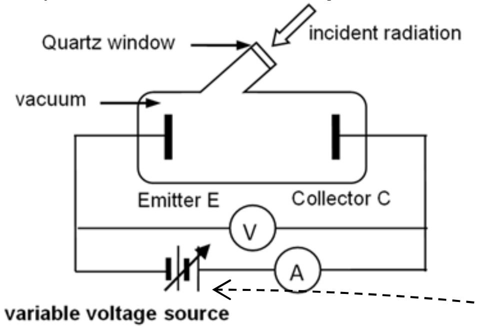
Quantum Physics I

PHOTOELECTRIC EFFECT

- Photoelectric effect is the phenomenon where electrons are emitted from a metal surface when electromagnetic radiation of sufficiently high frequency is incident on the surface.

- The photoelectric effect provides **evidence for the particulate nature** of electromagnetic radiation:
  (1) Existence of a threshold frequency below which no photoelectrons are emitted proves that electromagnetic radiation (EM) consists of discrete quanta of energy given by *hf*.
  (2) Instantaneous emission of photoelectrons when all the photon energy is delivered immediately to the electron in a single collision.
  (3) Maximum kinetic energy of the photoelectrons (existence of a stopping potential) being dependent only on the discrete energy of photon and independent on the intensity of radiation.

- Set-up for the **Photoelectric Experiment**:



  - When radiation of sufficiently high frequency (greater than the threshold frequency) is incident on the emitter plate E, electrons near the surface of the metal plate will gain sufficient energy to escape.
  - The variable voltage source maintains electrodes at different known potentials.
  - The emitted electrons that have sufficient energy will travel to the collector C and a current will be detected by the ammeter.

- To **determine Stopping Potential / max KE of photoelectrons**:
  - Illuminate metal E with an electromagnetic radiation of sufficient frequency. Adjust the potential difference between the emitter E and the collector C such that potential of C is held negative with respect to E, ***by reversing the polarity of the voltage source***.
  - Adjust the variable voltage source slowly such that the negative potential is made more negative just until no electron can reach C which is indicated as zero photocurrent by the ammeter. This is the stopping potential where this minimum negative potential will stop even the most energetic electron from reaching C.
  - In this situation, all the kinetic energy ($\frac{1}{2}mv^2$) of the fastest electrons will be converted into electric potential energy ($U = q\Delta V$) just before reaching C.

- Photoelectric equation:

Photon energy = Work function energy + max KE of photoelectron

$$hf = \Phi + E_{k\,max}$$

$$\frac{hc}{\lambda} = hf_o + \frac{1}{2}m\left(v_{max}\right)^2$$

$$= \frac{hc}{\lambda_o} + eV_s$$

- A ***photon*** is a discrete bundle (or quantum) of electromagnetic energy.
  Energy of a single photon, $E = hf = \frac{hc}{\lambda}$
  Intensity of a beam of EM radiation, $\text{intensity} = \frac{P}{A} = \frac{E_{total}}{tA} = \frac{NE_{1photon}}{tA} = \frac{Nhf}{tA}$

- The **work function energy** Φ of a material is defined as *minimum* amount of the energy necessary to remove an electron from the *surface* of the material energy
  It is constant for a given metal.

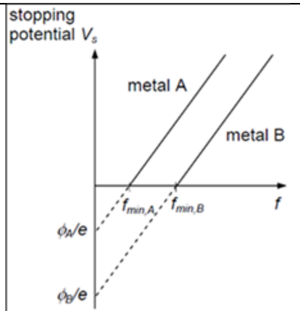
- The **threshold frequency**, f_o is the minimum frequency of the incident radiation for the electron to escape.
  For photoelectric emission to occur**,** $f > f_o$ or $\lambda < \lambda_o$

- **Stopping potential**, V_s is the minimum retarding potential to stop all the electrons from reaching the collector plate.

- Electrons are emitted with a range of KE. Those most loosely-bound electrons will be emitted with more KE while the more tightly-bound ones will be emitted with smaller KE.

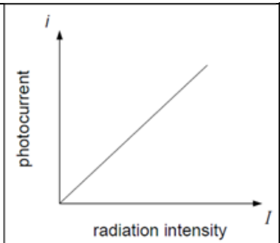
- **Photoelectric Electric Graphs**:

1.



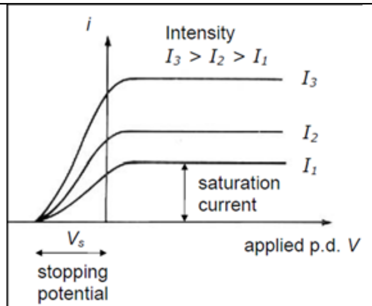
- Respective threshold frequencies are different as the metals have different work functions.
- The slope of the lines is the same since the slope is given by (h / e)

2.



- The photocurrent I (rate of emission of photoelectrons) is proportional to the intensity of EM radiation (rate of photons incident) and a straight line graph is obtained. (assumes constant frequency f and $f > f_o$)

3.



- Retarding potential V is increased negatively, the stopping potential V_S is the same for a beam of low intensity and one of high intensity.
- When V is positive all the photoelectrons are collected so that the current is constant.
- A beam of high intensity produces more electrons than one of low intensity.

WAVE-PARTICLE DUALITY

- Waves can exhibit particle-like characteristics and particles can exhibit wave-like characteristics.
- **de Broglie wavelength** of a particle:
  $\lambda = \frac{h}{p} = \frac{h}{mv}$
- Packets of EM radiation of wavelength λ would therefore possess a momentum $p = \frac{h}{\lambda}$. When photons are incident on a surface, they therefore exert a force on the surface, resulting in a pressure on the surface. This pressure is known as “radiation pressure”.
- Using $KE = \frac{p^2}{2m}$, the wavelength of a particle can be related to its *KE* by $\lambda = \frac{h}{\sqrt{2m(KE)}}$
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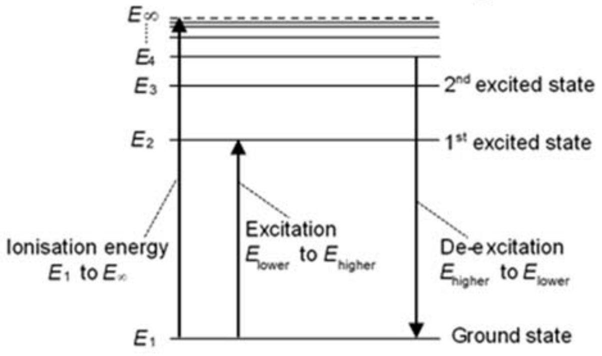
Observation	Evidence
Light as a wave	Double slit interference fringes are observed. Light through single slit undergoes diffraction. Light can be polarized.
Light as particles	Observations of **photoelectric effect** can only be explained if light is quantized.
Electrons as particles	Electrons undergo collision, has mass and charge
Electrons as a wave	**Electron diffraction** where electron beam produces a diffraction pattern when passed through a thin carbon film.

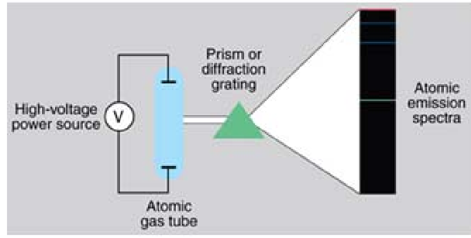
ENERGY DIAGRAMS & LINE SPECTRA

- Line Spectra provides evidence for the existence of **discrete energy levels** in the atom.
- Electrons can revolve round the nucleus only in *certain allowed orbits.*

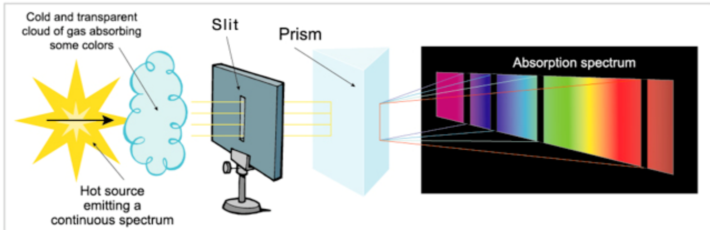


- An atom can only absorb or emit energy when an electron transits from one state to another.
  $\Delta E = E_{higher} - E_{lower} = hf = \frac{hc}{\lambda}$
- Excitation by absorption of photons or high speed collision by another particle.
- An atom in excited states are very unstable and the electron would almost immediately de-excites to a lower energy level, emitting a photon corresponding to the energy difference in the process.

- **Emission line spectrum** consists of discrete bright coloured lines in a dark background.
  It is produced when
  (1) Gases are placed in a discharge tube at low pressure. A voltage (several kilo-volts) is applied between metal electrodes in the tube which is large enough to produce an electric current in the gas.
  (2) The gas becomes excited by the collisions with the electrons passing through the tube, from cathode to anode of the discharge tube.
  (3) The excited gas atoms are unstable. When the gas atoms transits to a lower energy level, the excess energy is emitted as electromagnetic radiation (photon) with a specific frequency.
  (4) The frequency *f* of the emission line is dependent on the difference between the high and low energy levels, $\Delta E = hf$. Due to the discrete energy levels, only certain high-to-low energy level transitions are possible within the atom, therefore only certain frequency lines are present in the spectrum.

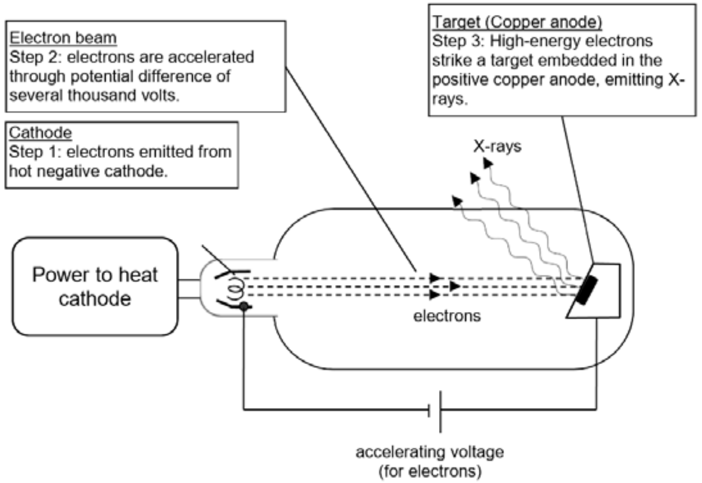


- **Absorption line spectrum** consists of dark lines against a continuous spectrum of the white light.
  It is produced when
  (1) It is produced when white light containing all frequencies passes through a cold gas.
  (2) Those incident photons whose energies are exactly equal to the difference between the atom’s energy levels are being absorbed. Since the energy levels are discrete, only photons of certain frequencies are absorbed.
  (3) When the atoms transit back to the ground state, the photons of the same frequencies are then re-radiates but *in ALL directions*.
  (4) Consequently, the parts of the spectrum corresponding to these wavelengths appear dark (or “missing”) in comparison with the other wavelengths.



Quantum Physics II (X-Rays & Uncertainty Principle)

X-ray Production



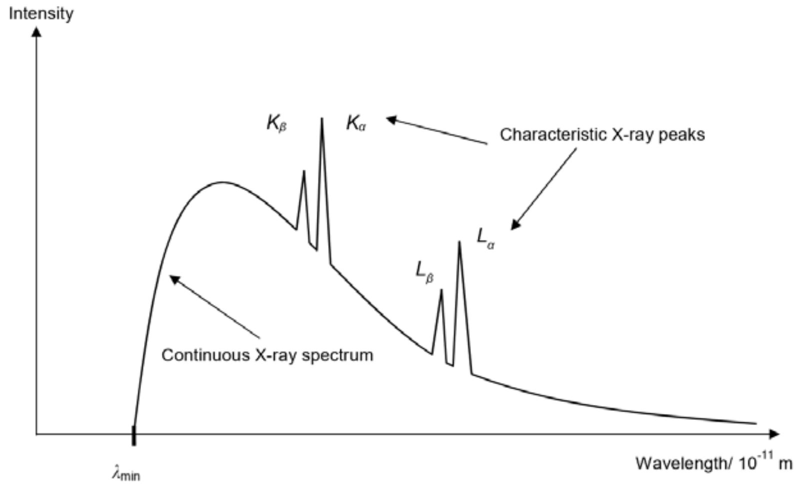
Heisenberg Uncertainty Principle

$$\Delta p \Delta x \gtrsim h$$

where h = Planck's constant 6.63×10^{-34} J s

It tells us that *simultaneous measurement of both position and momentum of an object precisely is not possible*. The more accurately we attempt to measure the position so that Δx is small, the greater will be the uncertainty in momentum Δp, and vice-versa.

X-ray Spectrum



Characteristic X-ray peaks

- An accelerated electron from the cathode collides into an orbiting electron of a target atom that is orbiting in the *K-shell*. If sufficient energy is transferred by the accelerated electron to the orbiting electron, the latter electron can be ejected from the target atom, leaving a *vacancy* in the K-shell.
- When the vacancy in the *K*-shell (n = 1) is filled by an electron from the *L*-shell (n = 2), an X-ray photon of the $\boldsymbol{K_\alpha}$ characteristic X-ray is emitted
- If the vacancy in the K-shell is filled by an electron dropping from the *M*-shell (n = 3), an X-ray photon of the $\boldsymbol{K_\beta}$ characteristic X-ray is emitted
- The wavelengths of these X-rays produced can be determined by the following equation: $hf = \frac{hc}{\lambda} = E_n - E_1$; $n = 2, 3, \ldots$
- Since the energy differences between the discrete energy levels are characteristics of the target atom, the wavelengths of the K_α and K_β characteristic X-rays are unique for each element.

Continuous X-ray spectrum

- An electron with an initial kinetic energy $E_{k,initial}$ collides with a target atom
- As the electron approaches a nucleus in the target atom, it deflects due to the attractive force between the nucleus and the electron and emits electromagnetic energy in the form of a photon (X-ray)
- Hence it loses kinetic energy
- The energy of the photon released depends on the magnitude of the acceleration. The closer an electron approaches the nucleus, the larger the deflecting force, the higher the energy of the photon.
- As different electrons approach the nucleus with different proximity, there will be a distribution of photon energies, and hence a wide range of wavelengths.
- There is a sharply defined minimum wavelength λ_{min} that corresponds to the highest energy x-ray photon, resulting from a collision in which an incident <u>highly energetic electron stops abruptly</u> in <u>a single collision</u> and <u>all the kinetic energy</u> of the electron is completely converted into a <u>single X-ray photon</u>.