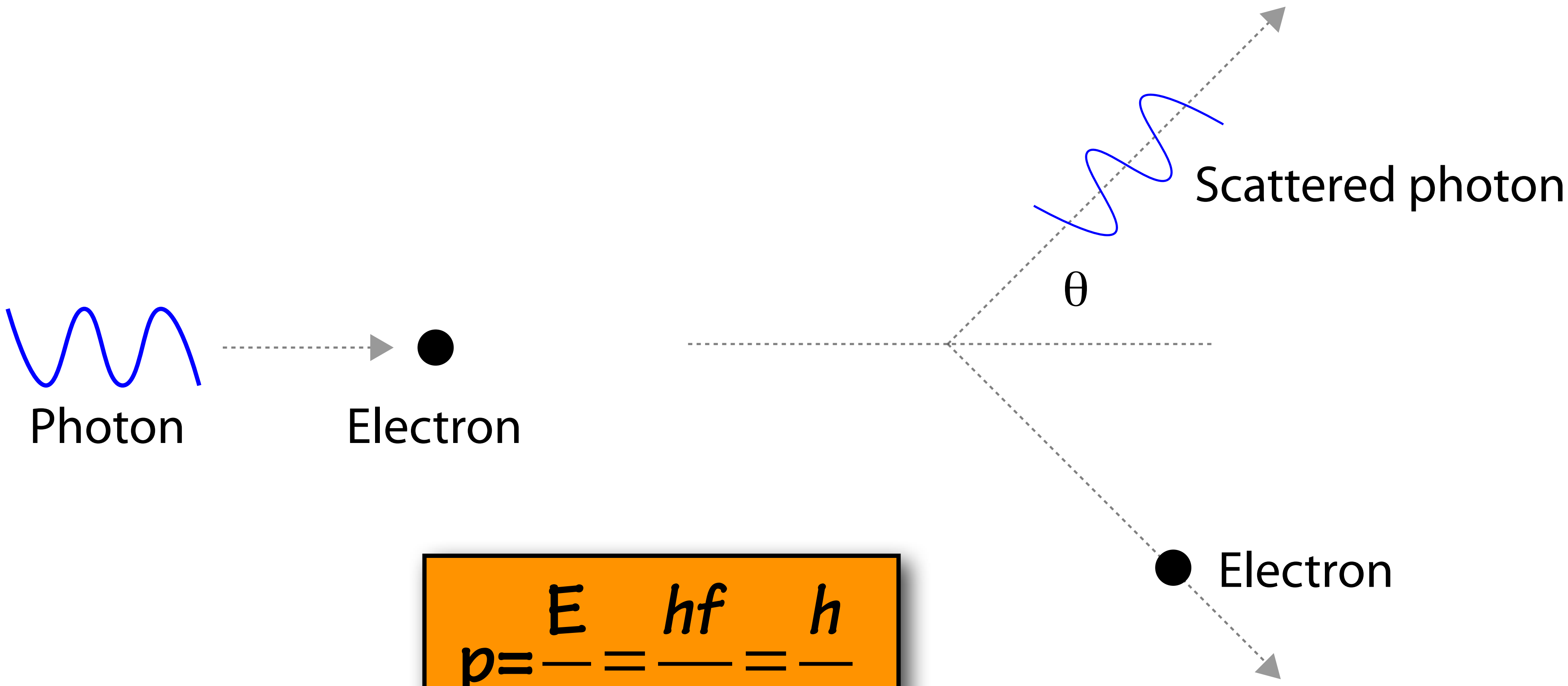
Matter & waves

Photon momentum

- The Compton effect: x-ray photons will cause a recoil of electrons.
- Photons carry momentum.
- The gain in momentum of the electron causes a loss of momentum & energy of the photon: the scattered photon has a longer wavelength.



$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Photon momentum calculations

- eg. for violet light $\lambda = 4\times10^{-7}$m
- Recall that a 1mW violet laser emits ~2×10^{15} photons per second:

Momentum per photon:

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

$$p = \frac{6.63\times10^{-34}\ Js}{400\times10^{-9}\ m}$$

$$p = 1.7\times10^{-27}\ \mathrm{kgm/s}$$

Force when photons are absorbed over a second

$$F = \frac{\Delta p}{\Delta t}$$

$$F = (1.7\times10^{-27}\ Ns/photon) \times (2\times10^{15}\ Photons/s)$$

$$F = 3\times10^{-12}\ N$$

Solar sail

De-Broglie wavelength

- Double slit experiment with electrons showed interference patterns.
- Evidence of electrons showed wave properties.
- Louis De-Broglie's idea: every particle has a De-Broglie wavelength dependent upon its momentum
- larger p = small λ
- eg. a tennis ball p = (0.05 kg)(30 m/s) = 1.5 kgm/s

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

$$\lambda = \frac{6.63 \times 10^{-34}\ Js}{1.5\ kgm/s}$$

$$\lambda = 4.0 \times 10^{-34}\ m$$

Too small a wavelength to be noticeable: the ball acts as a particle

Electron diffraction

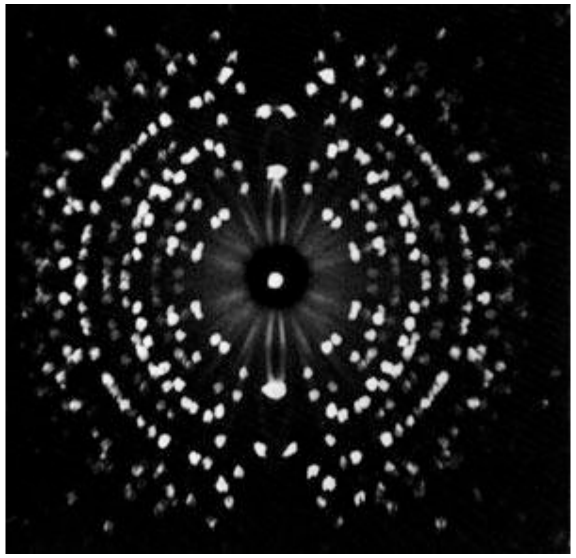
- Electrons carry much less momentum & have more noticeable wave properties.
- E = 100 eV (= 1.6×10^{-17} J), m ~ 9.1×10^{-31} kg
- This is of a size comparable to atoms, so diffraction from crystal structures is possible.

$$E_k = \frac{1}{2}mv^2 \rightarrow v = \sqrt{\frac{2E_k}{m}} \qquad v = \sqrt{\frac{2 \times 1.6\times10^{-17}\,\mathrm{J}}{9.1\times10^{-31}\,\mathrm{kg}}} = 5.9\times10^{6}\,\mathrm{m/s}$$

$$p = mv = (9.1\times10^{-31}\ \mathrm{kg}) \times (5.9\times10^{6}\ \mathrm{m/s})$$

$$p = mv = 5.4\times10^{-24}\ \mathrm{kgm/s}$$

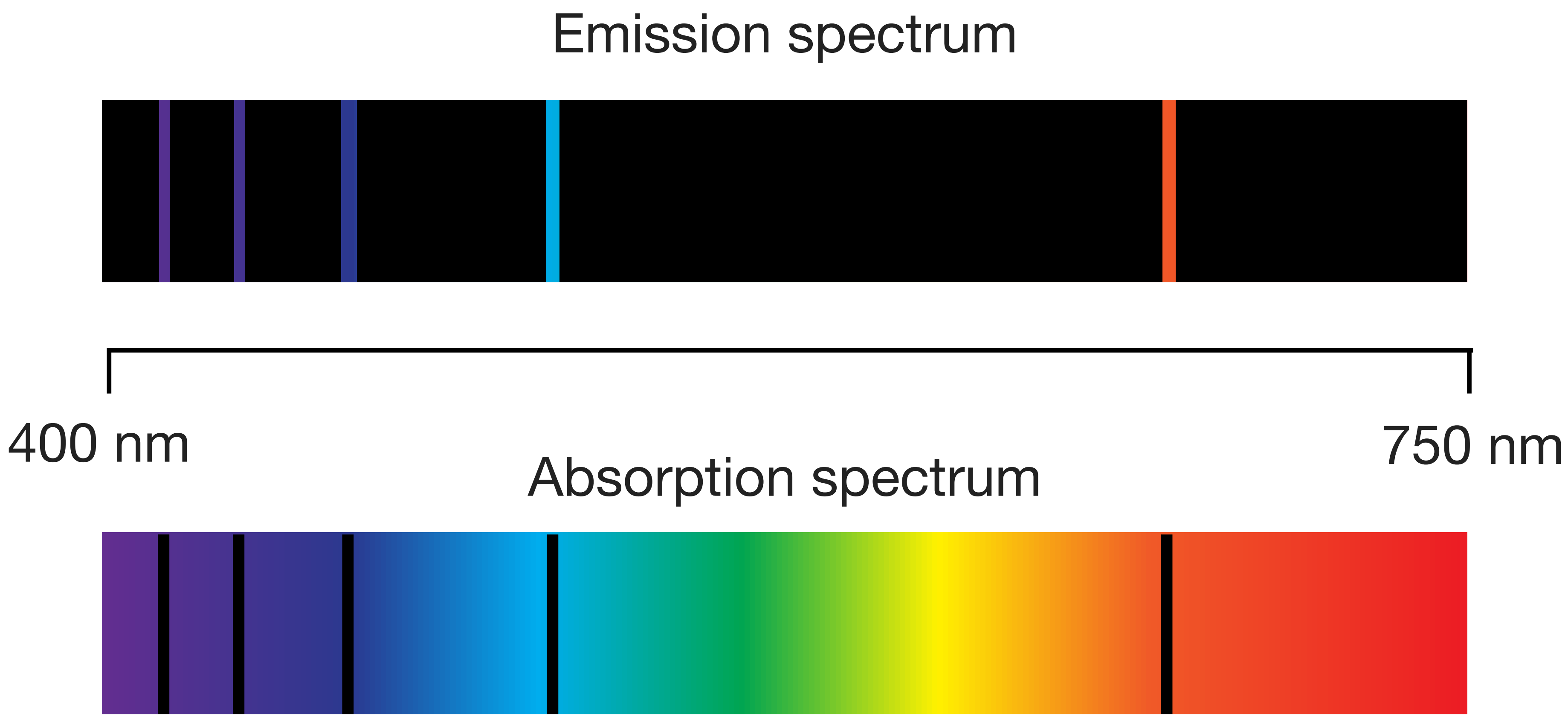
$$\lambda = \frac{6.6\times10^{-34}\ \mathrm{Js}}{5.4\times10^{-24}\ \mathrm{kgm/s}} = 1.2\times10^{-10}\,m$$



~ 10^{-10}m is considered the boundary of wave or particle behaviour

Emission & absorption spectra

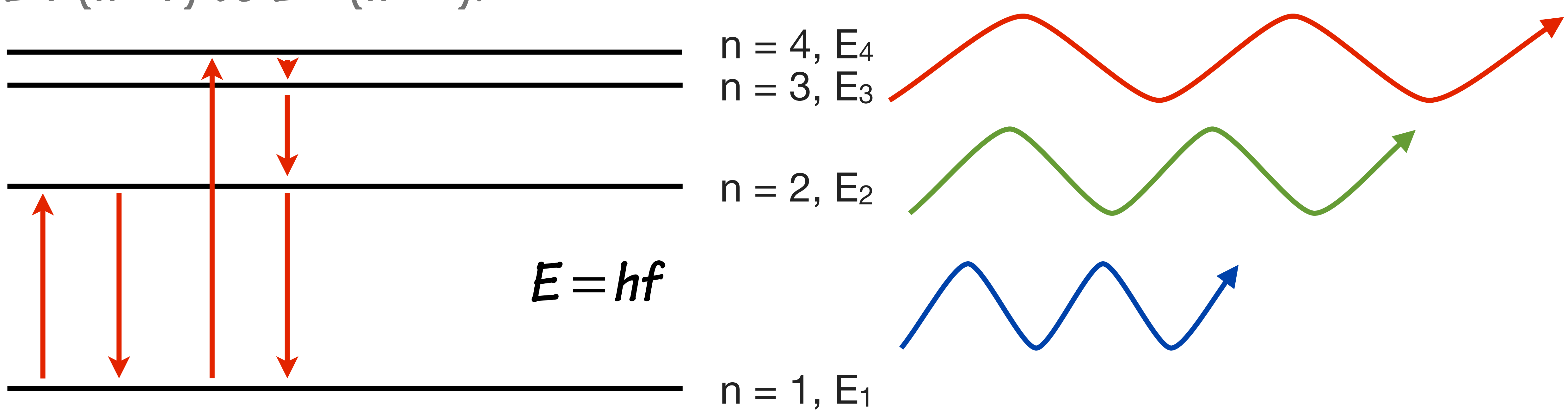
- Each element has a unique "fingerprint" - the spectrum of light that is produced when the gas is heated.
- Only certain wavelengths of light are emitted.
- If the light passes through the gas, those same wavelengths will be absorbed.



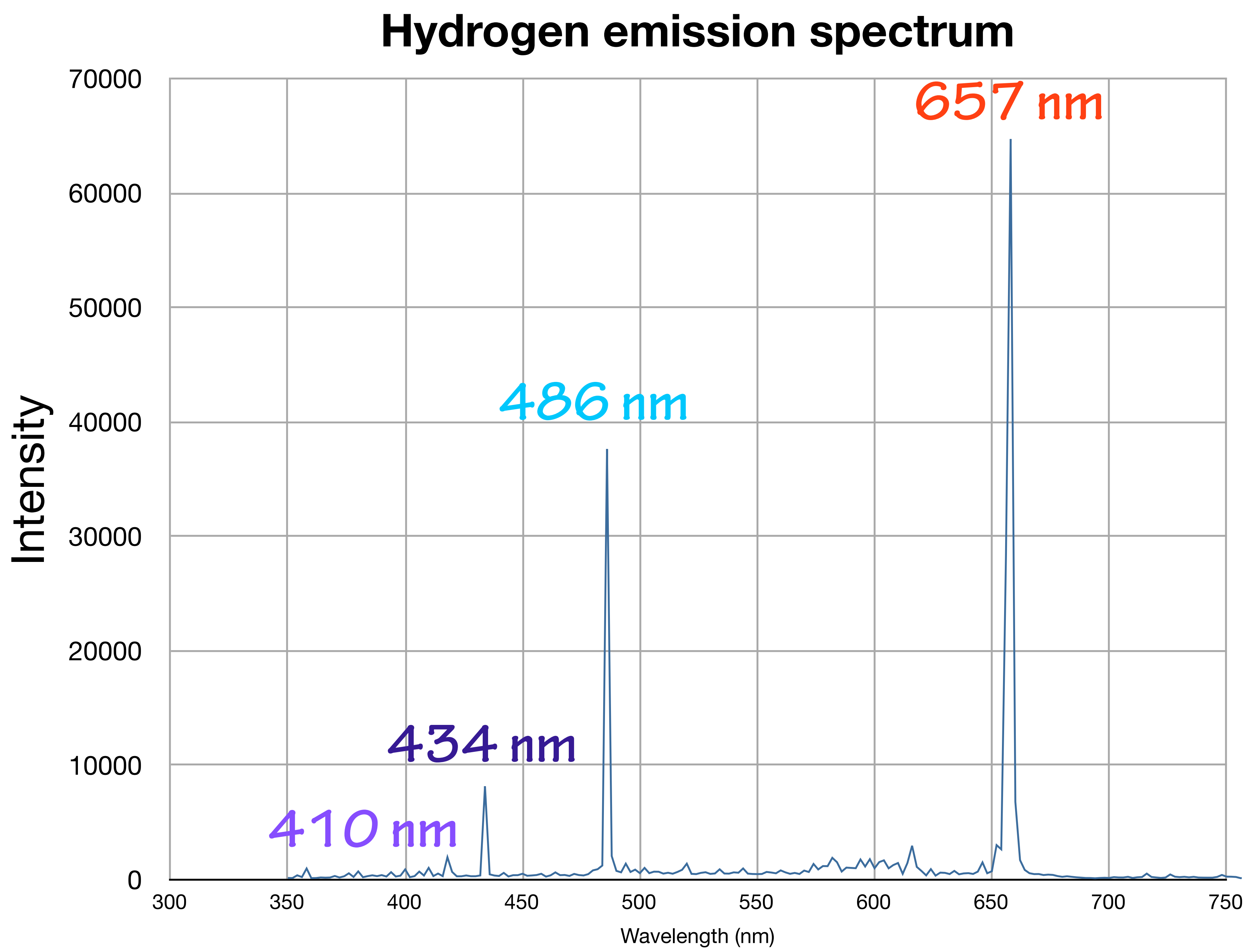
The wavelengths emitted are the same that are absorbed by the element.

Energy Levels - Bohr's model of electrons

- The "**ground state**" (E_1) is the lowest energy state.
- If an electron absorbs enough energy from a photon, then it can move up into a higher energy state.
- Likewise, an electron may emit a photon and drop down to a lower energy state. The photon energy is the difference of electron energies.
- This explains "Spectral lines": discrete wavelengths emitted (or absorbed) by a particular atom. (Used to identify what elements are present!)
- The "ionisation energy" is the energy required to bring an electron from E1 (n=1) to E∞ (n=∞).

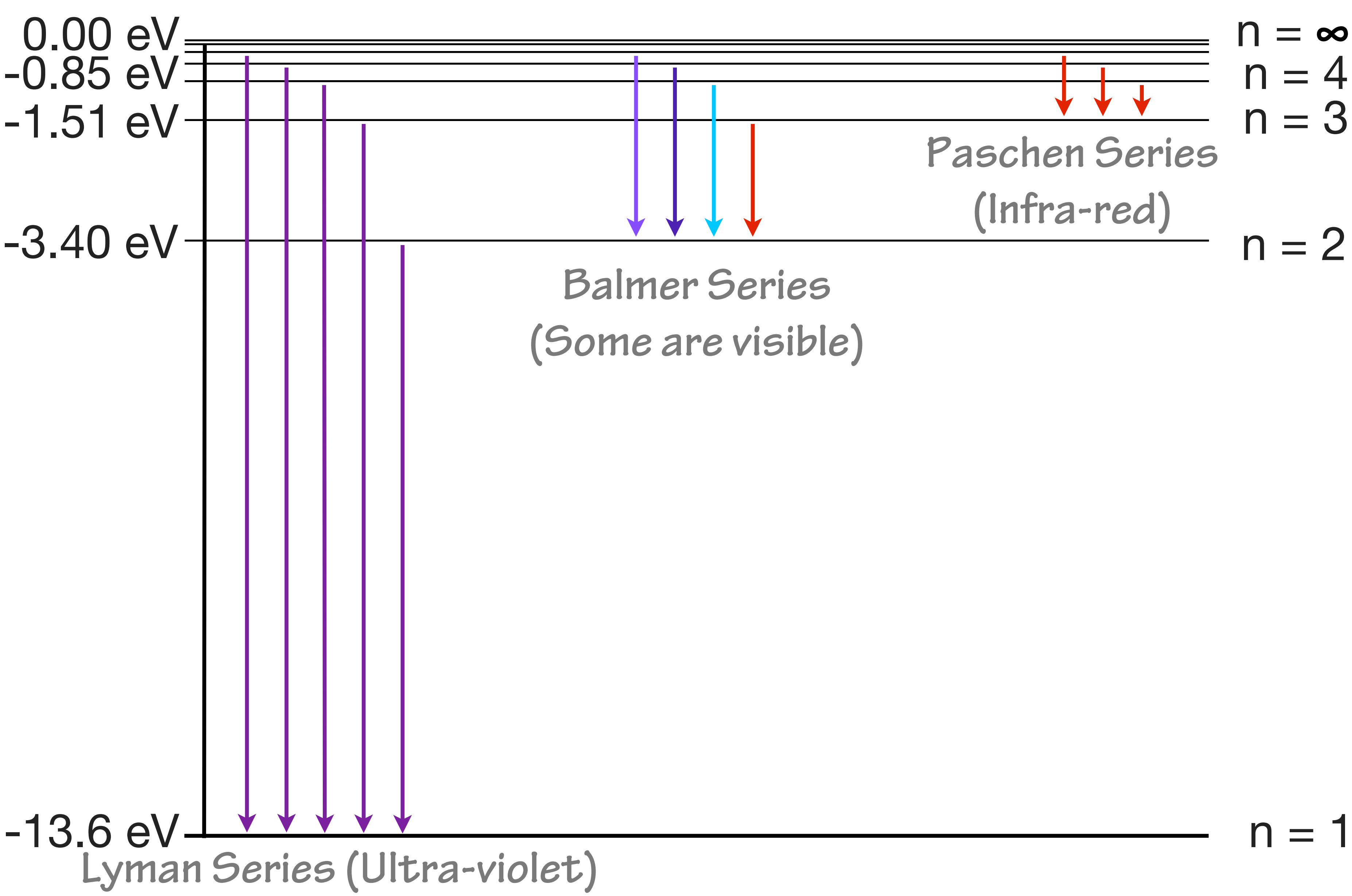


Hydrogen emission spectrum



Hydrogen emission series

- Distinct spectral lines are visible from hydrogen that correspond to the emission of energy from excited states to lower energy states.
- Each series represents the emission to one particular state.



$$E = \frac{-13.6eV}{n^2}$$

n	E
∞	0 eV
10	-0.14 eV
9	-0.17 eV
8	-0.21 eV
7	-0.28 eV
6	-0.38 eV
5	-0.54 eV
4	-0.85 eV
3	-1.51 eV
2	-3.40 eV
1	-13.60 eV

Hydrogen emission series - The Balmer Series

- The visible emission lines of Hydrogen are from the Balmer series, as electrons make the transition to the n = 2.

$$3 \rightarrow 2 \quad E = -3.40 eV - -1.51 eV = -1.89 eV$$

$$\lambda = \frac{hc}{E} = \frac{(4.14 \times 10^{-15} eVs)(3.00 \times 10^{8} m/s)}{1.89\ eV}$$

$$= 657 nm\ (red)$$

$$4 \rightarrow 2 \quad E = -3.40 eV - -0.85 eV = -2.55 eV$$

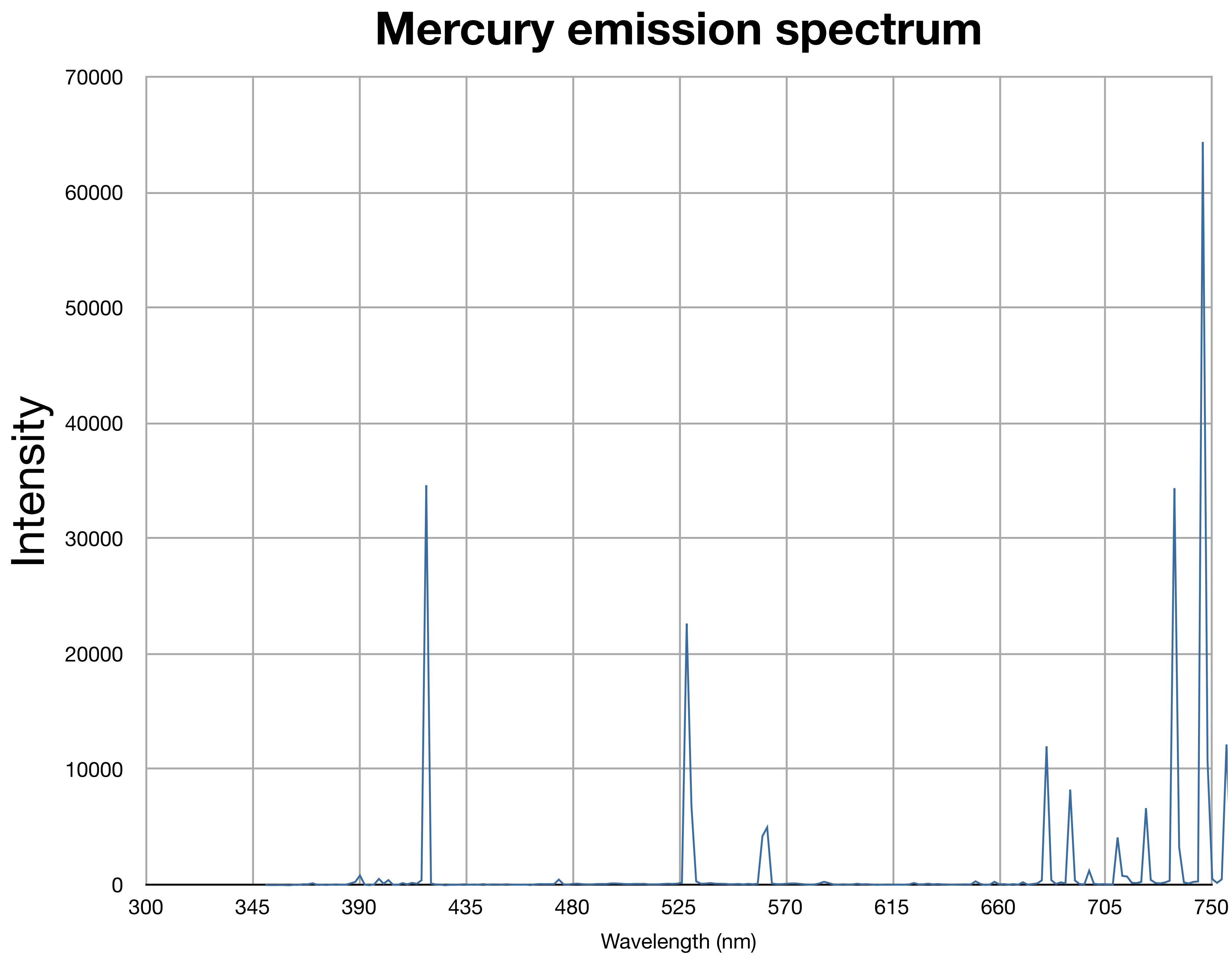
$$\lambda = \frac{hc}{E} = \frac{(4.14 \times 10^{-15} eVs)(3.00 \times 10^{8} m/s)}{2.55\ eV}$$

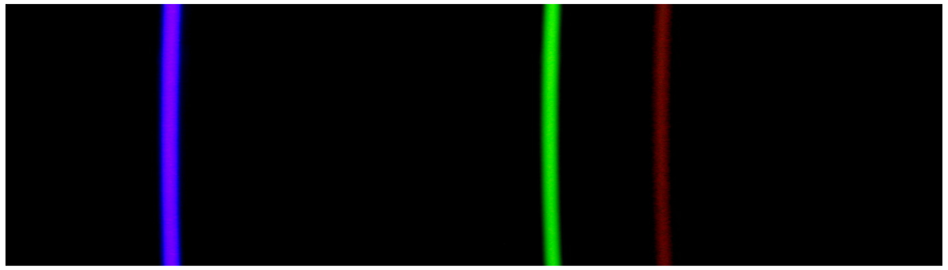
$$= 486 nm\ (cyan)$$

n	E
∞	0 eV
10	-0.14 eV
9	-0.17 eV
8	-0.21 eV
7	-0.28 eV
6	-0.38 eV
5	-0.54 eV
4	-0.85 eV
3	-1.51 eV
2	-3.40 eV
1	-13.60 eV

The visible spectrum ranges from 400 nm (3.1 eV) to 750 nm (1.7 eV)

Mercury emission spectrum

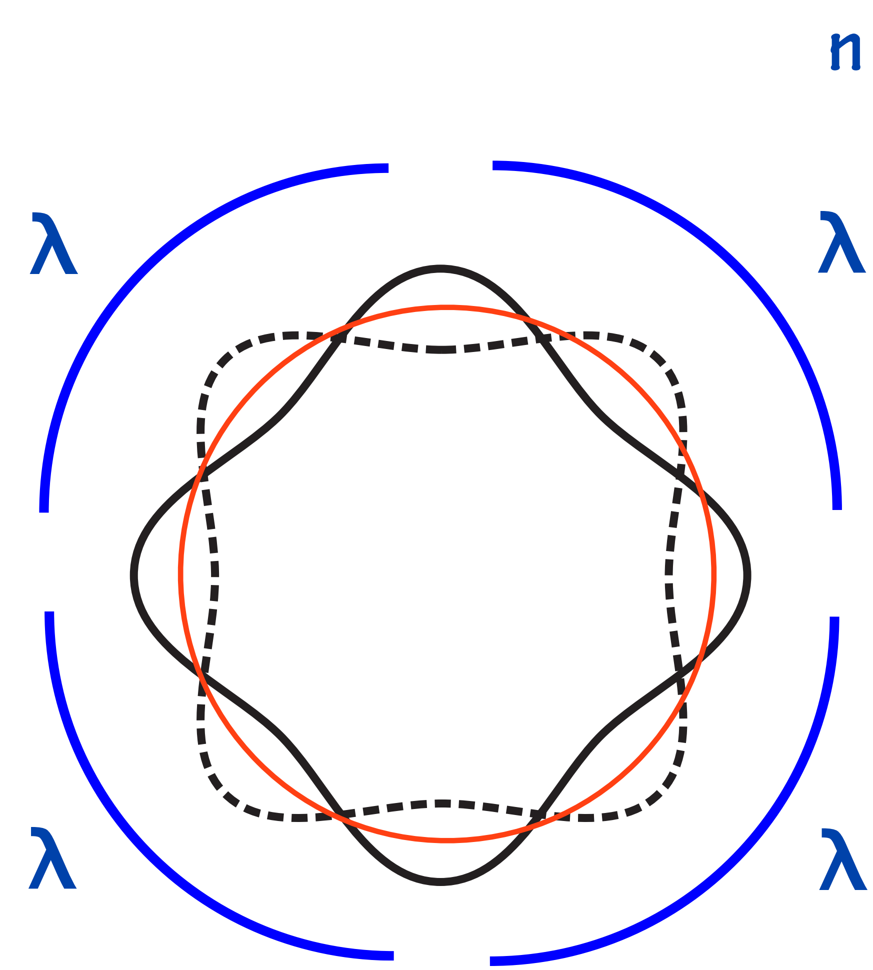




Electron waves

- Bohr developed a model of the atom in which the electrons could only occupy orbits of certain radii that correspond to discrete energy levels.
- De Broglie's hypothesis: the electron can only exist in an orbit if it forms a standing wave.
- The radius must be a multiple of a wavelength.
- If the radii are quantised, then so is the energy of the electrons.
- This explains why only certain energy levels & emission spectra are possible.

$$2\pi r = n\lambda = \frac{nh}{p}$$



Bohr's theory

Light - a wave or a particle?

- Light clearly shows wave properties (interference) & particle properties (photoelectric effect).
- Likewise, matter shows wave properties (electron diffraction).
- So it seems that we need to use both models to properly describe light.
- But as a general rule, the larger an object is - the more particle like it will be acting.
- For electromagnetic radiation - the shorter the wavelengths will act more like particles.
- Remember that waves or particles are just models to try to describe a physical situation.