22 Quantum physics

22.1 Energy and momentum of a photon

- 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
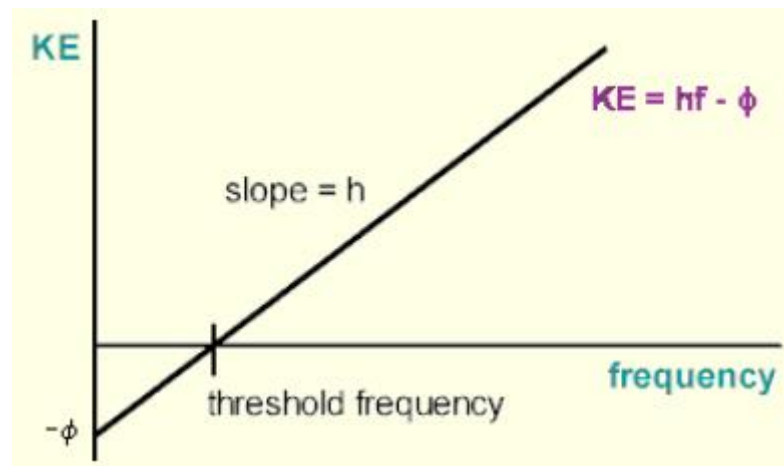
- From the graph
  -the x-axis intercept would represent the reciprocal of the threshold wavelength
  -the slope would equal h
  -the y-axis intercept would represent the work function
- If the incident photons do not have a high enough frequency (f) and energy to overcome the work function (Φ), then 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

- 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.
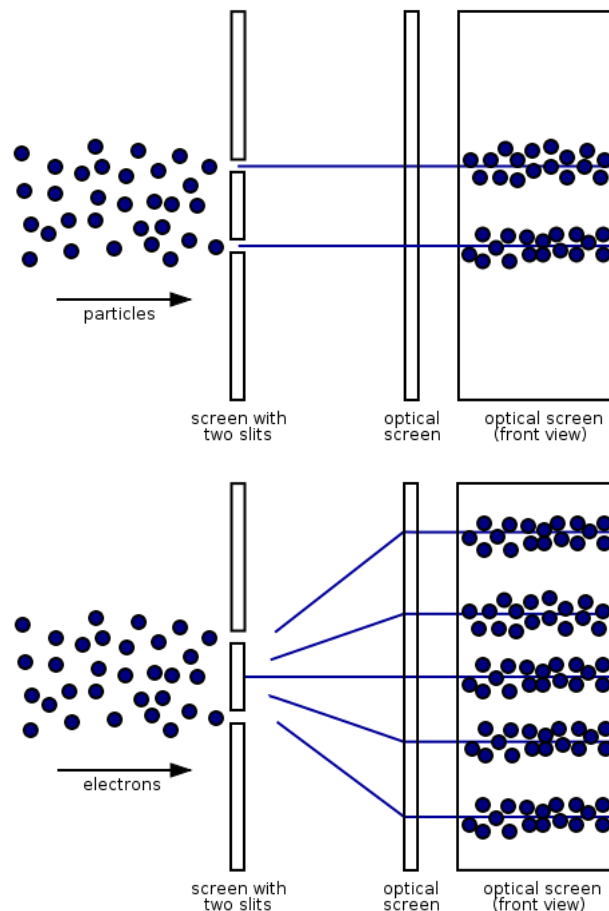
- De Broglie's experimental results were very similar to Young's Double slit experiment
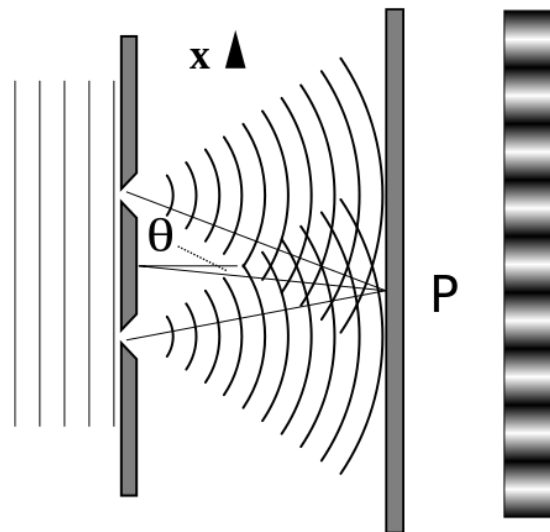
- De Broglie suggested that electrons must also hold wave like properties such as wavelength.
- The faster an electron travels, the larger its wavelength.
- This is **de Broglie's wavelength** which can be applied to all particles.
- An electron in a metal has de Broglie's wavelength around 10nm.
- A 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 λ 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.
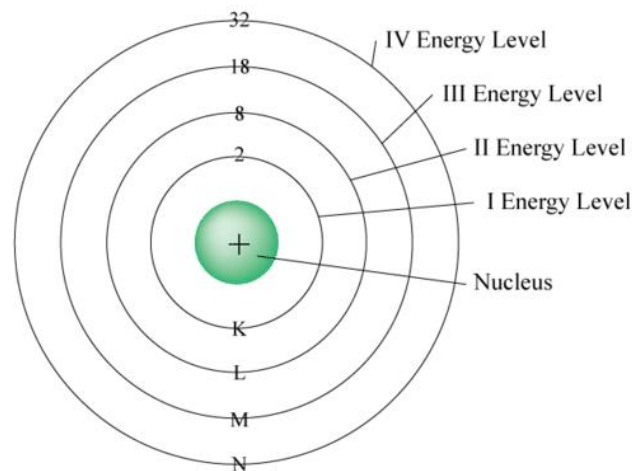
- Electrons usually occupy the lowest energy level available (ground state).
- Electrons can gain energy and move up levels if it absorbs energy by either:
  -collision with other atoms or electrons
  -absorbing a photon
  -a physical source, such as heat
- When a electron gets promoted to a higher level 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.
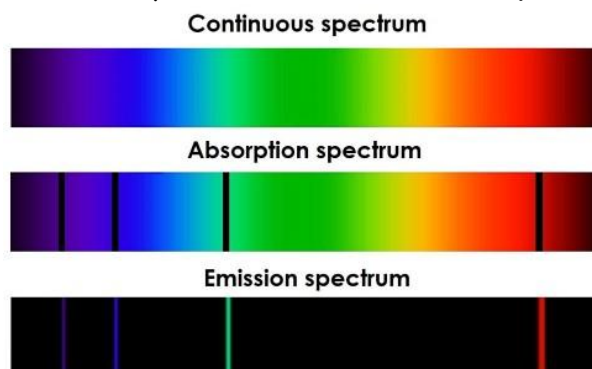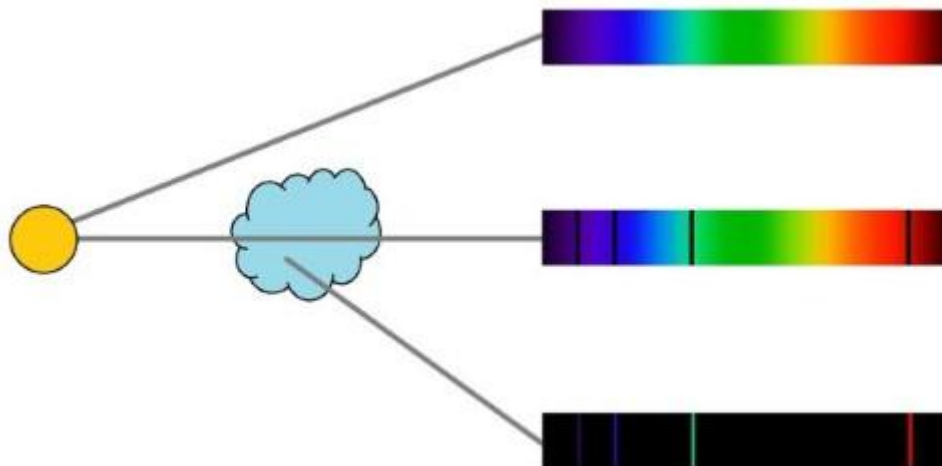
- When an electron transitions from a higher energy level to a lower energy level, this results in emission of a photon (emission spectra).
- An electron can be excited by the absorption of a photon.
- When white light passes through a cool, low pressure gas it is found that certain wavelengths are missing.
- 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)

$$hf = E_1 - E_2$$