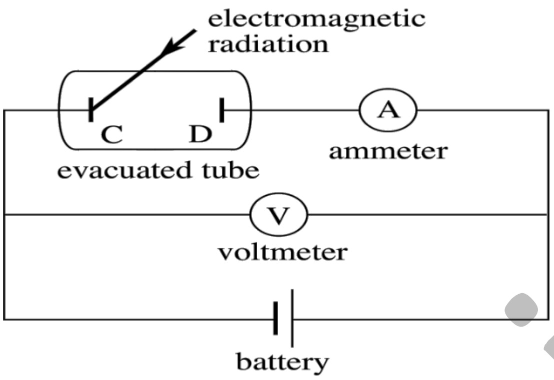
19 Quantum Physics

Energy of a Photon

The **photon** is a quantum of electromagnetic (EM) radiation. $E = hf = \frac{hc}{\lambda}$, where $h = 6.63\times10^{-34}$ Js (given)

The **electronvolt** (eV) is the KE gained by a single unbound electron when it passes through a p.d. of 1V in a vacuum. 1 eV = 1.60×10^{-19} J

The Photoelectric Effect



The **photoelectric effect** is when photoelectrons are emitted from a metal surface when EM radiation of sufficient frequency falls on it.

Experimental results and explanations

Result 1: For a given metal, no photoelectrons are emitted when illuminated by light below a minimum **threshold frequency** f_0, regardless of intensity.
Explanation: The **work function ϕ** of a metal is the minimum energy required to liberate a delocalized electron from the surface of the metal. One electron only interacts with one photon at a time. Since all the energy of each photon is given to an electron,
$\Phi = E_{min}$ of photon $= hf_0$

Result 2: For incident light of frequency > f_0, V_S increases with f but is independent of intensity.
$E_{photon} = \phi + KE_{max}$.

The Photoelectric Effect

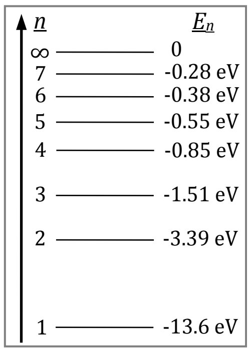
Experimental results and explanations

Result 3: Increasing the **intensity** of light increases the photoelectric current.
Intensity $I = \frac{P}{A} = \frac{n_p}{t} \times \frac{hf}{A}$, where intensity is proportional to no. of photons, while current is proportional to no. of electrons.

Energy Levels in Atoms

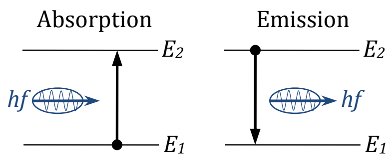
Key ideas of Bohr Model of the atom

- Electrons can only exist in orbits that have discrete quantized energy.
- Minimum energy required to remove electrons from outermost energy level is the **ionisation energy**.
- All energy levels are negative since $E_\infty = 0$ and ground state E_1 is most stable.



Methods of excitation/de-excitation

- Absorption/Emission of a photon with energy exactly equivalent to the difference in energy levels
- Absorption/Transfer of energy from/to other atoms or electrons



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Line Spectra

Emission Line Spectra

An **emission line spectrum** consists of a series of separate bright coloured lines on a dark background, and is formed when hydrogen gas is heated and the light given off is passed through a prism.

Atoms are excited to higher excited states via thermal agitation or electric field. When the atoms de-excite spontaneously, photons corresponding energy level differences are emitted.

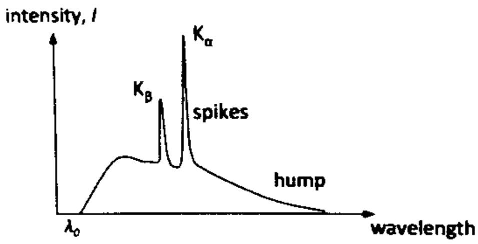
Absorption Line Spectra

An **absorption line spectrum** is a continuous spectrum crossed by dark lines, produced when white light is passed through a cool vapour or gas. Photons corresponding to the difference in energy levels of the gas atoms are absorbed, while those not absorbed form the continuous spectrum background in the forward direction.

The excited atoms then de-excite, re-emitting photons of similar energies to those absorbed, but in random directions, hence intensity in the forward direction is reduced, forming discrete dark lines.

X-ray Spectra

In an X-ray tube, emitted electrons are accelerated towards a metal anode. Photons are produced when the fast moving electrons interact with the anode atoms.



X-ray Spectra

The typical x-ray spectrum consists of:

- The **hump**, or **continuous spectrum**, which is generated by 'braking' (**bremsstrahlung**) radiation, is due to photons emitted by electrons as they undergo different degrees of scattering and lose KE upon hitting target atoms
- The lowest, or **cut-off wavelength** λ_0 corresponding to the highest energy of the x-ray emission, and is due to the fastest electrons having all their KE converted to photons. Given that an electron is accelerated through a p.d. V,
  $KE_{max} = eV = \frac{hc}{\lambda_0} \rightarrow \lambda_0 = \frac{hc}{eV}$
- The **several spikes** depending on the target metal used. Electrons may have sufficient energy to knock out inner-shell electrons of target atom, leaving vacancies.
- Outer-shell electrons can de-excite, producing x-ray photons with energies equivalent to energy level differences.

Wave-particle Duality

In 1923, Louis de Broglie suggested that all matter has a wave-like nature, with wavelength λ given by $\lambda = \frac{h}{p} = \frac{h}{mv}$, which was confirmed through **electron diffraction**.

Photon momentum

Photons, while massless, have momentum given by $p = \frac{h}{\lambda}$. Since KE = $\frac{1}{2}mv^2$, KE = $\frac{p^2}{2m}$.

The Uncertainty Principle

Position-momentum uncertainty

$\Delta x \Delta p_x \geq h$, i.e. the more precise a particle's position, the less precise its momentum.

