SENIOR SIX TERM 3

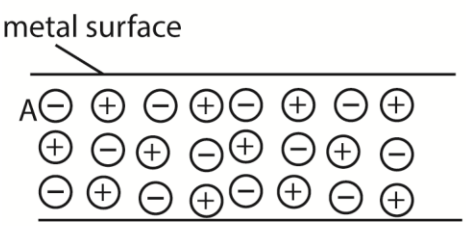
TOPIC 2/3: QUANTUM THEORY

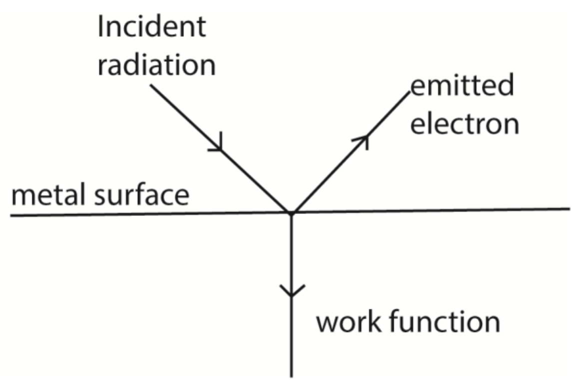
Competency: The learner examines how electromagnetic waves carry energy in packets and that this behaviour can be harnessed in a variety of fields.

Photoelectric effect

Photoelectric effect is the emission of electrons from a material caused by light or electromagnetic radiations.

In metals, atoms exist as positive ions in a sea of electrons. An electron near the surface of the metal, say A, experiences an attractive inward force from the positive charges below it.





For such an electron to escape from the metal surface, a specific amount of work has to be done to overcome these inward forces.

Terminologies

Photoelectric emission is the liberation of electrons from a metal surface by use of light of a suitable frequency. That is, the light (radiation) supplies the electrons with an amount of energy equal or exceeding the energy that binds them to the surface.

Thermionic emission is the liberation of electrons from a metal surface by application of heat.

Photoelectrons are electrons liberated by light striking a metal surface.

Photo emissive surfaces are metal surfaces that emit electrons when struck by light.

Generally K, Na, Ca and other elements with low ionization energy or work functions have surfaces that are photo emissive.

Work function is the minimum energy required to liberate an electron from a metal surface. Each element is characterized by a specific value of work function.

Laws of photoelectric emission

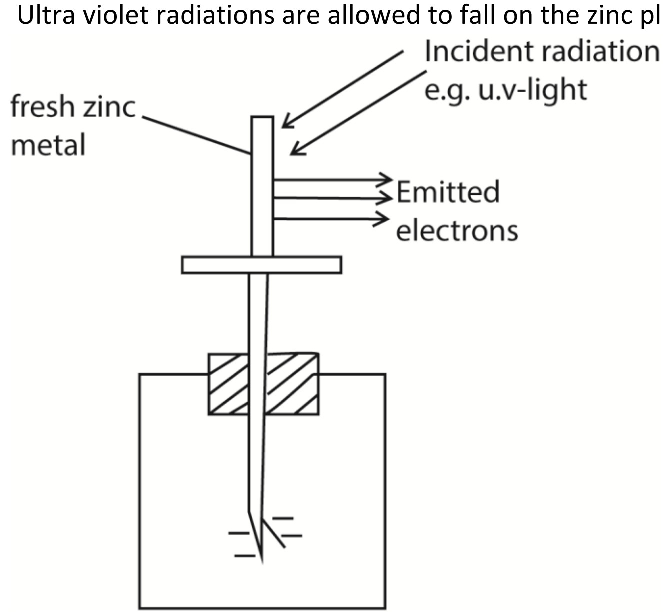
The laws, characteristics or features of photoelectric emission are a summary of experimental results on photoelectric effect.

1. The time lag between irradiation of the metal surface and emission of the electrons by the metal surface is negligible.
2. For a given metal surface, there is a minimum value of frequency of radiation called threshold frequency (f_0) below which no photo electrons are emitted from the metal however intense the incident radiation may be.
3. The number of photoelectrons emitted from the surface per second is directly proportional to the intensity of incident radiation for a particular incident frequency
4. The K.E of the photoelectrons emitted is independent of the intensity of the incident radiation but depends only on its frequency

A simple experiment to demonstrate Photo electric effect

(i) A freshly cleaned Zinc plate is connected to the cap of a negatively charged gold leaf electroscope.

(ii) Ultra violet radiations are allowed to fall on the zinc plate



Observations

- The leaf of the electroscope gradually falls
- This shows that both the zinc plate and the electroscope have lost charges.
- The lost charges are found to be electrons, hence photoelectric effect has occurred.

Note: If a positively charged electroscope is used instead, there is no observable change in the divergence of the leaf because the emitted electrons are immediately attracted back by the positive charges on the cap of the electroscope hence restoring the charges.

Planks Quantum theory

States that the energy /radiation emitted or absorbed by an electron is discrete or in packets called quanta.

That's, we can have integral values such as 1, 2, 3 … n, but not fractional amount of energy

The energy E, contained in a quantum of radiation is proportional to the frequency f, of the radiation i.e. $E \propto f$ or $E = hf$ where h = Planks constant (6.626×10^{-34}Js)

Dimensions of h

$$h = \frac{energy}{frequency} = \frac{force\ x\ distance}{frequency}$$

$$=> [h] = \frac{[force][distance]}{[frequency]} = \frac{MLT^{-2} x\ L}{T^{-1}} = ML^2T^{-1}$$

For an electromagnetic radiation of wavelength, λ; we have $c = \lambda f$

⇨ $E = \frac{hc}{\lambda}$

Thus $E \propto f$ and $E \propto \frac{1}{\lambda}$

When the photon (of energy hf) collides with an electron, it is either

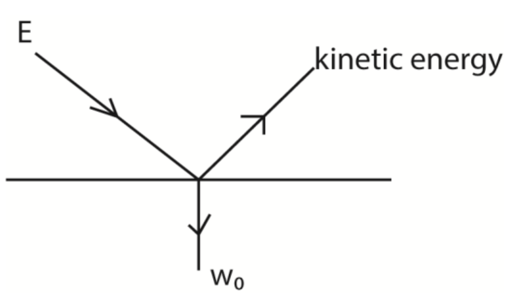
a) Reflected with no change in its energy or

b) Absorbed by the electron and the photon gives up all its energy to that single electron without sharing with other electrons

If the energy E, (hf) is greater than the work function (w_o) of the metal, the excess energy ($hf - w_o$) is absorbed as the K.E of the emitted electron or photoelectron

i.e. $hf - w_0 = ½ mv^2$ where v is the velocity of emitted electron

or $hf = w_0 + ½ mv^2$; also called Einstein photo electric equation



Since the work function w_0 is constant for a particular metal, there exists a minimum frequency (threshold frequency, f_0) given by $w_0 = hf_0$

From, $hf - w_0 = ½ mv^2$

then $h(f-f_0) = ½ mv^2$

Also, $w_0 = hf_0$ and $f_0 = \frac{c}{\lambda_0}$

- $w_0 = \frac{hc}{\lambda_0}$
- If an electron of charge e is accelerated by a voltage V volts, it gains K.E given by K.E = eV.
  Hence from above $h(f - f_0) = eV$
- An electron volt (eV) is the K.E gained by an electron which has been accelerated through a p.d of one volt
- $1eV = 1.6 \times 10^{-19}J$
- The values of the constants are $h = 6.64 \times 10^{-34}Js$, $c = 3.0 \times 10^8 ms^{-1}$, $e = 1.6 \times 10^{-19}C$

Definitions

Threshold wavelength is the maximum wavelength that is required to emit the electrons from a metal in the photo electric effect

Threshold frequency is the minimum frequency of incident radiation below which photoelectric emission cannot occur.

Example 1

Monochromatic radiation of frequency 1.0×10^{15} Hz is incident on a clean magnesium surface for which the work function is $0.59 \times 10^{-18}J$. Calculate

(i) the maximum kinetic energy of the emitted electrons

kinetic energy = $hf - w_0$

$= 1 \times 10^{15} \times 6.64 \times 10^{-34} - 0.59 \times 10^{-18}J$

$= 7.4 \times 10^{-20}J$

(ii) the potential to which the magnesium surface must be raised to prevent the escape of electrons

potential energy = kinetic energy

$eV = 1.04 \times 10^{-19}J$

$V = 7.4 \times 10^{-20}J/1.6 \times 10^{-19}$

$= 0.46V$

(iii) The cut-off wavelength.

From $w_0 = \frac{hc}{\lambda_0}$

$$\lambda_0 = \frac{6.64 \times 10^{-34} \times 3 \times 10^8}{0.59 \times 10^{-18}} 3.38 \times 10^{-7}m$$

Example 2

Calcium has a work function of 2.7eV.

a) What is the work function of calcium in Joules?

$1eV = 1.6 \times 10^{-19}J$
$\therefore 2.7eV = 2.7 \times 1.6 \times 10^{-19} = 4.3 \times 10^{-19}J$

b) What is the threshold frequency of calcium?
$hf_0 = 4.3 \times 10^{-19}$
$6.64 \times 10^{-34} \times f_0 = 4.3 \times 10^{-19}$
$f_0 = 6.5 \times 10^{14}Hz$

c) What is the maximum wavelength that will cause emission from calcium metal?
$\lambda_0 = \frac{C}{f_0} = \frac{3 \times 10^8}{6.5 \times 10^{14}} = 4.6 \times 10^{-7}m$

Example 3
Light of frequency $6 \times 10^{14}Hz$ is incident on a metal surface and the emitted electrons have kinetic energy of $2 \times 10^{-29}J$. Calculate:

(i) Work function
From $hf = w_0 + \frac{1}{2}mv^2$
$6.63 \times 10^{-34} \times 6 \times 10^{14} = w_0 + 2 \times 10^{-29}$
$w_0 = 3.978 \times 10^{-19}J$

(ii) Threshold frequency of the metal.
From $w_0 = hf_0$
$3.978 \times 10^{-19} = 6.63 \times 10^{-34} \times f_0$
$f_0 = 6 \times 10^{14}Hz$

Example 4
Calculate the maximum speed of photoelectrons emitted by a cesium surface when irradiated with light of wavelength 484mm if the work function of cesium is $3 \times 10^{-19}J$.
($c = 3 \times 10^8ms^{-1}$, $h = 6.63 \times 10^{-34}Js$, $Me = 9.1 \times 10^{-31}kg$)

From $hf = w_0 + \frac{1}{2}mv^2$
$\frac{hc}{\lambda} = w_0 + \frac{1}{2}mv^2$
$$\frac{6.63 \times 10^{-34} \times 3 \times 10^8}{484 \times 10^{-3}} = 3 \times 10^{-19} + \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2$$
$v = 4.938 \times 10^5ms^{-1}$

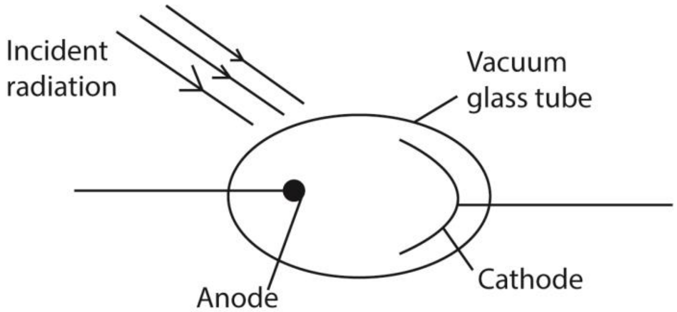
Example 5
A photo emissive metal has a threshold wavelength of 0.45µm. Calculate the kinetic energy of emitted electrons when light of wavelength 0.35µm falls on this metal
($c = 3 \times 10^8ms^{-1}$, $h = 6.63 \times 10^{-34}Js$)

From $\frac{hc}{\lambda} = \frac{hc}{\lambda_0} + K.E$
$K.E = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{0.35 \times 10^{-6}} - \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{0.45 \times 10^{-6}} = 1.263 \times 10^{-19}J$

The Photocell

A photocell is a unit that changes radiation/light energy into electric current.

The structure of a photocell is illustrated below



- It consists of an anode made of a thin wire so that it does not obstruct the incident radiation and a photo-emissive cathode of a large surface area to collect large amount of light radiations placed in a vacuum because the metals are reactive.

Applications of Photocells

(i) It used to demonstrate photoelectric emission.

(ii) It used to determine the stopping voltage of a particular in order to derive the planks constant, h, the work function, threshold frequency and threshold wavelength of a particular metal.

(iii) A photocell can make doors open automatically in buildings when a light beam is interrupted by somebody/obstacle.

(iv) Intruder alarm systems. The intruder intercepts the infrared beam falling on a photocell, hence cutting off of current. This interruption therefore sets the alarm on.

(v) Photovoltaic cells are used in solar panels, calculators and for powering electronic watches.

(vi) Used as automatic devices for switching on light at night when it tries to darken or when the frequency of the light reduces.

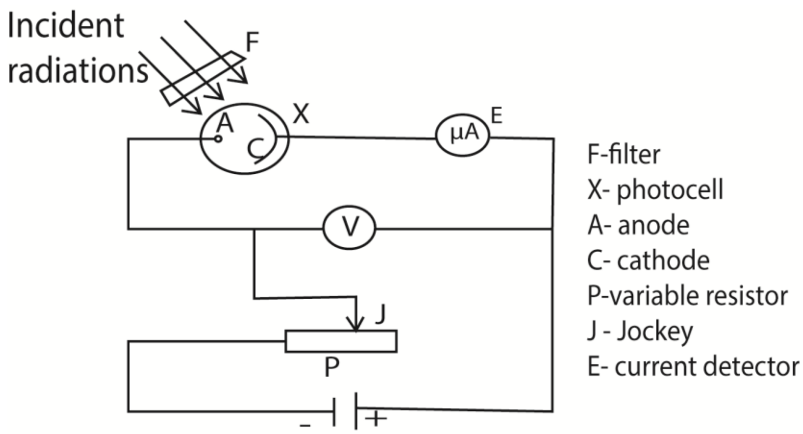
(vii) Automatic counting machines in industries.

(viii) Production of sound from a film

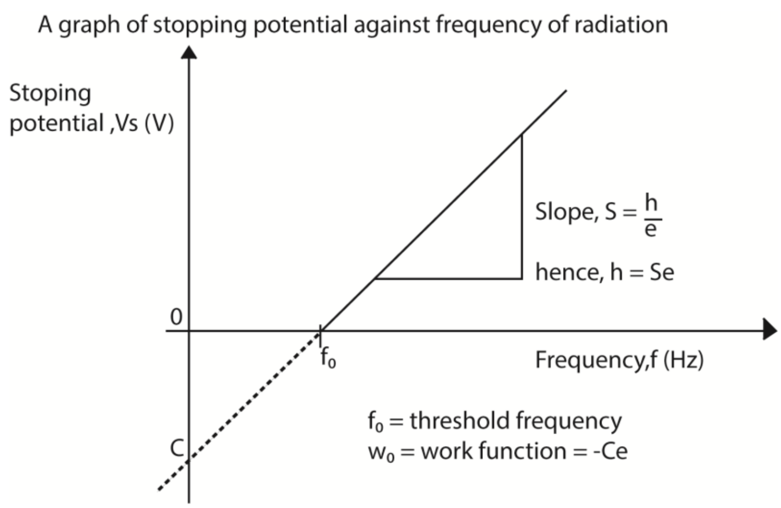
Stopping potential

Stopping potential is the minimum potential between the cathode and the anode that prevents the most energetic electrons from reaching the anode.

Experiment to measure the stopping potentials in order to verify Einstein's photoelectric equation and to determine Plank's constant h



- A radiation of known frequency, f, is made incident on the photocathode
- Emitted electrons travel to the anode and cause a current to flow that is detected at E.
- The p.d V is adjusted until the reading of E is zero or when there is no current flow.
- The minimum value of p.d that prevents the most energetic electron from reaching the anode called the stopping potential (Vs) is recorded from the voltmeter V.
- The procedure is repeated with light of different frequencies, f.
- A graph of stopping potential (Vs) against frequency (f) is plotted



From the graph

(a) Threshold frequency, f_0 is intercept on the frequency (horizontal) axis.

(b) Slope of the graph, S = $\frac{h}{e}$ where e is the electron volt;

hence, Plank's constant , h = Se

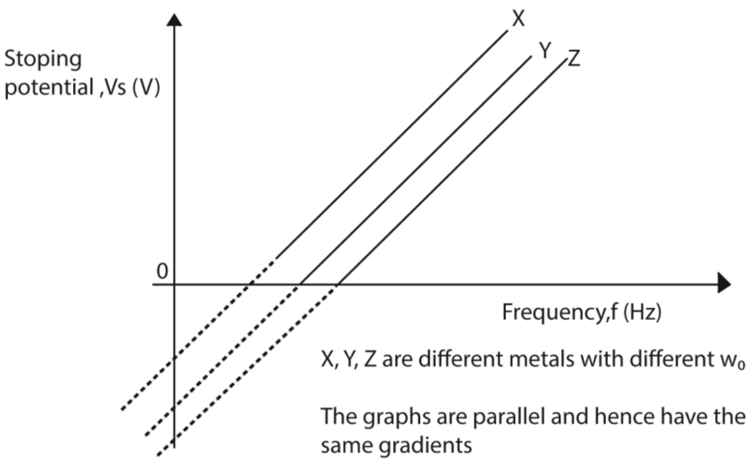
(c) The nature of the curve verifies the equation i.e. $V_s = \frac{h}{e}f - \frac{h}{e}f_0$

(d) The work function, w_0 = -Ce, where C is the intercept on the vertical axis

Also threshold wavelength, $\lambda_0 = \frac{c}{f_0}$

(e) When the experiment is carried out on different metals of different work functions, parallel graphs are obtained with constant slope, S = $\frac{h}{e}$ as illustrated below

A graph of stopping potential against frequency of radiation for different metals



Note that;

(a) The elements X, Y and Z have different work functions

(b) The graphs are parallel because they have the same gradient, S = $\frac{h}{e}$

Example 6

Sodium has a work function of 2.3eV. Calculate the

(i) Threshold frequency

From $w_0 = hf_0$

$2.3 \times 1.6 \times 10^{-19} = 6.63 \times 10^{-34} f_0$

$f_0 = 5.55 \times 10^{14}$Hz

(ii) Stopping potential when it is illuminated by light of wavelength 5×10^{-7}m (1eV = 1.6×10^{-19}J)

From $hf = hf_0 + eV$

$$V = \frac{h(f - f_0)}{e} = \frac{6.63 \times 10^{-34}\left(\frac{3 \times 10^8}{5 \times 10^{-7}} - 5.55 \times 10^{14}\right)}{1.6 \times 10^{-19}} = 0.186\text{V}$$

Explanation of the laws of photoelectric emission using quantum theory

The quantum theory states that "light is emitted and absorbed in discrete packets of energy called photons"

When light is incident on a metal surface, each photon interacts with a single electrons giving it all its energy. The photon is absorbed if its energy is greater than the work function and if it is less, the photon is rejected.

Increasing the intensity of light increases the number of photons striking the metal surface per second. Therefore more electrons are emitted per second and the photocurrent increases with intensity.

Increasing the frequency of incident radiation increases the energy of each photon and therefore the maximum kinetic energy of the liberated electrons increases with the frequency of radiation.

Increasing the intensity of light only increases the number of photons but not the energy in each photon. Hence kinetic energy of the emitted electrons is independent of the intensity of the incident radiation

i.e K.E = hf + w_0 where **K.E** = kinetic energy of emitted electron, **h** = Plank's constant, **f** = frequency of the radiation, **w_0** = work function (minimum energy required to dislodge an electron from a material)

Failures of the wave theory (classical theory) to account for the photoelectric emission

(i) Existence of threshold frequency

According to the classical theory, the energy of the incident radiation depends on its intensity; the greater the intensity of illumination, the greater the supply of energy. This would imply that radiations of high enough intensity should cause emission even when the frequency is below the minimum value. However as long as the incident radiation is below the threshold frequency, no photoelectrons are emitted however intense the incident radiation is

(ii) Instantaneous emission of photoelectrons

Classical theory suggests that the energy of the incident radiation would be continuously absorbed by the electron. Implying that the electron would take some time to accumulate sufficient energy that would enable them escape from the metal surface. By this theory, emission of photoelectrons would not be instant

(iii) Variation of K.E of the emitted photoelectrons

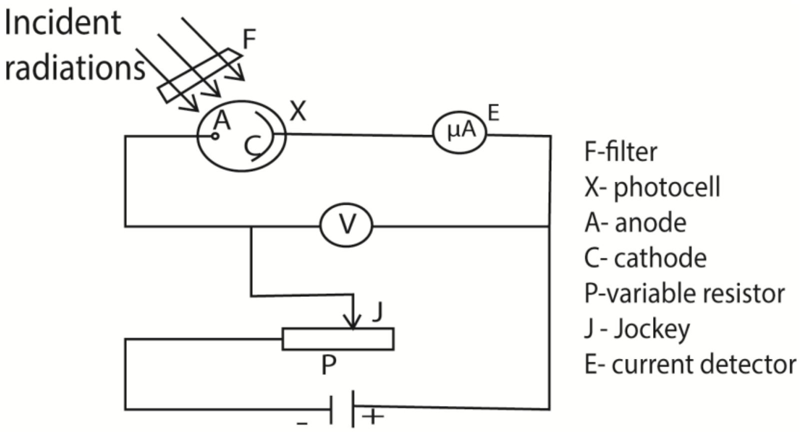
According to the classical theory, increasing the intensity of the incident radiation would mean more incident energy and a greater maximum K.E of the emitted photoelectrons. But instead the maximum K.E of the photoelectrons emitted depend on the frequency of the incident radiation.

(iv) Variation of photoelectric current with intensity

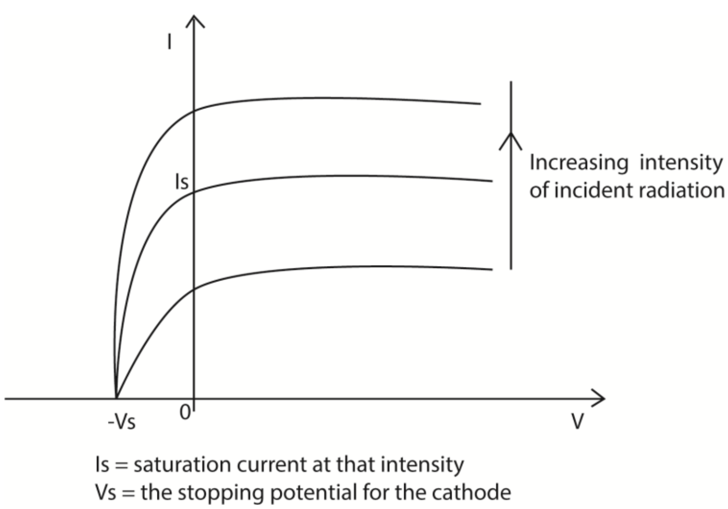
When the intensity of illumination is increased, the number of photons incident on the metal surface also increases. Hence more free electrons in the metal receive sufficient energy to escape. The rate of emission increases and therefore a large current flows. Thus the size of the photocurrent depends on the intensity of the incident radiation. However, According to classical theory, increase in the intensity would increase the K.E of the emitted electron and they would escape with greater speed instead, which is false

Experiment to show the variation of current (I) with p.d (V) of a photocell

The setup is shown below



- A monochromatic light i.e. constant frequency is used.
- The photocurrent (I) is measured for increasing values of V at constant light intensity.
- For negative values of V, the polarity of the battery is reversed.
- The experiment is repeated by increasing the intensity of the radiations; by moving the light source closer to the photocell.
- A plot of graphs of photocurrent (I) against the p.d V is shown below.

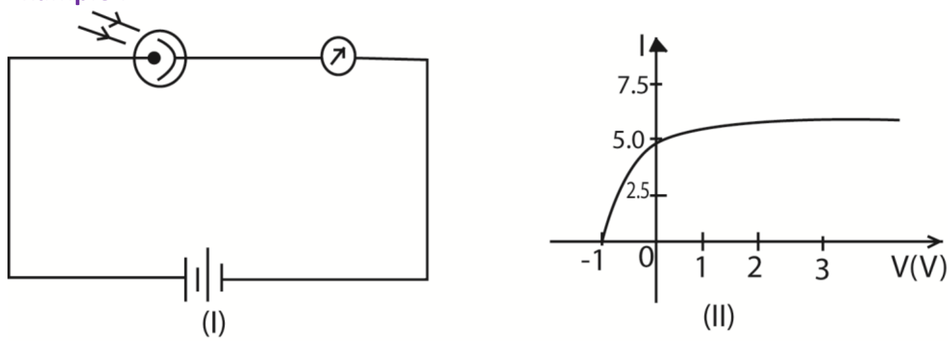


Note that

(a) Current increases with intensity due to increase in the number of photons striking the cathode/metal surface.
(b) For each light intensity value, there a maximum current that can be obtained called saturation current. It occurs when the anode collects all the photons emitted by the cathode.

(c) The photocurrent is not zero even when the p.d is zero because electrons are emitted with varying velocities (K.E). Hence, some of the electrons have sufficient energy to overcome the repulsive electric field and reach the anode.

Example 7



A photocell is connected in the circuit as shown in figure (I) above. The cathode is illuminated with monochromatic light of wavelength 390nm and the current I in the circuit recorded for different p.d V applied between the anode and the cathode. The graph fig (II) shows the results obtained.

(a) Find the maximum K.E of the photoelectrons

From the graph Vs = -1V

$K.E_{max} = eV = 1.0 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-19}J$

(b) What is the work function of the cathode in eV?

$K.E_{max} = \frac{hc}{\lambda} - w_0$

$w_0 = \frac{hc}{e\lambda} - K.E_{max}$

$= \frac{6.64 \ x\ 10^{-34}\ x\ 3.0\ x\ 10^{8}}{1.6\ x\ 10^{-19} x\ 390\ x\ 10^{-9}} - 1$

= 2.19eV

(c) If the experiment is repeated using monochromatic light of wavelength 310nm, where would the new graph cut the V-axis?

$K.E_{max} = \frac{hc}{e\lambda} - w_0$

$= \frac{6.64\ x\ 10^{-34}\ x\ 3.0\ x\ 10^{8}}{1.6\ x\ 10^{-19} x\ 310\ x\ 10^{-9}} - 2.19$

= 1.83eV

Hence the graph would cut the v-axis at – 1.83V

Example 8

A 100mW beam of light of wave length 4.0×10^{-7}m falls on a caesium surface of a photocell.

(i) How many photons strike the caesium surface per second?

$E = \frac{hc}{\lambda} = \frac{6.64\ x\ 10^{-34}\ x\ 3\ x\ 10^{8}}{4.0\ x\ 10^{-7}} = 4.98 \times 10^{-19}J$

Number of photons per second, n = $\frac{total\ energy}{Energy\ of\ one\ photon}$

$= \frac{100\ x\ 10^{-3}}{4.98\ \ x\ 10^{-19}}$

$= 2 \times 10^{17} s^{-1}$

(ii) If 80% of the photons emit photoelectrons. Find the resulting photocurrent.

Number of electrons emitted = 2 x $10^{17}s^{-1}$ x 80%
= 1.61 x 10^{17}

Current = ne
= 1.61 x 10^{17} x 1.6 x 10^{-19}
= 2.57 x 10^{-2}A

(iii) Calculate the kinetic energy of each photoelectron if the work function of caesium is 2.15eV.

$K.E_{max} = \frac{hc}{e\lambda} - w_0$ where $\frac{hc}{e\lambda}$ is energy in eV

$= \frac{6.64 \, x \, 10^{-34} \, x \, 3 \, x \, 10^{8}}{4.0 \, x \, 10^{-7} \, x \, 1.6 \, x \, 10^{-19}} - 2.15$

= 0.96eV

=1.54 x10^{-19}J

Or $K.E_{max} = \frac{hc}{\lambda} - w_0$

$= \frac{6.64 \, x \, 10^{-34} \, x \, 3 \, x \, 10^{8}}{4.0 \, x \, 10^{-7}} - 2.15 \text{ x } 1.6 \text{ x } 10^{-19}$

= 1.54 x10^{-19}J

Differences between x-ray production and photoelectric effect

Photoelectric effect	X-rays
Electromagnetic radiation falls on metal surface and electrons are emitted	Fast moving electrons hit the metal target and x-rays (electromagnetic radiation) is produced
Little heat is generated	A lot of heat is generated

Experimental evidence for quantum theory

(i) **Photoelectric effect:**
To liberate an electron from a metal surface, a quantum or packet of energy called the work function which is characteristic of the metal surface has to be supplied
i.e. $hf - w_0 = \frac{1}{2}mv^2$ where w_0 is the work function.

(ii) Optical spectra:
A line in the optical emission spectrum indicates the presence of a particular frequency f of light and is considered to arise from loss of energy which occurs in an excited atom when an electron jumps directly or in steps from a higher energy level E_2 to lower energy level E_1.
The frequency of the packet of energy emitted is given by $hf = E_2 - E_1$.

(iii) X-ray line spectra:
Electron transition from one shell to another leads to liberation of energy in packets characteristic of the target atom.

Differences between classical theory and quantum theory

Classical(wave) theory	Quantum theory
It allows continuous absorption and accumulation of energy.	No continuous absorption is allowed. The energy is either absorbed or rejected.
Energy of radiation is evenly distributed over the wave front.	Energy is radiated, propagated and absorbed in packets (quanta or photons).
What matters is total energy of the incident radiation (beam).	What matters is the energy of individual photon.

Bohr's model of the atom and how it can be used to explain

i) origin of absorption and emission spectra;
ii) presence of energy levels in atoms; and
iii) ionisation in atoms and calculate ionisation energy.

Bohr's model explains atomic phenomena by postulating that electrons orbit the nucleus in specific, discrete energy levels and can transition between them by absorbing or emitting fixed amounts of energy (photons)

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(i) Origin of Absorption and Emission Spectra

- **Quantization Postulate:** Bohr proposed that electrons can only exist in specific, stable, circular orbits, each associated with a definite, discrete amount of energy. These are the "energy levels".
- **Emission Spectra:** When an atom is excited (e.g., by heat or electricity), an electron jumps from a lower energy level to a higher, less stable, energy level. It then quickly falls back to a lower energy level, releasing the energy difference as a photon of light. Since only specific energy differences are possible (due to the discrete energy levels), only photons of certain, precise frequencies/wavelengths are emitted, resulting in a characteristic line emission spectrum for each element.
- **Absorption Spectra:** When white light passes through a cool gas, electrons in the atoms absorb photons with energies exactly matching the difference between their current energy level and a higher, unoccupied energy level. This causes dark lines (missing colors) to appear in the continuous spectrum at the same characteristic wavelengths that the element usually emits, creating a unique absorption spectrum.

(ii) Presence of Energy Levels in Atoms

The presence of energy levels is a fundamental postulate of Bohr's model, introduced to overcome the limitations of classical physics which predicted that orbiting electrons would continuously lose energy and spiral into the nucleus.

- **Stationary Orbits:** Bohr stated that electrons can revolve in certain discrete, non-radiating orbits (called stationary orbits) without losing energy, contrary to classical electromagnetism.
- **Quantized Angular Momentum:** The condition for these stable orbits is that the angular momentum of the electron is a whole-number multiple of $h/(2\pi)$ (where h is Planck's constant). This mathematical condition directly leads to the derivation of specific, quantized values for the radii and energies of these allowed orbits.
- **Analogy:** The energy levels are often compared to rungs on a ladder; an electron can stand only on a rung, not in between, and moving between rungs requires a specific, fixed amount of energy.

(iii) Ionisation in Atoms and Calculation of Ionisation Energy

- **Ionisation Explained:** Ionisation is the process of completely removing an electron from an atom. In the Bohr model, this occurs when an electron absorbs enough energy to move from its initial bound orbit (usually the ground state, n_1) to an infinite distance away from the nucleus (n_f=∞). At an infinite distance, the electron is no longer bound to the nucleus, and its energy is considered to be zero.

- **Calculation:** The ionisation energy (IE) is the minimum energy required to achieve this state. It is calculated as the difference between the energy of the electron in the initial orbit and the energy at infinity.
    - The energy of an electron in a specific energy level (n) of a hydrogen-like atom (one electron system) is given by the Bohr formula:

      $E_n = -13.6eV\ x\ \frac{Z^2}{n^2}$ where Z is atomic number and n the principal quantum number

    - For ionization, the energy change is

      ΔE = $E_\infty - E_n$

Since $E_\infty = 0eV$, the ionisation energy from a given level n is the positive value of E_n

i.e $I.E = 13.6eV\ x\ \frac{Z^2}{n^2}$

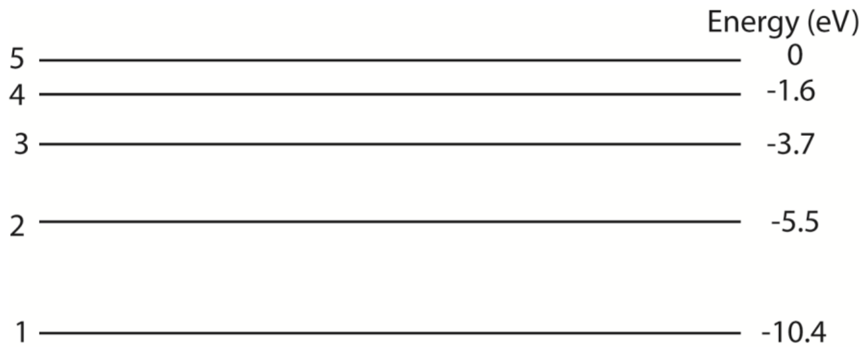
Example 9

(Hydrogen): For a hydrogen atom (Z=1) in its ground state (n=1) the ionisation energy is:

$I.E = 13.6eV\ x\ \frac{1^2}{1^2} = 13.6eV$ /atom

Example 10

Some of the energy levels of mercury are shown in the diagram below. Level 1 is the ground state level occupied by the electrons in an unexcited atom



(i) Calculate the ionization energy of mercury atom in Joules

Ionization energy = $E_I = E_\infty - E_1$

= 0 – (-10.4)

= 10.4eV

= 10.4 x 1.6 x 10^{-19}

= 1.66 x 10^{-18}J

(ii) (ii) Calculate the wavelength of the radiation emitted when an electron moves from level 4 to level 2.

Solution

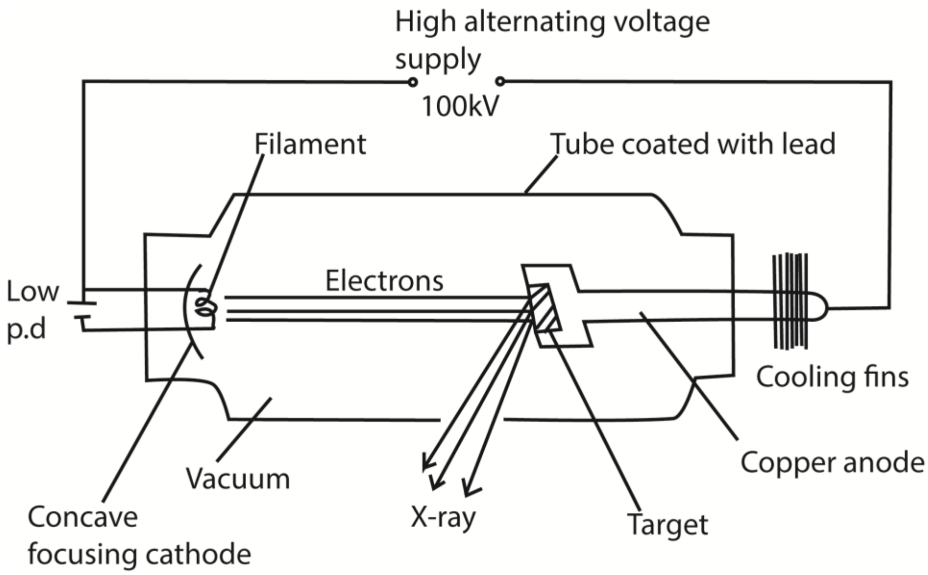
$E_4 - E_2 = \frac{hc}{\lambda}$

$\lambda = \frac{6.63\ x\ 10^{-34}\ x\ 3\ x\ 10^{8}}{-(1.6-5.5)x\ 1.6\ x\ 10^{-19}}$ = 3.2 x 10^{-7}m

X-Rays

X- Rays are electromagnetic radiations of short wavelength produced when fast moving electrons are stopped by heavy metal target.

Production of X – Rays



Mode of operation

- The filament is heated by a low voltage supply and the electrons are emitted by thermionic emission.
- The concave focusing cathode focuses the electrons from the filament onto the target.
- These electrons are accelerated towards the anode by the high voltage between the filament and the Anode.
- When the electrons (cathode rays) strike the metal target, about only 1% their kinetic energy is converted to X-rays and the 99% of their kinetic energy is converted to heat, which is conducted away by the cooling fins.

Note.

i) The target is made of a high melting point metal.

ii) ii) The X-ray tube is covered by a lead shield with a small window for the X-rays to prevent the leakage of the X-rays.

Intensity of X-rays (Quantity or number of X-rays)

- The intensity of X- rays in an X – ray tube is proportional to the number of electrons colliding with the target.
- The number of electrons produced at the cathode depends on the filament current supply.
- The greater the heating current, the greater the number of electrons produced and hence more x- rays are produced.
- Therefore the intensity of X- rays is controlled by the filament current.

Penetration of X – rays (quality)

- Penetration power of X-rays depends on the kinetic energy of the electrons striking the target.
- The higher the accelerating voltage, the faster the electrons produced.

- Faster electrons possess higher kinetic energy and shorter wavelength x-rays of greater penetration power are produced.
- Hence penetrating power of X-rays is determined by the accelerating Voltage across the tube.

Types of X-rays

There are two types of X-rays, namely: Hard X-rays and soft X- rays

Hard X-rays:

- They are produced when a high p.d is applied across the tube.
- They have very short wave lengths
- They have a high penetrating power. This is because they have very short wavelengths

Soft X-rays:

- They are produced by electrons moving at relatively lower velocities than those produced by hard X –rays.
- They have longer wavelengths.
- They have a low penetration power compared to hard x-rays. This is because of their long wavelengths

Note:

- Hard X-rays can penetrate flesh but are absorbed by bones, they are therefore used to study bone fractures.
- Soft X-rays are used to show malignant growths since they only penetrate soft flesh. They are absorbed by such growths.

Properties of X –rays

(i) They travel in a straight line at a speed of light in vacuum
(ii) They are not deflected by both magnetic and electric fields. This indicates that they carry no charge.
(iii) They penetrate all matter to some extent. Penetration is least in materials with high density and atomic number e.g. lead.
(iv) They ionize gases through which they pass.
(v) They affect photographic plates.
(vi) They cause fluorescence in some materials.
(vii) They cause photoelectric emission
(viii) They are diffracted by crystals leading to an interference pattern.

Uses of X-rays

(i) Structural analysis, stresses, fractures in solids, castings and welded joints can be analyzed by examining X-ray photograph.
(ii) Crystallography; Orientation and identification of minerals by analysis of diffraction patterns using Bragg's law.
(iii) Medical uses;

- Analytical uses. These include location of fractures, cancer and tumor/defective tissue absorbs x-rays differently from normal tissue.
- Therapeutics use for destroying cancerous cells and tumors. 4. Detection of fire arms at international airports

Health hazards caused by x-rays:

- Destroy living cells in our bodies especially hard X-rays.
- Cause Gene mutation (genetic changes in our bodies).
- Cause damage of our eye sight and blood. Produce deep skin burns.

NOTE: It's highly important to remember that each time you are exposed to X-rays, your health is also at risk yet we cannot live without them

Safety precautions:

- Avoid unnecessary exposure to X-rays.
- When exposure is necessary, keep it as short as possible.
- X-ray beams should ONLY be restricted to the body part being investigated.
- A worker should wear a shielding jacket with a layer of Lead.
- Exposure should be avoided for unborn babies and very young children.

Example 11

In an X-ray tube, the current through the tube is0.1mA and accelerating p.d 1.5kV. Calculate the:

(i) The number of electrons striking the anode per second

I = ne where n is the number of electrons striking the anode per second

n = $\frac{0.1 \times 10^{-3}}{1.6 \times 10^{19}}$ = 6.25 x 10^{14}

(ii) The speed of electron striking the anode

$\frac{1}{2}mv^2 = eV$

$v = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 1.5 \times 10^3}{9.11 \times 10^{-31}}}$ 2.295 x $10^7 ms^{-1}$

(iii) The rate at which cooling fluid at 10^0 must be circulated through the tube if the anode is to be maintained at 35^0C.

[Assume all electrical energy is converted into heat energy and S.H.C of fluid is 2000$Jkg^{-1}K^{-1}$]

IVt = mc ($\theta_2 - \theta_1$)

IV = $\frac{m}{t}(\theta_2 - \theta_1)$

= KC($\theta_2 - \theta_1$) where K is the rate of flow

K = $\frac{0.1 \times 1.5 \times 10^3}{2000 \times (35-10)}$ = 3 x $10^{-3} kgs^{-1}$

Example 12

In an X-ray tube, 90% of the electrical power supplied is dissipated as heat. If the accelerating potential difference across the tube is 75kV and 742.5W is dissipated as heat, calculate the:

(i) Current in the tube

P = IV; V = 75kV

90% of IV= heat lost

$\frac{90}{100}\ x\ I\ x\ 75\ x\ 10^3 = 742.5$

$I = 0.011A$

(ii) Number of electrons arriving at the target per second

I = ne where n is the number of electrons per second

n = $\frac{0.011}{1.6\ x\ 10^{-19}}$ = 6.875 x 1016

Example 13

The current in a water-cooled X-ray tube operating at 60kV is 30mA. 99% of the energy supplied to the tube is converted into heat which is removed by water at a rate of 0.06kgs^{-1}. Calculate the:

(i) Number of electron hitting the target per second

Number of electrons per second = $\frac{I}{e} = \frac{30\ x\ 10^{-3}}{1.6\ x\ 10^{-19}}$ = 1.875 x 10^{17}electrons per second

(ii) Rate at which energy is being supplied to the tube

Power = IV = 30 x 10^{-3} x 60 x 10^{3} = 1800W

(iii) Rate of change in temperature of cooling water

99%IV = heat lost per second

$\frac{99}{100} IV = m'c\theta$ where m' is rate of flow kgs^{-1}

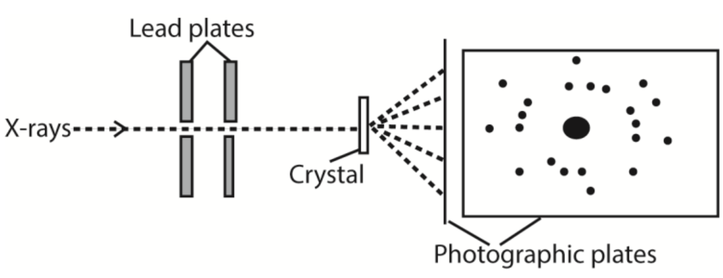
$\frac{99}{100}\ x\ 1800 = 0.06\ x\ 4200\ x\ \theta$

$\theta = 7.07Ks^{-1}$

X-ray diffraction

The wave nature of X-rays can be confirmed by their diffraction with crystals

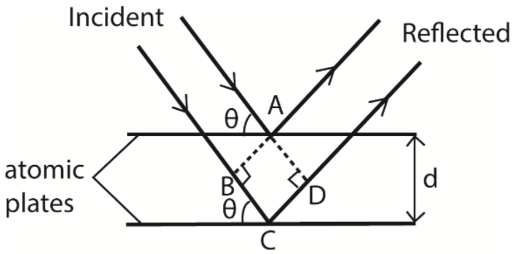
Laue's experiment:



- After long exposure of the crystal to the x-rays, the photographic plate is developed and printed.
- A regular pattern of dark sports called Laue spots is observed around a central dark image.
- The pattern is due to the X-rays which have been scattered by interaction of the X-rays with the electrons in the atoms of the crystal.
- The regularity of the Laue spots implies that the atoms in a crystal are arranged in a regular pattern.

Bragg's law

- A parallel beam of monochromatic X-rays incident on a crystal is reflected from successive atomic planes and super-imposed, forming an interference pattern.



For constructive interference to occur, the path difference is equal to the whole number of wavelength

Thus BC + CD = nλ

⇨ dsinθ + dsinθ = nλ

or 2dsinθ = nλ where n = 1, 2, 3, 4 …

Example 22

A second order diffraction mage is obtained by reflection of X-rays at atomic planes of a crystal in sodium chloride at glancing angle of 11^0. Calculate the atomic spacing of the planes if the wavelength of X-rays is 4×10^{-11}m.

From 2dsinθ = nλ

$d = \frac{2 x\, 4\, x\, 10^{-11}}{2 \sin 11}$ = 2.096×10^{-10}m

Example 14

X-ray of wavelength 1.55×10^{-10}m are incident on a copper crystal of atomic spacing 4.25×10^{-10}m

(i) Calculate the smallest angle at which radiation will be first reflected.

From 2dsinθ = nλ

$\sin\theta = \frac{1\, x\, 1.55\, x\, 10^{-10}}{2\, x\, 4.25\, x\, 10^{-10}}$

θ = 10.5^0

(ii) If the temperature of the crystal is increased by 600^0, calculate the change in the angle that will be obtained. [the coefficient of linear expansion of copper is $1.7 \times 10^{-5}K^{-1}$]

From $C_\theta = C_0(1 + \alpha\theta)$

$d_\theta = 4.25 \times 10^{-10}(1 + 1.7 \times 10^{-5} \times 600) = 4.29335 \times 10^{-10}$m

$\sin\theta' = \frac{1\, x\, 1.55\, x\, 10^{-10}}{2\, x\, 4.29335\, x\, 10^{-10}}$

θ = 10.4^0

change in angle = 10.5 – 10.4 = 0.1^0

Example 15

A monochromatic beam of X-rays of wavelength 2 x 10^{-10}m is incident on a set of cubic planes in potassium chloride crystal. First order diffraction is observed at glancing angle 18.5^0.

Calculate

(i) The inter-atomic spacing on potassium chloride.

From 2dsinθ = nλ

$d = \frac{1 \, x \, 2 \, x \, 10^{-10}}{2 \sin 18.5}$ = 3.152 x 10^{-10}m

(ii) The density of potassium chloride if the RFM is 75.5grams

For the two ions in KCl

V = $2d^3$ = 2 x $(3.152 \times 10^{-10})^3$ = 6.263 x $10^{-29}m^3$

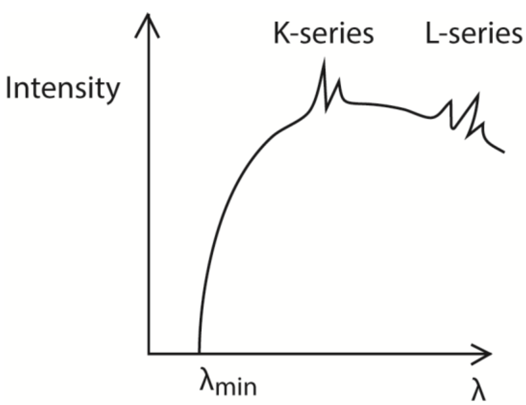
RFM KCl = 75.5

6.02 x 10^{23} molecules of KCl weigh 75.5g

1 molecule weighs $\frac{75.5}{6.02 \, x \, 10^{23}}$ = 1.254 x 10^{-22}g

ρ = $\frac{m}{V} = \frac{1.254 \, x \, 10^{-22}}{6.263 \, x \, 10^{-29}}$ = 2002.2kgm^{-3}.

X-rays Emission spectrum



The spectrum consists of two major components, i.e. the continuous (background) spectrum and the very sharp line spectrum superimposed onto the background spectrum.

The continuous spectrum is produced when electrons make multiple collisions with the target atoms in which they are decelerated. At each deceleration, X-rays of differing wavelength are produced.

The shortest Wavelength X-rays are produced when electrons lose all their energy as X-ray photon in a single encounter with the target atoms. The wavelength of the X-rays at this point is known as the cut off wavelength. At cut off wavelength, energy in an X-ray photon equals kinetic energy of the electron; i.e. hf = eV or $\frac{hc}{\lambda_{max}} = eV$ where V = p.d

The line spectrum

At high tube voltages, the bombarding electrons penetrate deep into the target atoms and knock out electrons from inner shell. The knocked out electrons occupy vacant spaces in higher unfilled shells putting the atom in excited state and making them unstable.

Transition of an electron from higher to lower energy levels results in an emission of X-ray photon of energy equal to energy difference between the energy levels.

If the transition ends in the K-shell, it produces K-series and if the transition ends in L-shell. It produces L-series.

Thank you
Dr. Bbosa Science