22 Quantum physics

22.1 Energy and momentum of a photon

Candidates should be able to:	
1	understand that electromagnetic radiation has a particulate nature
2	understand that a photon is a quantum of electromagnetic energy
3	recall and use $E = hf$
4	use the electronvolt (eV) as a unit of energy
5	understand that a photon has momentum and that the momentum is given by $p = E / c$

- In classical wave theory, electromagnetic (EM) radiation is assumed to behave as a wave.
- This is supported in that EM radiation exhibit wave like phenomena's such as diffraction, interference, refraction and interpolation.
- However, quantum mechanics also assumes that EM radiation behave as particles.
- An example of this is the **photoelectric effect**.
- Photons are fundamental particles which make up all forms of EM radiation.
- A photon is a massless "packet" or a "quantum" of EM energy
- Each photo carries a specific amount of energy, and transfers this energy all in one go.
- **A photon's** energy (E in Joules) can be calculated with the following equation

$$E = hf$$

Here h is Planck's constant (6.63×10^{-34} Js) and f is the frequency (Hz)

- The electronvolt (eV) is a unit usually used for the very small energies in quantum energies
- Electronvolt is derived from

$$V = \frac{E}{Q}$$

Rearranging this you will get

$$E = VQ$$

- The **electronvolt** is defined as **the energy gained by an electron travelling through a potential difference of 1 volt**

$$1eV = 1.6 \times 10^{-19} \text{ J}$$

- Einstein showed that a photon travelling in a vacuum has momentum (eventhough photos have no mass!)
- The momentum (p) of a photon is given by

$$p = \frac{E}{c}$$

Here E is the energy of the photon and c is the speed of light (3×10^8 ms^{-1}).

- The units for p is in **Ns**.

22.2 Photoelectric effect

Candidates should be able to:

1 understand that photoelectrons may be emitted from a metal surface when it is illuminated by electromagnetic radiation

2 understand and use the terms threshold frequency and threshold wavelength

3 explain photoelectric emission in terms of photon energy and work function energy

4 recall and use $hf = \Phi + \frac{1}{2}mv_{max}^2$

5 explain why the maximum kinetic energy of photoelectrons is independent of intensity, whereas the photoelectric current is proportional to intensity

- **Photoelectric effect**, is a phenomenon in which **electrons are released from the metal surface when it absorbs EM radiation.**
- Electrons released from photoelectric effect is called **photoelectrons**.
- Photoelectric effect is evidence that light is quantised (discrete) because each electron can only absorb **a single photon** and only at frequencies **above a threshold frequency**.
- The **threshold frequency** is **the minimum frequency of the EM radiation that is needed to remove a photoelectron from the surface of a metal**.
- The threshold wavelength can be determined from the wave equation

$$c = f\lambda$$

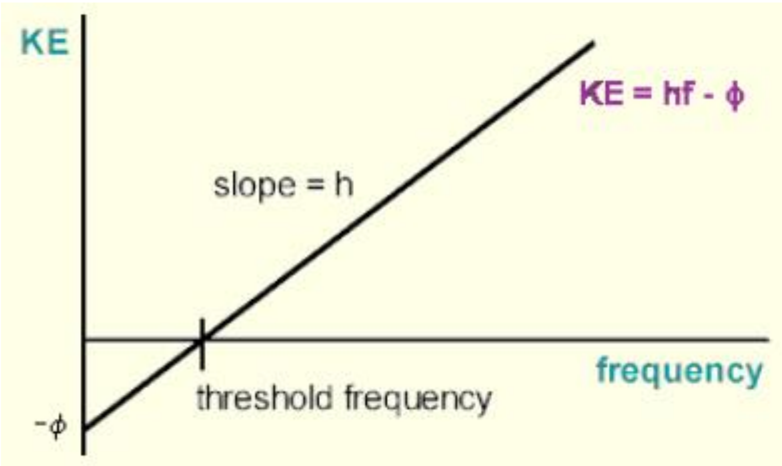
- **Threshold wavelength** is **the longest wavelength of incident EM radiation that would remove a photoelectron from the surface of a metal**.
- Since energy is conserved, total energy of a photon hitting the surface of the metal (hf) is equal to the **sum** of the threshold energy (Φ) with the KE of the photoelectron ($1/2mv^2$ or KE)

$$hf = \Phi + 1/2mv^2$$

rearranging you get

$$KE = hf - \Phi$$

- If you plot the above equation out you get



- From the graph
  -the x-axis intercept would represent the reciprocal of the threshold wavelength
  -the slope would equal h
  -the y-axis intercept would represent the work function
- If the incident photons do not have a high enough frequency (f) and energy to overcome the work function (Φ), then no electrons will be emitted
- When $hf_0 = \Phi$ and f_0 = threshold frequency, photoelectric emission just occurs.
- **KE** depends only on the **frequency** of the incident photon and not on the intensity of the radiation (number of photons striking the metal).
- This is because each electron can only absorb one photon to escape the surface of the metal (if the photon has an energy equal to Φ or higher)
- Different metals will have different Φ.
- Hence KE is **independent of intensity**.
- Photoelectric current on the other hand is dependent on intensity.
- This is because when more photos strike the metal surface, more photoelectrons are emitted.
- This is due to each electron absorbing a single photon.
- Hence, an increase number of photons increases the current.
- Photoelectric current is directly proportional to intensity.

22.3 Wave-particle duality

Candidates should be able to:

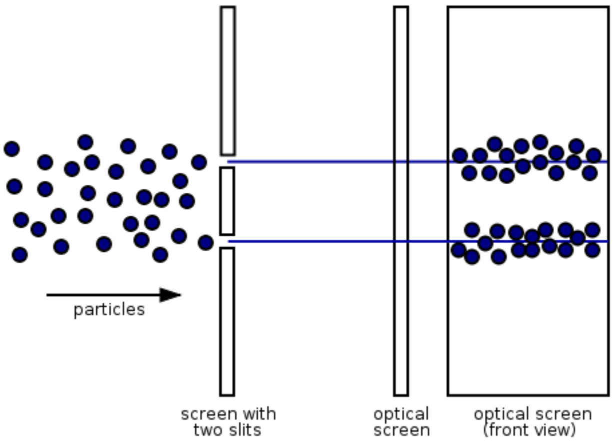
1 understand that the photoelectric effect provides evidence for a particulate nature of electromagnetic radiation while phenomena such as interference and diffraction provide evidence for a wave nature

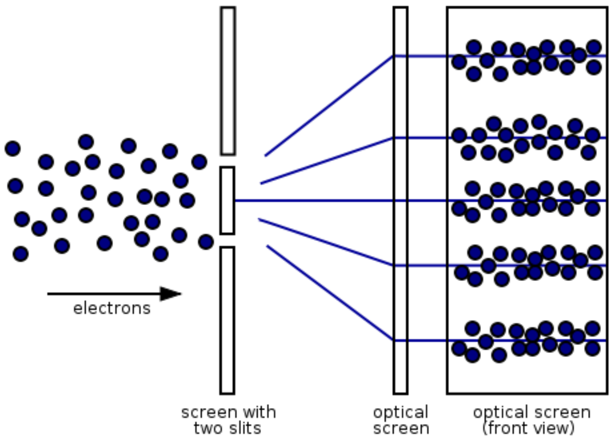
2 describe and interpret qualitatively the evidence provided by electron diffraction for the wave nature of particles

3 understand the de Broglie wavelength as the wavelength associated with a moving particle

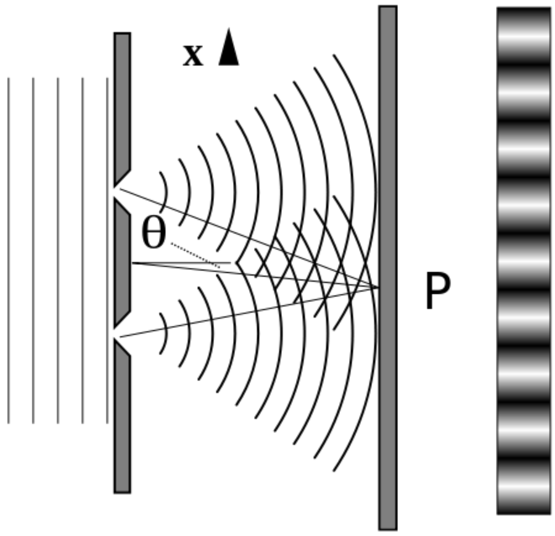
4 recall and use $\lambda = h / p$

- Light waves can be described as either a particle or a wave.
- This phenomenon is called the wave-light particle duality.
- Lights propagates as wave as is evident from Young's Double Slit Experiment
- Light can also interact with other matter such as electrons as evident in the photoelectric effect.
- Louis de Broglie discovered that matter such as electrons can behave as a wave.
- His experiment showed that a diffraction pattern is produced when a beam of electron is direct at a thin graphite film.
- Graphite is used because its structure allows for gaps between planes of atoms to act as slits.
- The results below show classical model vs actual wave property of electrons.





- De Broglie's experimental results were very similar to Young's Double slit experiment



- De Broglie suggested that electrons must also hold wave like properties such as wavelength.
- The faster an electron travels, the larger its wavelength.
- This is **de Broglie's wavelength** which can be applied to all particles.
- An electron in a metal has de Broglie's wavelength around 10nm.
- A particles width would need to be around that size in order to exhibit similar properties.
- De Broglie suggested that the momentum (p) of a particle can be determined from

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

Where h is the plank constant and ʎ the wavelength (meters).

22.4 Energy levels in atoms and line spectra

Candidates should be able to:

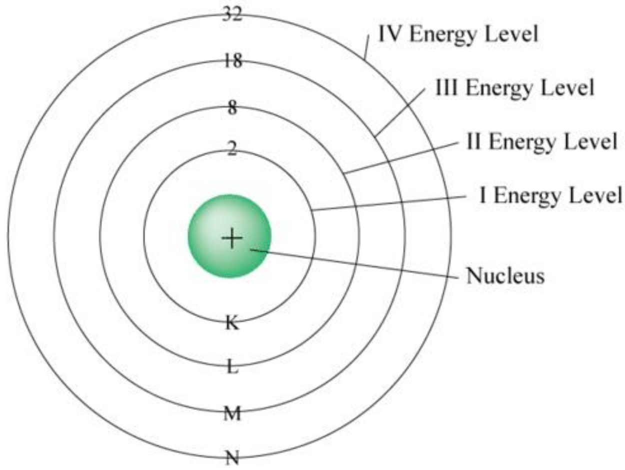
1 understand that there are discrete electron energy levels in isolated atoms (e.g. atomic hydrogen)

2 understand the appearance and formation of emission and absorption line spectra

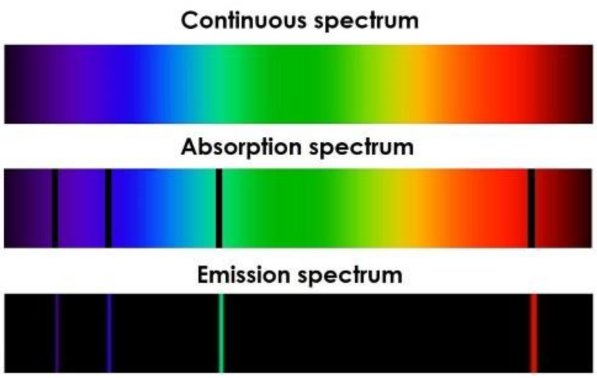
3 recall and use $hf = E_1 - E_2$

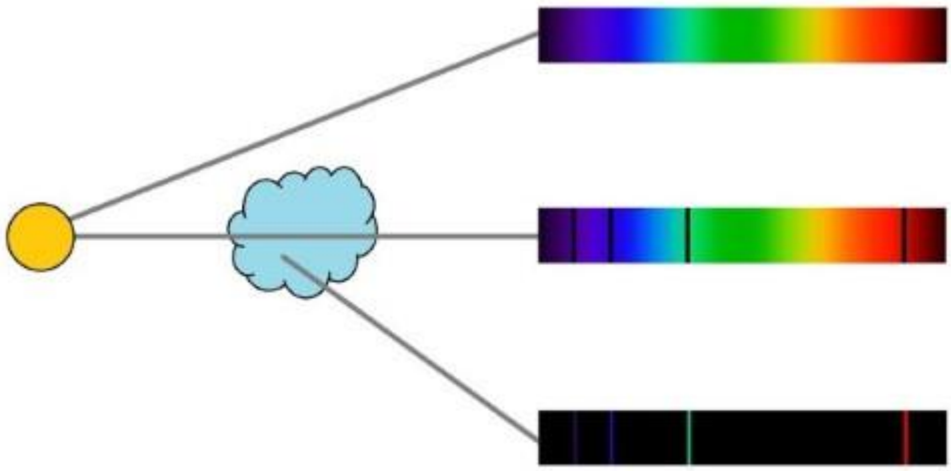
- **Energy levels** (also called electron shells) are fixed distances from the nucleus of an atom which electrons can be found.
- Energy levels are like staircase.
- You can stand on one step or another but not in-between.

- Electrons are the same thing; they can occupy one energy level or another but not the space in-between energy levels.



- Electrons usually occupy the lowest energy level available (ground state).
- Electrons can gain energy and move up levels if it absorbs energy by either:
  -collision with other atoms or electrons
  -absorbing a photon
  -a physical source, such as heat
- When a electron gets promoted to a higher level it is said to be in an **excited state**.
- This is known as **excitation**.
- If it gains enough energy to leave the atom, it is called **ionisation**.
- When an electron returns to a lower energy state from an excited state it releases the excess energy in the form of a **photon**.
- A **line spectra** is a phenomenon which occurs when excited atoms emit light of certain wavelengths which correspond to different colours.
- The light emitted can be observed as a series of coloured lines with dark spaces in-between.
- Each element produces a unique set of spectral lines.
- This allows the element to be identified by their line spectrum.
- There are two types of line spectra; **emission** and **absorption** spectra.





- When an electron transitions from a higher energy level to a lower energy level, this results in emission of a photon (emission spectra).
- An electron can be excited by the absorption of a photon.
- When white light passes through a cool, low pressure gas it is found that certain wavelengths are missing.
- This is line spectrum is called absorption spectrum.
- An absorption spectrum consists of a continuous spectrum containing all the colours with dark lines at certain wavelengths.
- When photons pass through the gas, electrons are excited to higher levels.
- When these electrons return to their ground state, the photons are emitted in all directions, rather than in the original direction of the light.
- This makes it appear to the observer that some wavelengths are missing.
- The wavelengths missing from an absorption spectrum are the same as their corresponding emission spectra of the same element.
- The different between two energy levels ($E_1 - E_2$) is equal to the photon energy emitted (hf)

$$hf = E_1 - E_2$$