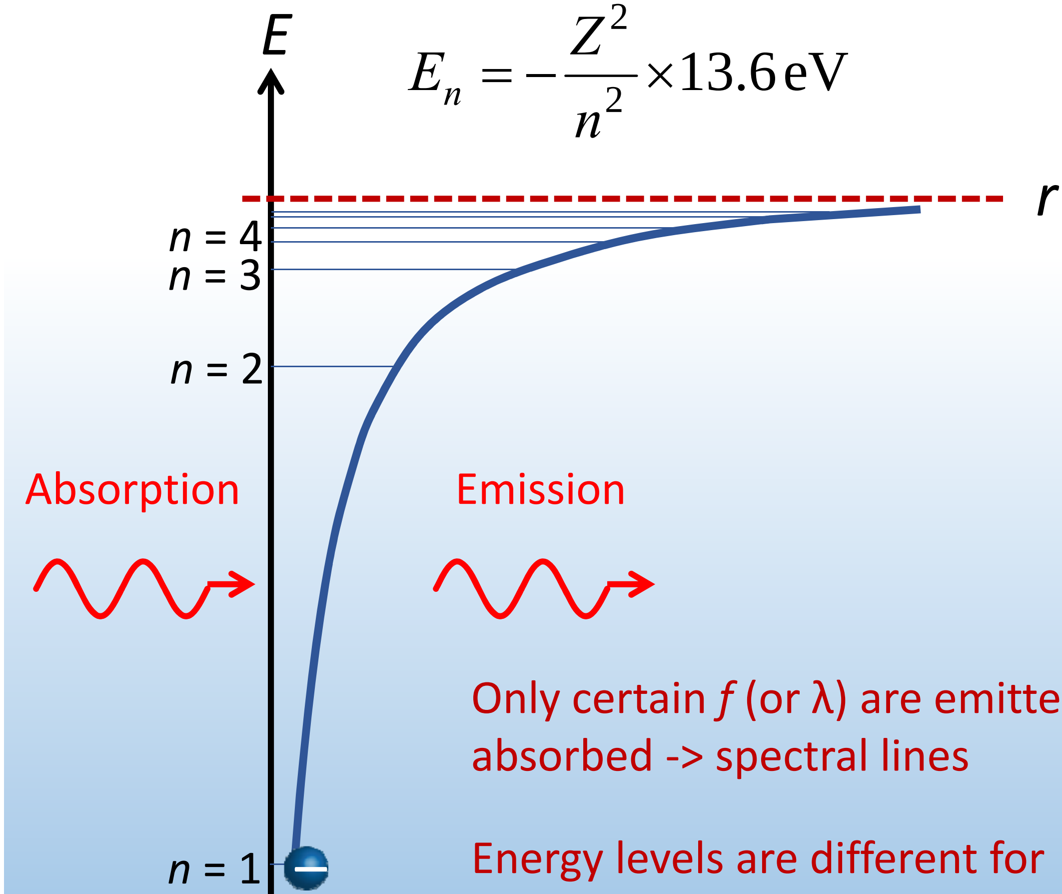
$$K_e = hf - W_0 > 0$$

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

Atomic spectra

Electrons in atom are in discrete energy levels

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



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

Energy levels are different for elements, so spectra are different

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)

$$E_i = E_f + hf$$

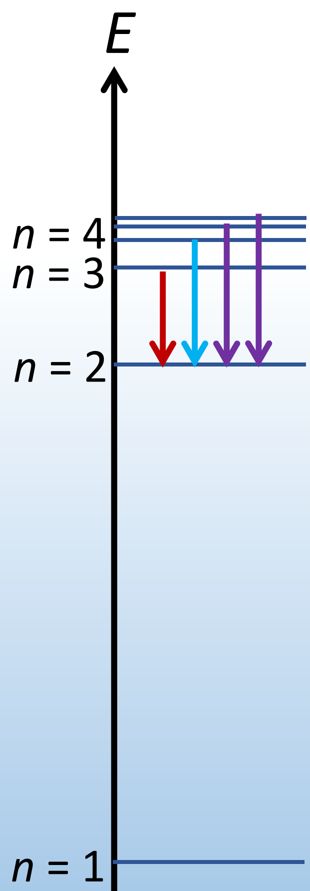
Energy is conserved

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

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

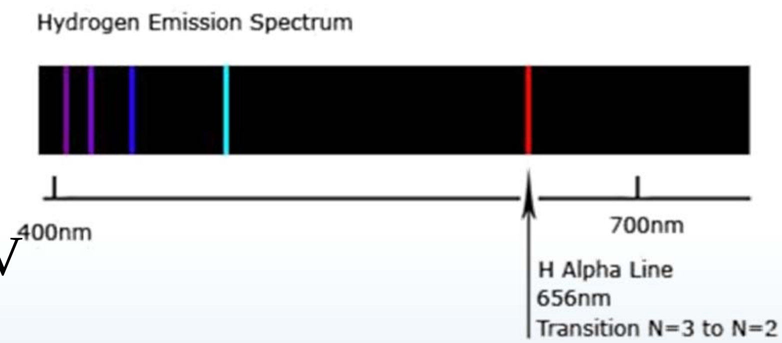


Emission:

$$hf = E_i - E_f$$

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

= 1 2 3



$$\frac{1}{\lambda} = Z^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)\times 1.097\times 10^{7}\,\mathrm{m}^{-1}$$

$$\frac{1}{\lambda} = \left(\frac{1}{2^2} - \frac{1}{3^2}\right)\times 1.097\times 10^{7}\,\mathrm{m}^{-1}$$

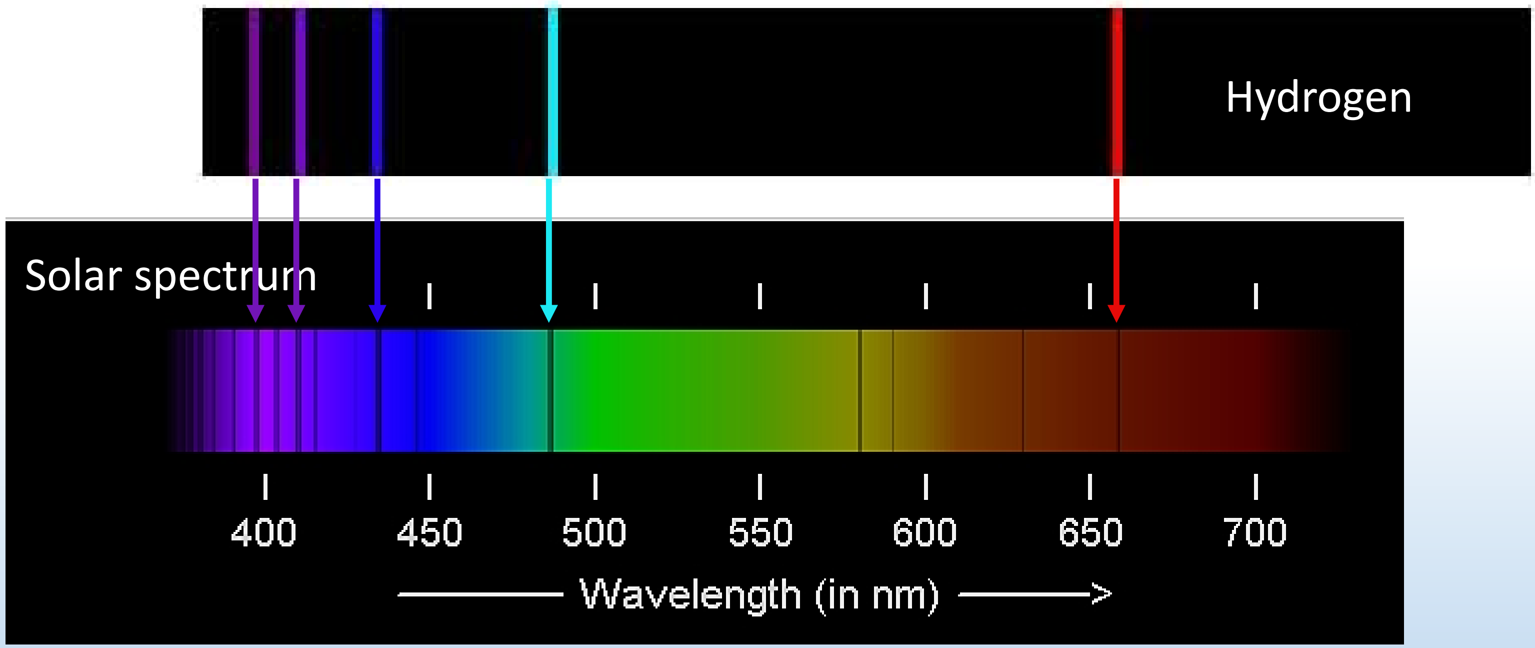
Using $hc = 1240\,\mathrm{eV}\cdot\mathrm{nm}$

$$\lambda = 6.56\times 10^{-7}\,\mathrm{m}$$

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

Solar spectrum

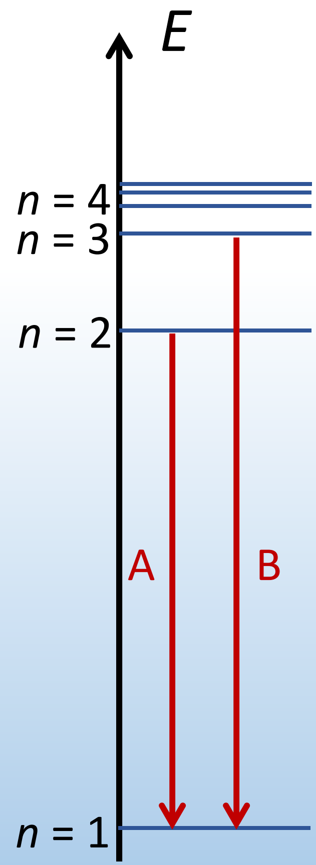
Spectrum from celestial bodies can be used to identify its composition



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?

47% A. Photon A

41% B. Photon B

11% 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?

13% A. 1

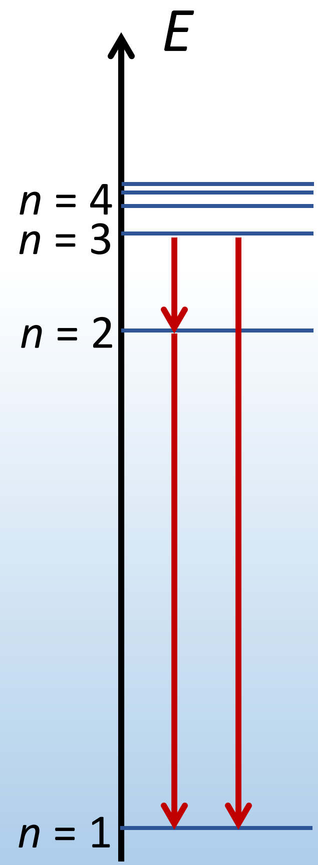
25% B. 2

47% C. 3

10% D. 4

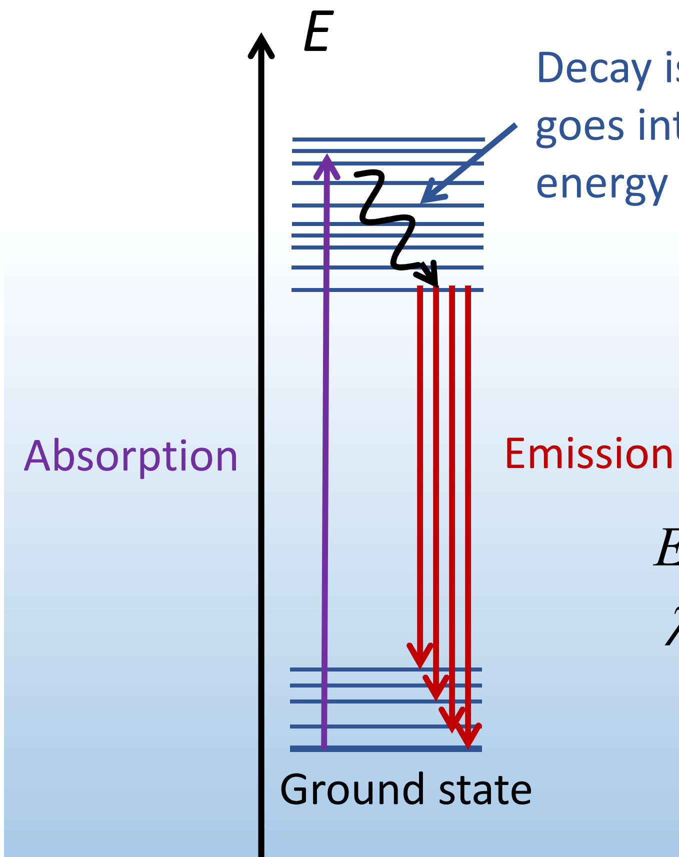
4% E. 5

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



Fluorescence

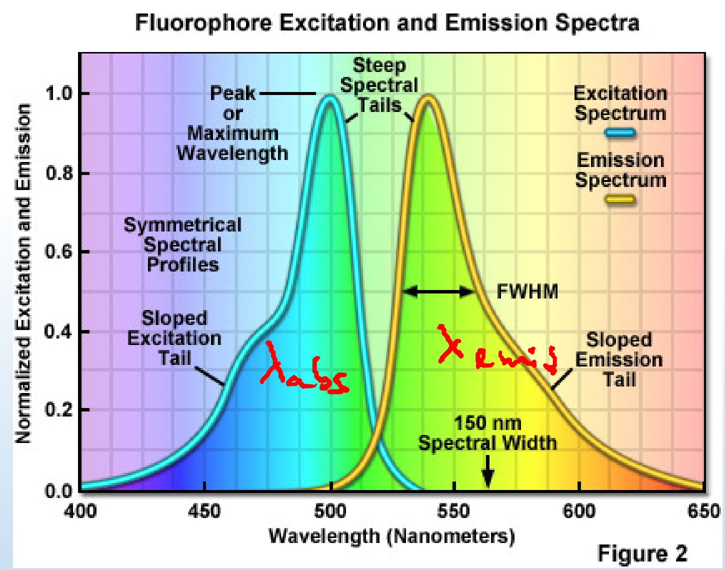
Molecules, like atoms, have discrete energy levels. Usually many more, and organized in *bands*



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

$$E_{emission} < E_{absorption}$$

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

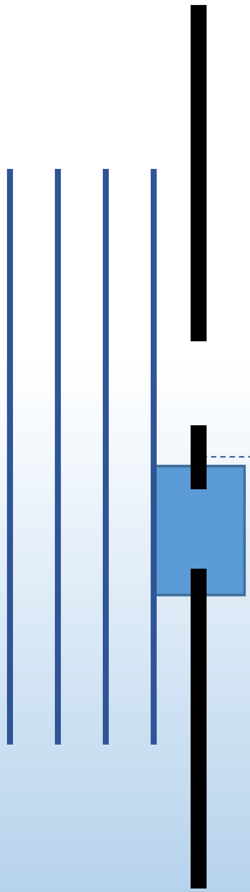


Fluorescent molecules that emit visible light absorb shorter λ (ex: UV)

DEMO

Young's double slit revisited

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



Interference pattern = probability

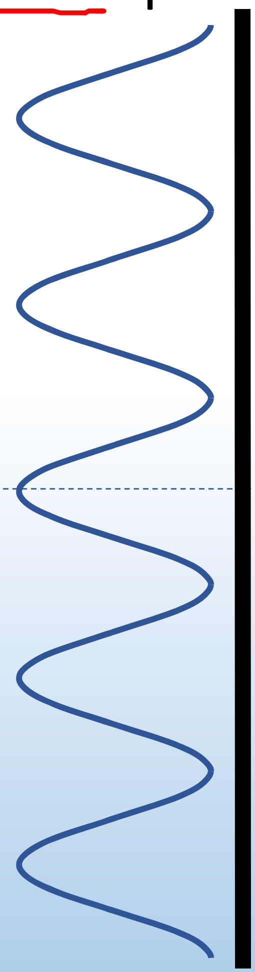
$$d \sin\theta = m\lambda$$

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

Therefore they must have the same wavelength.

A. True

B. False

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

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

$p = \frac{h}{\lambda}$

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

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

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)