

KHANDELWAL CLASSES

XII (Sc.)

Sub. Physics

Topic : Dual Nature of Radiation and Matter

Q. What is a photo-electric effect ?

Ans. Any metal contains large number of free electrons which move randomly within the metal like the molecules of a gas in a container but they can not leave the metal on their own as their energy is not sufficient to overcome the forces of attraction due to the electric field inside the metal. Therefore energy has to be supplied from external source in order to cause the emission of electrons.

It is found that when light of sufficiently high frequency is incident on metal then the surface of the metal begins to emit electrons. This phenomenon is called photoelectric effect.

Definition : The emission of electrons by a metal surface when light of sufficiently high frequency is incident on it, is known as photo-electric effect.

Note :

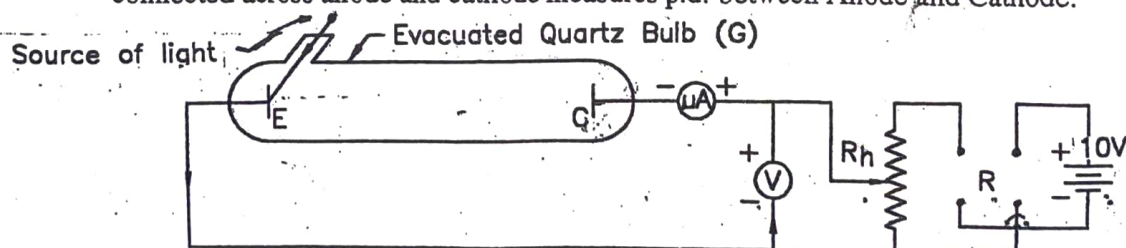
1. The plate which emit electrons by this process is known as "**photosensitive plate**". The electrons emitted by this process are known as '**photo-electrons**'. The current due to the flow of these electrons is known as '**photo-electrons current**'.
2. Most metals emit electrons when exposed to ultra-violet (high frequency) radiations, but alkali metals like sodium, potassium etc. emit electrons even when exposed to ordinary radiations. (visible, infrared).

Q. Describe an experiment of study "Photo-Electric Effect" ?

Ans. The circuit diagram to study photo-electric effect is as shown in the figure.

It consists of a highly evacuated quartz bulb (G) having a window through which light can enter. The light is made to incident on a photosensitive plate, known as emitter (E) or cathode. The other plate is known as collector (C) or Anode.

A variable P.D. is supplied between Emitter and Collector by a battery of about 10 V, which can be controlled by a Rheostat (R_h). A reversing key (R) enables both positive and negative potentials applied to the Anode. A micro-ammeter (μA) connected in series with Anode measures photo-electric current. A voltmeter connected across anode and cathode measures p.d. between Anode and Cathode.



E = Emitter plate (Cathode)

C = Collector plate (Anode)

μA = Micro Ammeter

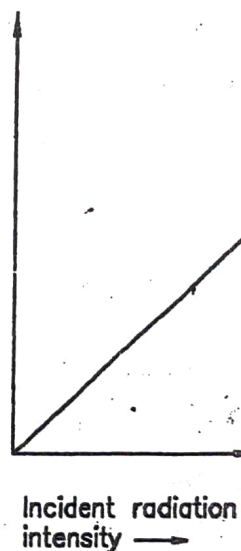
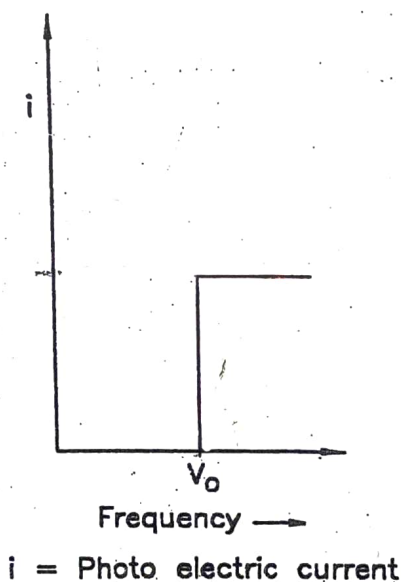
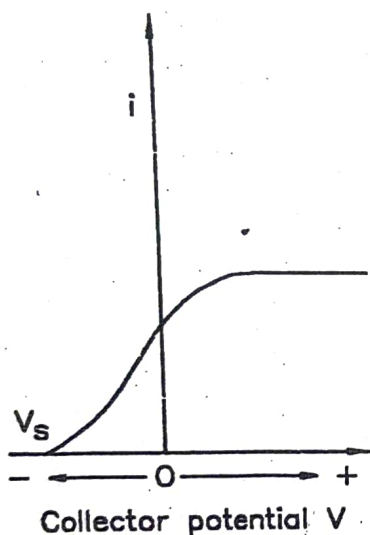
V = Voltmeter

R_h = Rheostat

R = Reversing Key

If C is maintained positive with respect to E and if light of sufficiently high frequency is incident on E, it emits electrons which are attracted by C & hence there is photo-electric current which is measured by micro ammeter. In the experiment we study the variation of photo-electric current w.r.t.

1. Applied P.D. (V)
2. The frequency ' ν ' of radiation
3. The Intensity 'I' of radiation.



Variation of i v/s V

Variation of i v/s ν

Variation of i v/s V Intensity

Q. State main features of Photo-Electric Effect ?

- Ans.**
1. Photo-electric effect is an instantaneous process that is there is no time lag between the arrival of light and emission of electrons.
 2. Photo-electrons are emitted by a metal only when the frequency of incident light is above a certain minimum value known as '**Threshold frequency**' (ν_0).
Below this value photo-electrons are not emitted however intense the light may be.

3. If the frequency of incident light is kept constant at a value greater, than ν_0 and the intensity of light is slowly increased, it is found that "As the intensity of light increases, photo-electric current also increases".
4. Different photo-electrons emitted from the same emitter plate have different kinetic energies ranging from zero to a certain maximum value which depend on frequency of light and nature of emitter plate but does not depend on intensity.

Q. Explain how Einstein arrived at the photo-electric equation using quantum theory?
Ans. Einstein made use of quantum theory to explain photo-electric effect.

According to quantum theory, radiation is not emitted continuously, but it is emitted in the form of packets or bundles of energy called **Quanta** or **Photons**. The energy of each photon is $h\nu$ where ν is the frequency of radiation & h is Planck's constant.

According to Einstein when light of frequency, ν is incident on a metal surface then the photons carrying energy $h\nu$ collide with the electrons in the metal. As a result of this, the entire energy $h\nu$ of photons is completely absorbed by the electron. This energy is used by the electron in the following manner.

1. Part of this energy is used by the electron to overcome the forces of attraction due to the electric field inside the metal. The minimum amount of energy required to liberate the electron from a metal is known as Photoelectric work function of that metal (W_0).
2. The remaining energy is converted into Kinetic Energy of the electron. Assuming no loss of energy by internal collisions, K.E. of the electron will be maximum. $[\frac{1}{2} mV_{max}^2]$

\therefore By law of conservation of energy

$$\boxed{h\nu = W_0 + \frac{1}{2} mv^2} \text{ or } \boxed{KE_{max} = h\nu - W_0} \longrightarrow (I)$$

eqn(1) is called Einsteins's photoelectric equation.

Note: KE_{max} is for surface e^{-1} which are most loosely bound.

Explain "How Einstein explained various features of photo-electric effect" ?

- Ans.** 1. As soon as light is incident on the surface of a metal, the photons are absorbed by the electrons and the photo electrons are ejected at once. As a result, there is no time lag between the arrival of light and emission of electrons. Therefore photoelectric effect is instantaneous.

2. Einstein's equation is given as

$$\therefore \frac{1}{2} m V_{\max}^2 = h\nu - W_0 \quad \longrightarrow (i)$$

From equation (i), we see that as frequency ν reduces, KE ($\frac{1}{2} m V_{\max}^2$) also reduces. When frequency reaches a certain value $\nu = \nu_0$, K.E. reduces to zero.

i.e. when $\nu = \nu_0$, $\frac{1}{2} m V_{\max}^2 = 0$,

substitute this condition in (i)

$$\therefore 0 = h\nu_0 - W_0$$

$$\therefore W_0 = h\nu_0, \text{ substitute in (i)}$$

$$\therefore \frac{1}{2} m V_{\max}^2 = h\nu - h\nu_0$$

$$\boxed{\therefore \frac{1}{2} m V_{\max}^2 = h(\nu - \nu_0)}$$

This equation shows that

- (a) If $\nu < \nu_0$ then K.E. is negative, which is not possible. The physical significance of this is that photo-electric emission is not possible.
- (b) If $\nu \geq \nu_0$ the K.E. is positive or zero which is possible. Hence the equation suggest that there is photo-electric emission from the surface.

$$\therefore \text{Photo electrons are emitted only if } \nu \geq \nu_0$$

3. According to quantum theory, intensity of radiation is directly proportional to the number of photons. One photon can cause emission of one photo-electron. Therefore if the intensity of radiation is increased then number of photons reaching the metal surface will be increased. Therefore there will be greater number of collisions so that greater number of photo electrons will be emitted.

This explains the increase in photo electric current with the increase in intensity of light.

4. If an electron is liberated from an atom which is situated on the surface of an emitter then its K.E. will be maximum. However photons can penetrate into the metal and can collide with electrons at different depths. Therefore if a photon collides with an electron situated well inside the metal & the electron is liberated, it will lose some energy in coming to the surface and will have less K.E.

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This explain different K.E. of different photo-electrons.

Note :

It should be noted that if $\nu = \nu_0$ then the electron is just separated without any K.E. and it represents the limiting case of photo-emission.

1. Photo Electric Work Function (W_0) :

Any metal contains large number of free electrons which move randomly within the metal like the molecules of a gas in a container but they can not leave the metal on their own as their energy is not sufficient to overcome the forces of attraction due to the electric field inside the metal. Therefore energy has to be supplied from external source in order to cause the emission of electrons. The minimum amount of energy required to separate the electron is called photo-electric work function.

Definition :

The minimum amount of energy that must be supplied by the photon to the atom in order to separate the electron from it is known as photo electric work function.

It is different for different metals.

$$\text{Also } W_0 = h\nu_0 \left(= \frac{hc}{\lambda_0} \right) \quad \text{where } h = \text{Planck's constant}$$
$$\nu_0 = \text{Threshold frequency}$$

Definition of "Threshold Frequency" (ν_0) :

"It is the minimum frequency of light that must be incident on the surface of a metal in order to just cause the emission of electrons from the surface of that metal.

Note: (1) It is different for different metals.

(2) If $\nu < \nu_0$, no photo-emission takes place.

$$(3) \because W_0 = h\nu_0 \quad \therefore \nu_0 = \frac{W_0}{h}$$

Definition of Threshold Wavelength (λ_0) :

It is the maximum wave length of light that must be incident on the surface of a metal in order to just cause the emission of electrons from the surface of that metal.

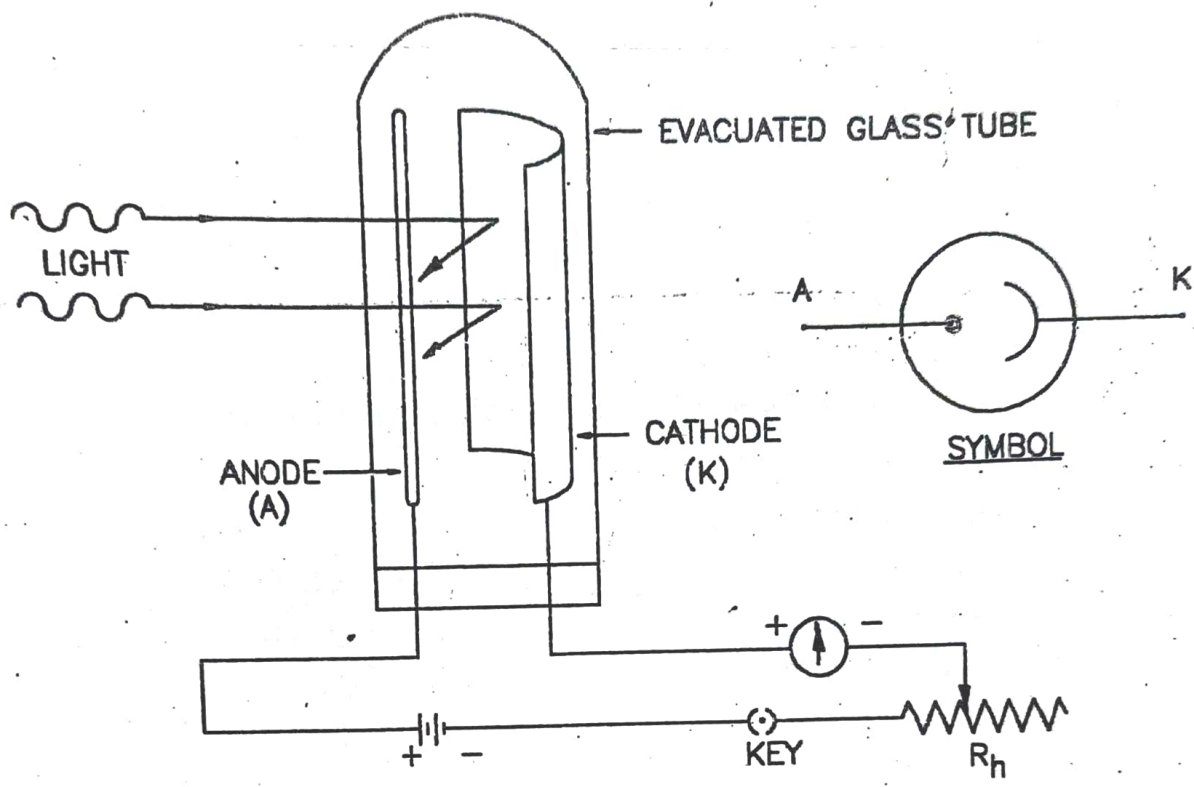
Note :

1. For photo-emission

$$(a) \nu \geq \nu_0$$

or

$$(b) \lambda \leq \lambda_0$$



Q. Write down Einstein's photoelectric equation & explain the terms involved in it ?

Ans. Einstein's photoelectric equation given by

$$\frac{1}{2} m v_{\max}^2 = h\nu - W_0$$

- where h = Planck's constant
- ν = Frequency of radiation
- $h\nu$ = Energy of photon
- W_0 = Photoelectric work function = The minimum amount of energy that must be supplied by the photon to the atom in order to separate the electron from it, is known as photoelectric work function.
- m = Mass of electron
- v_{\max} = Maximum velocity of electron
- $\frac{1}{2} m v_{\max}^2$ = Maximum K.E. of electron

Q.1 State four applications of photocells.**Ans. Applications of Photocell.**

- (i) It is used in exposure meter.
- (ii) It is used in burglar alarm.
- (iii) It is used in lux meter.
- (iv) It is used in smoke detector.
- (v) It is used as automatic street light
- (vi) It is used in reproduction of sound.

Q.2 What are photons?

Ans. (i) When an atom absorbs or emits light, the energy transfer occurs in discrete lumps (packets) of energy. These packets of energy are called as photons.

(ii) Photon energy is given by

$$E = h\nu = \frac{hc}{\lambda}, \text{ where } h \text{ Planck's constant whose value is } 6.63 \times 10^{-34} \text{ Js.}$$

Q3. Explain the term electron volt.

Ans. (i) When an electron is accelerated through a potential difference of one volt then energy gained by an electron is known as electron Volt (eV)

(ii) Energy of photon is usually expressed in electron

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

(iii) The larger units of energy are keV and MeV

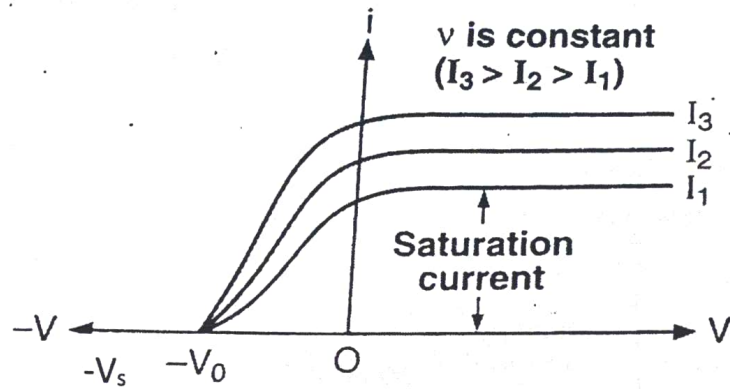
$$1 \text{ KeV} = 1.6 \times 10^{-16} \text{ J and}$$

$$1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$$

Q.4 State characteristics of photon.**Ans. Characteristics of photon**

- (i) In interaction with Matter, radiation behaves as particles called photons.
- (ii) The rest mass of a photon is zero.
- (iii) The photons are electrically neutral. Therefore, they are not deflected by electric and magnetic field.
- (iv) The photons travel with the speed of light.
- (v) All the photons of particular frequency (or wavelength) possess the same energy. Irrespective of the intensity of the radiation.
- (vi) The increase in the intensity of radiation imply an increase in the number of photons, with each photon having the same energy.
- (vii) During collision between a photon and a particle, the total energy and total momentum are conserved.

Graph of photoelectric current (i) v/s potential (v) at constant frequency but different intensities of light

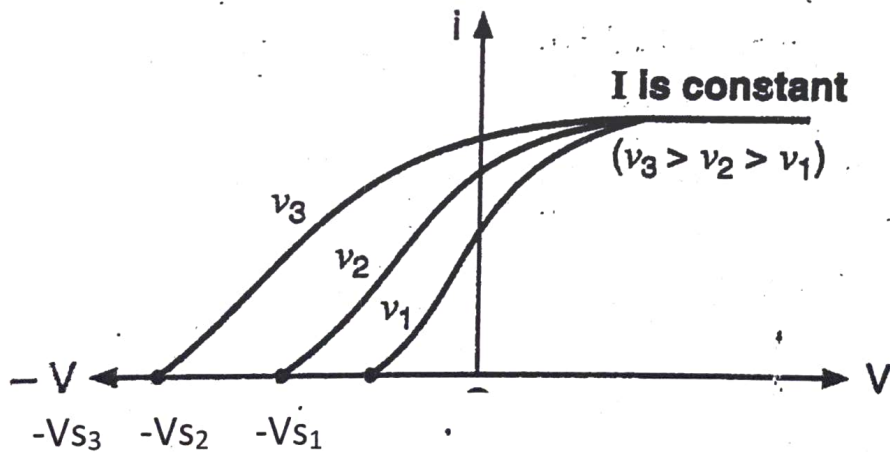


Conclusion : \therefore Stopping potential (V_s) is equal to KE_{\max} .

$$[\because e \cdot V_s = \frac{1}{2} m V_{\max}^2]$$

$\therefore V_s$ does not depend on intensity if frequency (η) is constant.

Graph of photoelectric current (i) v/s stopping potential varying for frequency but i constant intensity of light



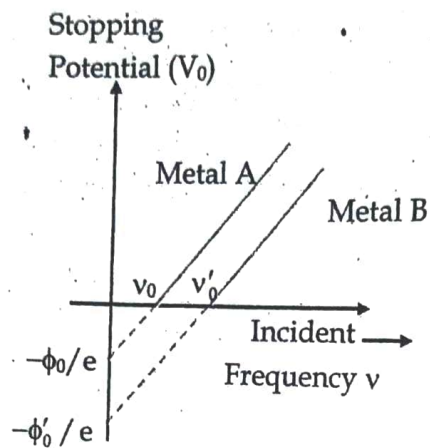
Conclusion : We find that stopping potential (V_s) for each frequency is different

\therefore If $\nu_3 > \nu_2 > \nu_1$

$\therefore KE_3 > KE_2 > KE_1$

$\therefore V_{s3} > V_{s2} > V_{s1}$ (in magnitude)

Graph of stopping potential (V_s) v/s frequency (ν) of incident light for metal A and metal B



$$\therefore e V_s = h\nu - W_0$$

$$\therefore V_s = \left(\frac{h}{e}\right)\nu - \left(\frac{W_0}{e}\right) \quad \dots\dots(1)$$

$$y = mx + c$$

Conclusion : (1) Slope $= \frac{h}{e} =$ constant for both metals A and B

Put $V_s = 0$ in (1)

$$\therefore \left(\frac{h}{e}\right)\nu = \frac{W_0}{e}$$

$$\therefore \nu = \frac{W_0}{h} = \frac{h\nu_0}{h} = \nu_0$$

Conclusion : (2) ν_0 values are different for metals A & B

Put $\nu = 0$ in (1)

$$\therefore V_s = \left(\frac{W_0}{e}\right)$$

Conclusion : (3)

\therefore y intercept represent $V_s = \left(\frac{W_0}{e}\right)$ & values are different.

Q11. Explain de Broglie's Hypothesis?

Ans. We know that radiation possess dual nature. As per de Broglie's hypothesis, matter also possess dual nature, i.e. particle nature and wave nature. As per this hypothesis, the moving particle of matter like electrons, protons, atoms possess the wave like properties under suitable conditions. de Broglie's hypothesis is based on following observations:

- i. The whole energy in the universe is in the form of matter and electromagnetic radiation.
- ii. Nature loves symmetry hence two physical quantities like matter and energy must be symmetrical. In other words, if energy has dual nature, then matter must also have dual nature i.e. particle nature and wave nature.

As per this hypothesis moving particle behaves like waves of definite wavelength. The waves associated with matter are called as **Matter waves** or **de Broglie's waves**.

Statement of de-Broglie's Hypothesis: Every moving particle has a wave associated with it.

Q.12 Derive an expression for wavelength of de-Broglie's waves?

Ans. According to Planck's quantum theory, the radiation is emitted in the form of packets or bundles of energy called as quanta or photon. The energy of each photon is given by

$$E = h\nu \quad \dots\dots(I)$$

where h = Planck's constant and ν = frequency of radiation.

The photon is considered as particle. According to Einstein's mass energy relation, the energy of photon can be given as:

$$E = mc^2 \quad \dots\dots(II)$$

$$\therefore (II) = (I)$$

$$mc^2 = h\nu$$

$$mc = \frac{h\nu}{c}$$

But $mc = mv = P$ = momentum of photon (where v = velocity)

$$\therefore P = \frac{h\nu}{c}$$

$$\text{But } c = v\lambda$$

$$\therefore P = \frac{h\nu}{v\lambda}, \quad \therefore P = \frac{h}{\lambda}$$

$$\therefore \lambda = \frac{h}{P} \quad \dots\dots \text{(III)} \quad \text{or}$$

$$\lambda = \frac{h}{mc} = \frac{h}{mv} \quad \dots\dots \text{(IV)}$$

de Broglie suggested eq. (III) and (IV) is general formula. It is applicable to photons as well as other moving particles.

Note:

(1) Eq. (III) and (IV) connects momentum, which is characteristic of the particle with the wavelength which is characteristics of a wave.

(ii) In (IV) mass (m) is relativistic mass of particle. It is given by Einstein's equation.

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

(ii) The energy is carried by the moving particles like electrons and not by matter waves associated with it.

(iv) From $\lambda = \frac{h}{P} = \frac{h}{mv}$ we can say that

(a) $\lambda \propto \frac{1}{m}$ i.e. lighter particles have large wavelength.

(b) $\lambda \propto \frac{1}{v}$, i.e. for fast moving particle, λ is small.

(c) λ does not depend on charge of the particle.

(d) de Broglie waves (or matter waves) are different from mechanical waves as well as electromagnetic waves.

Q13. Derive an expression for de Broglie's expression for wavelength of an electron?

Ans. Consider an electron of mass m and charge e accelerated through a P.D. of volts. The energy acquired by an electron is given by:

$$E = eV \quad \dots(I)$$

If v is the velocity of electron, then its energy can be given as:

$$E = \frac{1}{2} mv^2 \quad \therefore v^2 = \frac{2E}{m} \quad \therefore v = \sqrt{\frac{2E}{m}} \quad \dots(II)$$

Now de Broglie's wavelength is given by:

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

$$\therefore \lambda = \frac{h}{m\sqrt{\frac{2E}{m}}} \quad [\text{using II}]$$

$$\therefore \lambda = \frac{h}{\sqrt{2mE}}$$

$$\therefore \lambda = \frac{h}{\sqrt{2meV}} \quad [\text{using I}]$$

Substituting, $m = 9.1 \times 10^{-31} \text{ kg}$; $e = 1.6 \times 10^{-19} \text{ C}$; $h = 6.63 \times 10^{-34} \text{ J.s}$

$$\text{we get, } \lambda = \frac{12.27}{\sqrt{V}} \times 10^{-10} \text{ m} = \frac{12.27}{\sqrt{V}} \text{ \AA} = \frac{1.227}{\sqrt{V}} \text{ nm}$$

Note:

$$(i) \text{ If } V = 100 \text{ volt} = \frac{12.27}{\sqrt{100}} = 1.227 \text{ \AA}$$

$$\text{If } V = 15000 \text{ volt} = \frac{12.27}{\sqrt{15000}} = \frac{12.27}{122.7} = 0.1 \text{ \AA}$$

These values of λ are within the range of X-ray wavelengths and they are of same order as the spacing between atomic planes in crystals. This suggests that the matter waves associated with electron can be verified and measured by crystal diffraction experiments using X-rays.

(ii) For high-speed electrons, we have to consider relativistic correction for mass.

(iii) It is not easy to measure the wavelength of heavy particles. For e.g. Consider a body of 1 kg moving at 100 m/s

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{1 \times 100} = 6.63 \times 10^{-34} \text{ m}$$

This wavelength is so small that it cannot be measured.

Q. Explain: Davisson and Germer Experiment

Aim: To prove wave nature of electron.

Apparatus: It consists of an Electron gun nickel crystal and electron detector. Electron gun has tungsten filament coated with barium oxide for high emission efficiency. Filament works as thermionic cathode.

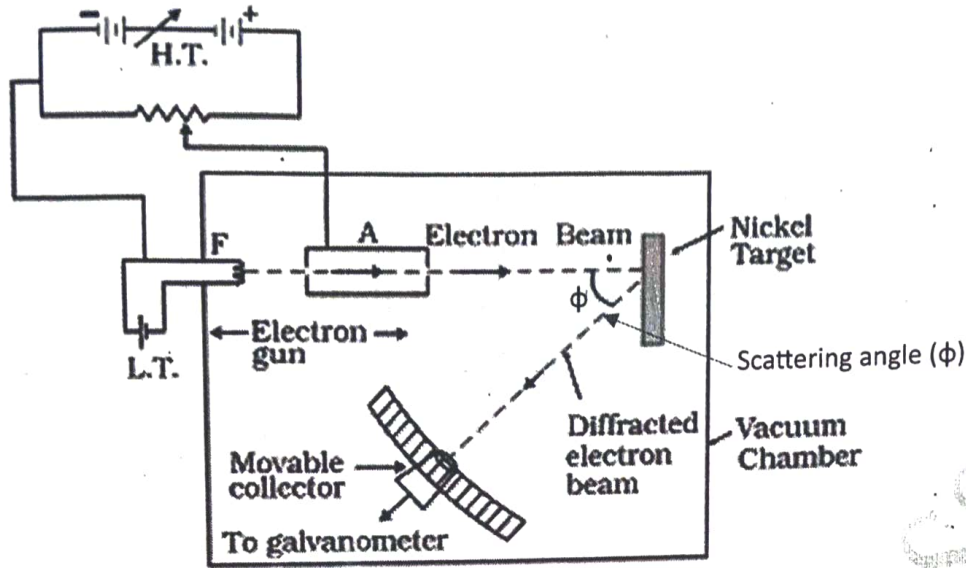
Procedure:

- (i) The electrons are accelerated by cylindrical anode kept at fixed known high positive voltage (V). This anode imparts the desired velocity of electrons. The electrons emerge out of anode aperture as fine beam.
- (ii) This beam is made to fall on surface of nickel crystal. The electron beam gets scattered in all directions. The intensity of scattered electrons in a particular direction is measured by the moving collector (or electron detector), which can be moved on a circular scale.
- (iii) This experiment was performed at different accelerating potential V but significant intensity of electron was observed around 44 V - 68 V
- (iv) The detector is connected to a sensitive galvanometer whose deflection is directly proportional to intensity of electrons received by the detector. The whole setup is enclosed in an evacuated chamber.

Measurements: The intensity of scattered beam is recorded for different scattering angles (ϕ) and for different accelerating voltages (V). It is observed that, galvanometer showed maximum deflection for scattering angle $\phi = 50^\circ$ and accelerating voltage of 54 V. The maximum intensity is due to constructive interference of electron waves scattered from different atomic layers.

Calculations:

According to **Bragg's diffraction** formula, for 1st order diffraction maxima $\lambda = 2d \sin \Theta$ where, d is the spacing between atomic planes; λ is the wavelength of associated wave and Θ is the glancing angle



(ii) For scattering angle $\phi = 50^\circ$, glancing angle is $\Theta = 65^\circ$ (glancing angle $= 90^\circ - \frac{\phi}{2}$)
 and spacing between atomic planes for nickel is $d = 0.91 \text{ \AA}$
 $\therefore \lambda = 2 \times 0.91 \times 10^{-10} \times \sin(65)$

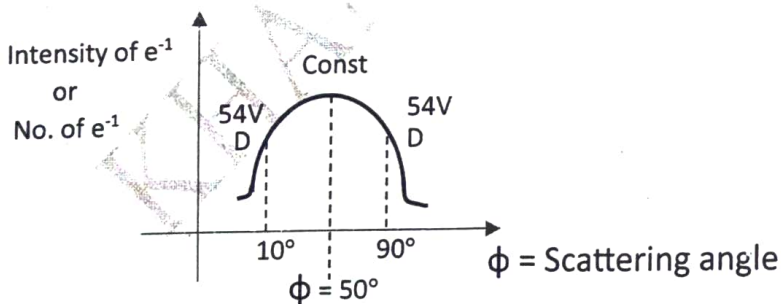
$$\lambda = 1.65 \text{ \AA}$$

This is wavelength of electron wave found experimentally.

(iii) By using de Broglie's relation, the wavelength of electron at accelerating voltage 54 V is given by

$$\lambda = \frac{12.27}{\sqrt{V}} \text{ \AA} = \frac{12.27}{\sqrt{54}} = 1.67 \text{ \AA}$$

Conclusion: This is excellent agreement between experimental value of Wavelength of electron. This confirms the **wave nature** of particle electron.



FAILURE OF WAVE THEORY TO EXPLAIN PHOTO ELECTRIC EFFECT

1. **Instantaneous Emission** : Wave theory expect that the metal surface will absorb incident energy continuously and all electron near the surface will go on accumulating this energy till after a certain time, this energy is equal to work function (W_0) .

a) **As per wave theory** , if the intensity is large, it will take small time to eject electrons and vice versa

These arguments were contrary to observation since photoelectron effect is an instantaneous process.

2. **Kinetic Energy** : As per wave theory, larger intensity means larger energy and electrons are expected to be emitted with larger K.E. But observation showed that the maximum K.E. does not depend on intensity but depended on incident frequency.

3. **Frequency**: As per wave theory of light, frequency has no role in determining K.E. of photo electrons. Moreover wave theory expected photo electrons to be emitted for any frequency if the intensity is large enough . But observations are contradictory since below a certain frequency called threshold frequency photo electrons were not emitted even if the intensity was large.

DUAL NATURE OF RADIATION & MATTER - SUMMARY OF FORMULAE

PART A : PHOTOELECTRIC EFFECT

1. Must Know following values:

$$c = 3 \times 10^8 \text{ m/s}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$m = 9.1 \times 10^{-31} \text{ kg}$$

$$1 \text{ \AA} = 10^{-10} \text{ m}, 1 \text{ nm} = 10^{-9} \text{ m}$$

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

2. $c = \nu\lambda = \nu_0\lambda_0$

→ For Photoemission

3. $E = h\nu = \frac{hc}{\lambda} \text{ (J)}$

$$= \frac{h\nu}{x} = \frac{hc}{\lambda x} \text{ (eV)}$$

$$\nu \geq \nu_0 \text{ Minimum Frequency } (\nu_0)$$

or

$$\lambda \leq \lambda_0 \text{ Maximum wavelength } (\lambda_0)$$

4. $W_0 = h\nu_0 = \frac{hc}{\lambda_0} \text{ (J)}$

$$= \frac{h\nu_0}{x} = \frac{hc}{\lambda_0(x)} \text{ (eV)}$$

In formula 3 to 5

$$x = 1.6 \times 10^{-19}$$

5. $h\nu = W_0 + \frac{1}{2}mv_{max}^2$

$$\therefore \frac{1}{2}mv_{max}^2 = h\nu - W_0 = h\nu - h\nu_0 = h(\nu - \nu_0)$$

$$= \frac{hc}{\lambda} - W_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

$$= hc \left[\frac{1}{\lambda} - \frac{1}{\lambda_0} \right] \text{ (J)}$$

$$= \frac{hc}{x} \left[\frac{1}{\lambda} - \frac{1}{\lambda_0} \right] \text{ (eV)}$$

6. $eV_s = \frac{1}{2}mv_{max}^2$

7. $h\nu = W_0 + eV_s$

8. Power = (No. of Photons per second) x Energy of one photon.

$$= N \times (h\nu) = N \times \left(\frac{hc}{\lambda} \right)$$

9. For same metal, W_0 is constant

SOME IMPORTANT VALUES

$$E = \left[\frac{1250}{\lambda} \right] \text{ eV nm} = \left[\frac{12500}{\lambda} \right] \text{ eV. \AA} \text{ (Note sometime : 1240 or 12400)}$$

$$hc \approx 2 \times 10^{-25} \text{ Jm}$$

10. As Intensity increases, photoelectric current increases but Energy of photon remains constant.
11. As Frequency increases, K.E. increases but electric current remains constant.

PART B : de Broglie's Hypothesis

$$1. \lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE}} = \frac{h}{\sqrt{2meV}}$$

2. For electron

$$\lambda = \frac{h}{\sqrt{2meV}} = \frac{12.28}{\sqrt{V}} \text{ \AA} = \frac{1.228}{\sqrt{V}} \text{ nm}$$

$$3. E = mc^2 = (mc)c = p.c$$

$$\therefore p = \text{momentum of photon} = \frac{E}{c}$$