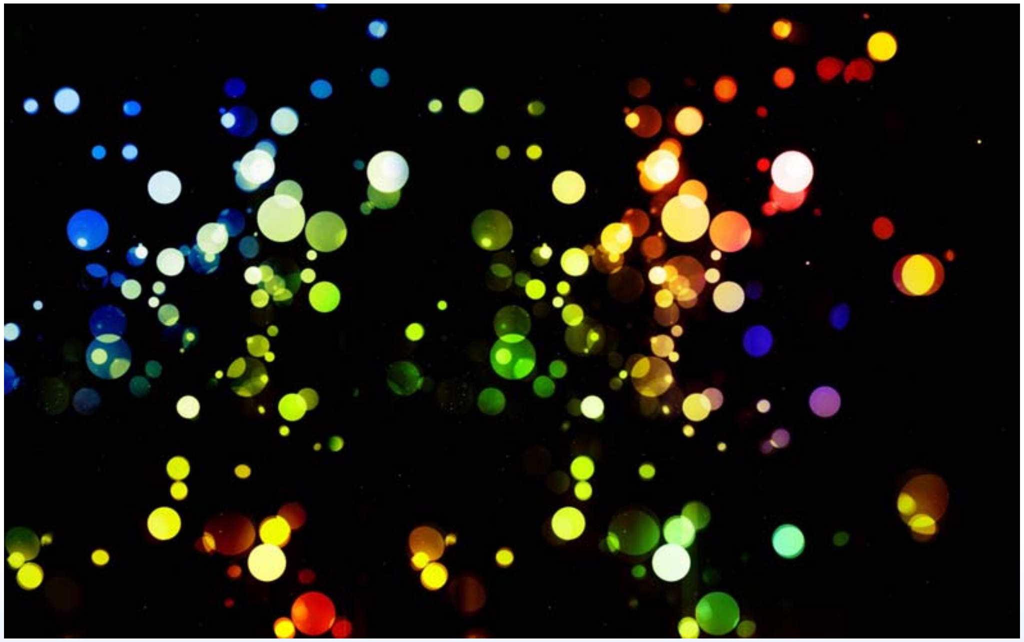


Phys 102 – Lecture 25

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

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

  Angular momentum, energy, radius quantized

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

- Today: Quantum model of light

  Einstein's photon model

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

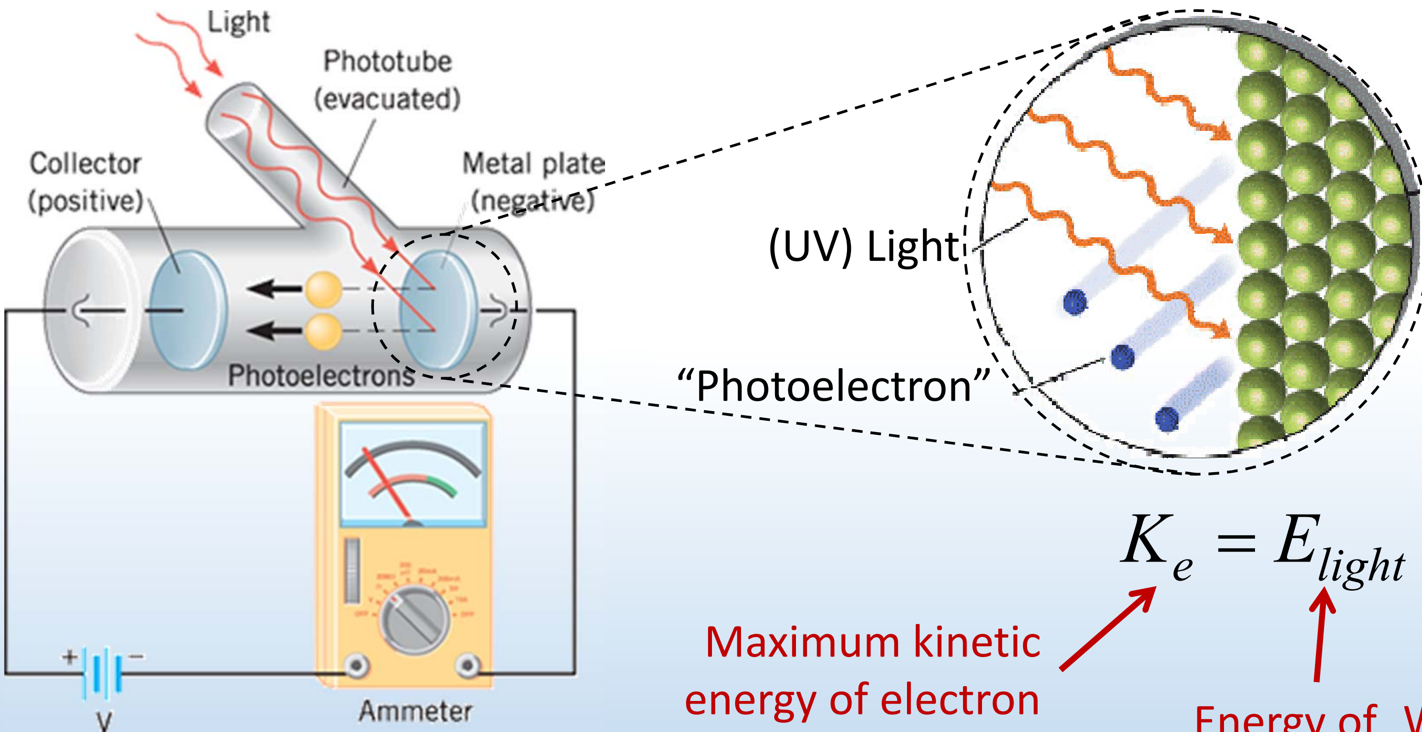
$$hc \approx 2\times10^{-25}\,\mathrm{J\cdot m} = 1240\,\mathrm{eV\cdot nm}$$

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 (K_e)

Energy of EM wave (E_{light})

Work function of metal (W_0)

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

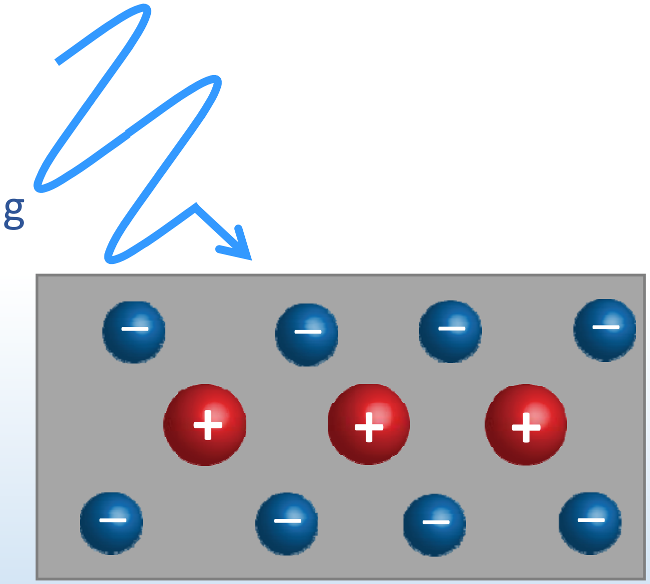
Classical model vs. experiment

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

Classical prediction

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

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



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 → $$E_{photon} = hf$$ ← 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)

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

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.

Which one emits more photons/second?

A. Red
B. Blue
C. The same

Photoelectric effect explained

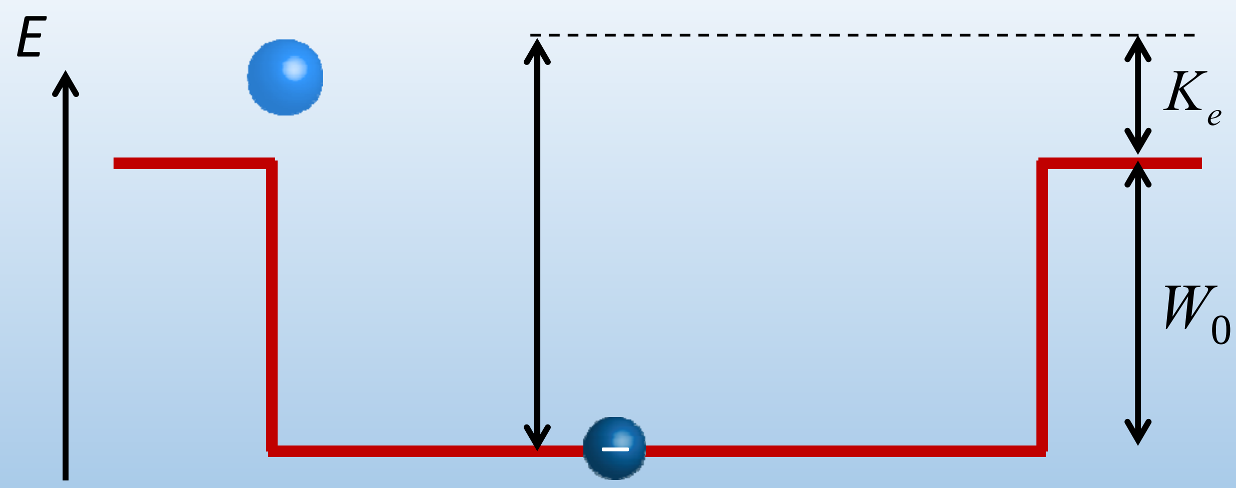
Quantum model

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

$$K_e = hf - W_0$$



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

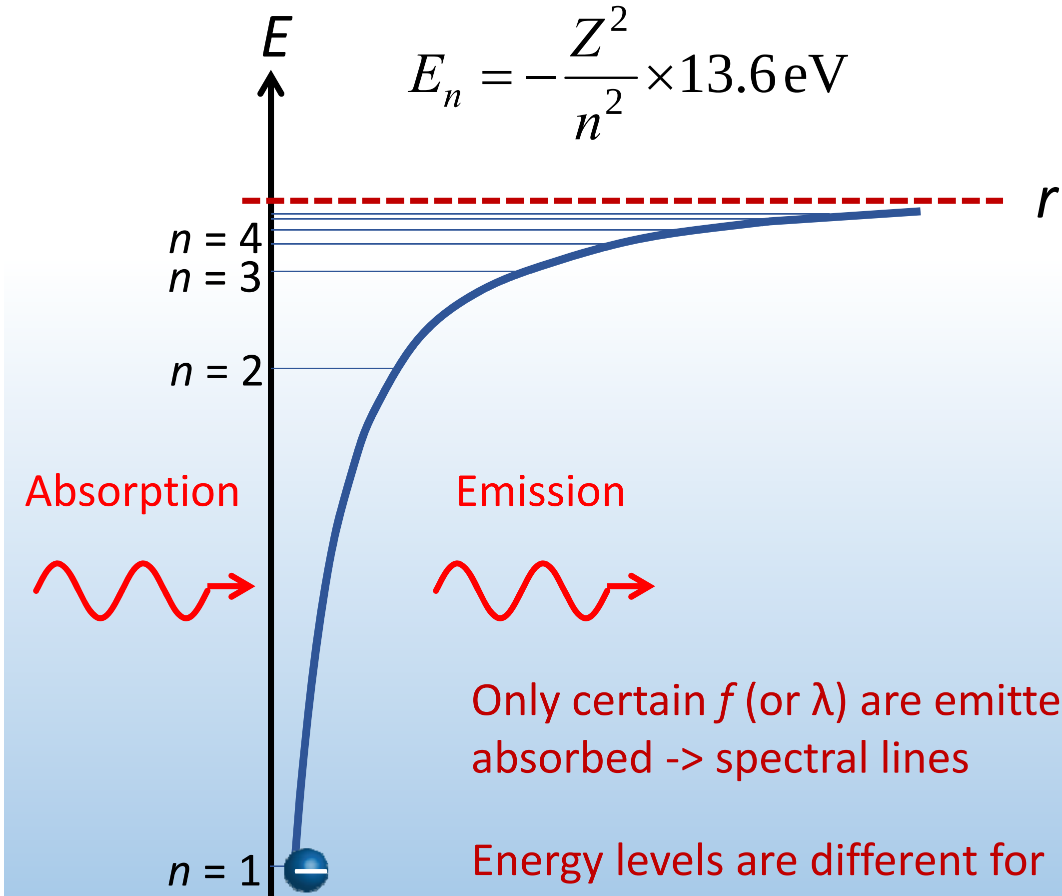
You have a choice of 3 metals. Which will work?

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

Atomic spectra

Electrons in atom are in discrete energy levels

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



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

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

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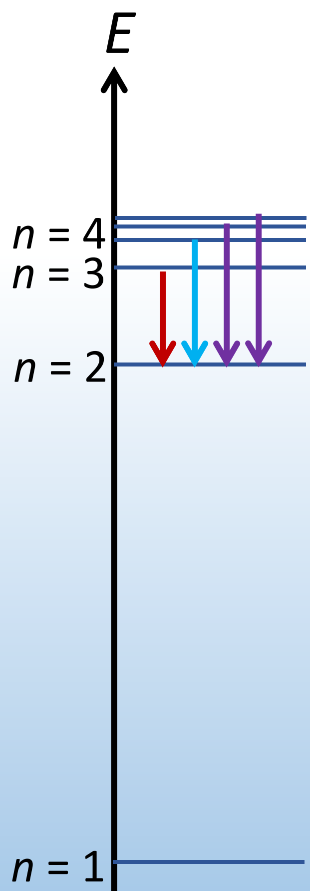
Calculation: H spectral lines

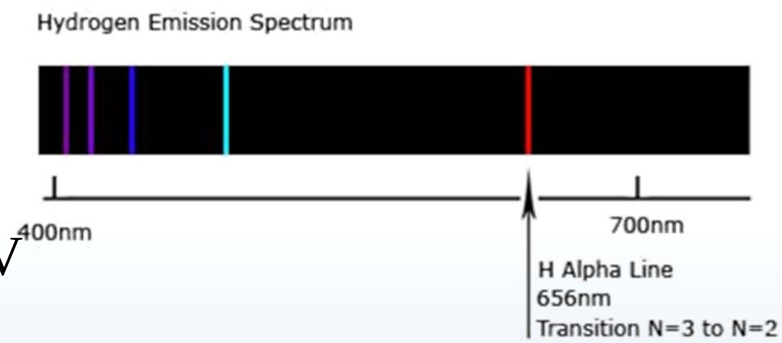
Calculate the wavelength of light emitted by hydrogen electrons as they transition from the *n* = 3 to *n* = 2 levels



Emission:

$$hf = E_i - E_f$$

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



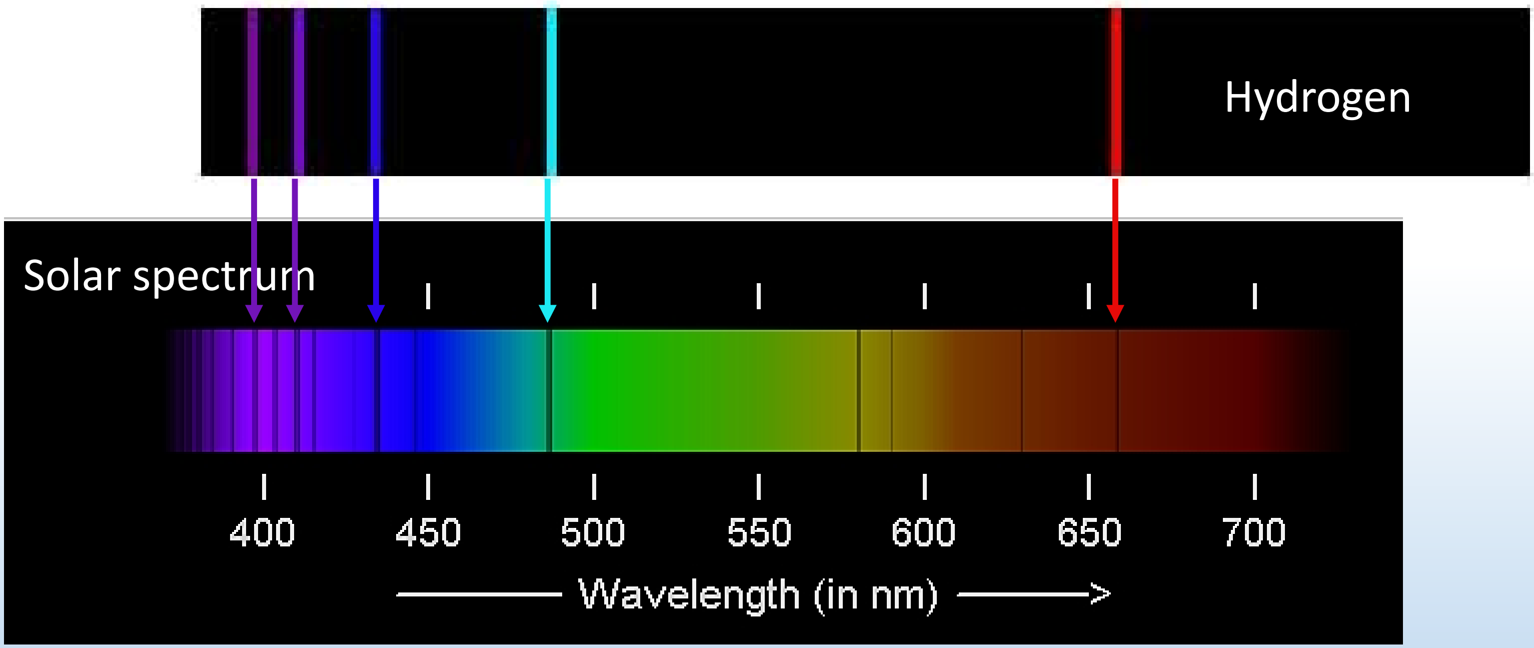
$$\frac{1}{\lambda} = Z^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)\times 1.097\times 10^{-7}\,\mathrm{m}^{-1}$$

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

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

Solar spectrum

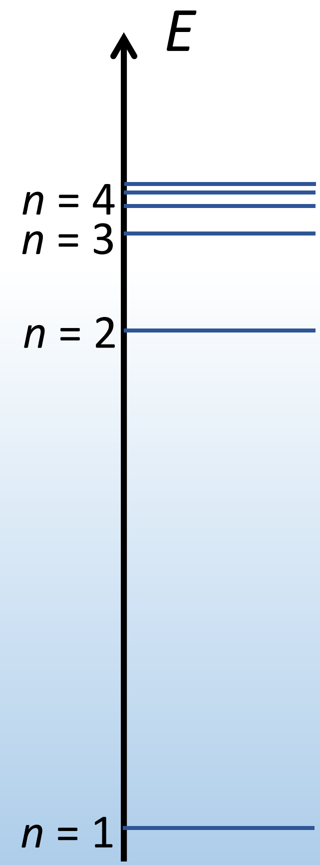
Spectrum from celestial bodies can be used to identify its composition



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?

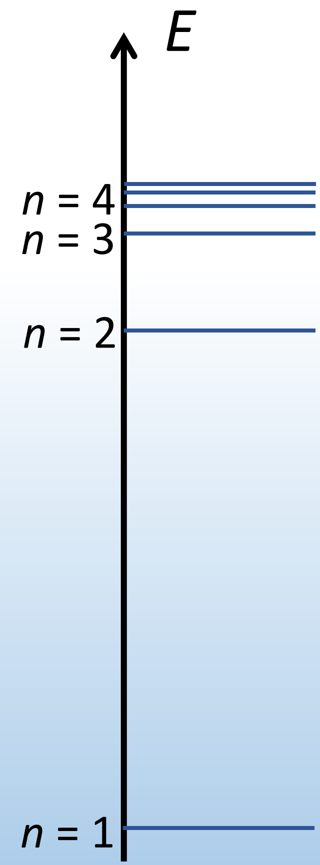
A. 1

B. 2

C. 3

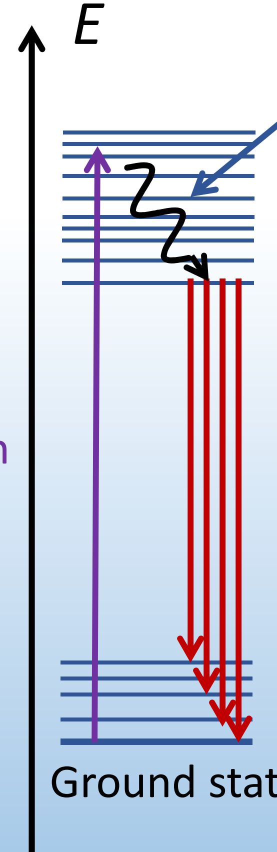
D. 4

E. 5

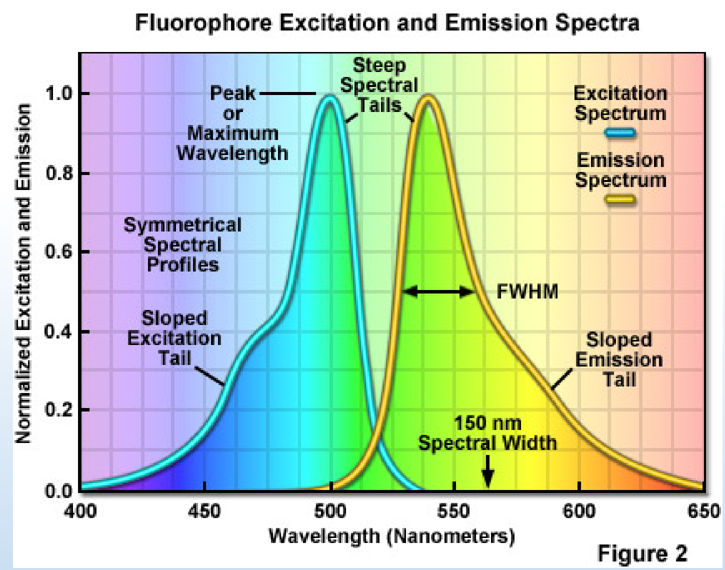


Fluorescence

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



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

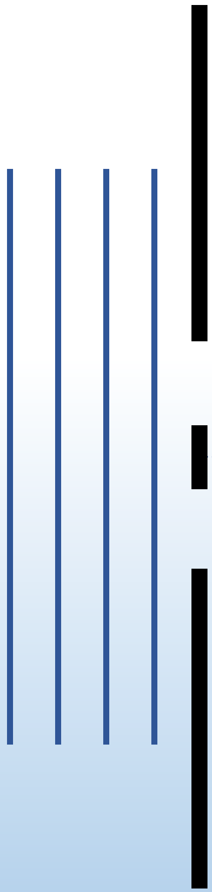


Fluorescent molecules that emit visible light absorb shorter λ (ex: UV)

DEMO

Young's double slit revisited

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



Interference pattern = probability

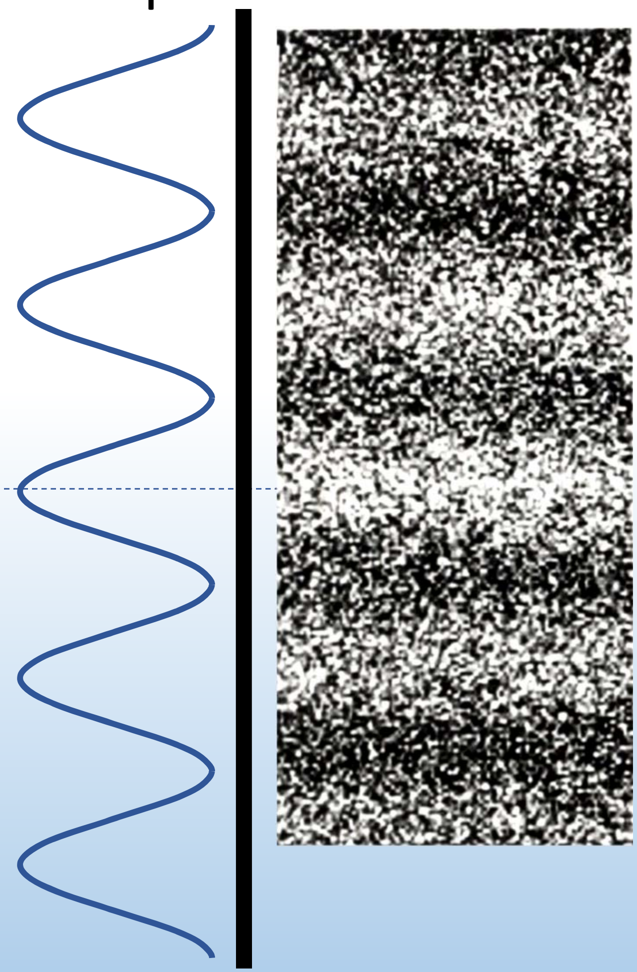
$$d \sin\theta = m\lambda$$

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 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)