PHYSICS

Class XII

Chapter 11- Dual Nature of Radiation and Matter

1 Mark Question

Question 1.
An electron and alpha particle have the same de-Broglie wavelength associated with them. How are their kinetic energies related to each other?
Answer:

$$E_K = \frac{p^2}{2m} \quad \text{where} \begin{bmatrix} E_K = \text{Kinetic energy} \\ p = \text{momentum} \\ m = \text{mass of the particle} \end{bmatrix}$$

de-Broglie wavelength, $\lambda = \frac{h}{p}$

...where [h = Planck's constant

$$\therefore \quad \lambda = \frac{h}{\sqrt{2mE_K}}$$

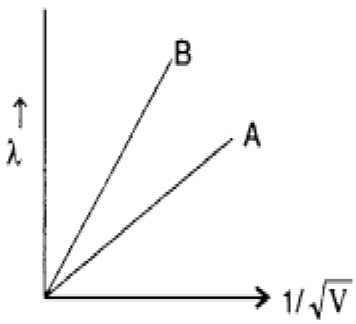
$\because$ Both the particles have the same de-Broglie wavelength ...[Given

$$\therefore \quad \frac{h}{\sqrt{2m_e E_{Ke}}} = \frac{h}{\sqrt{2m_\alpha E_{K\alpha}}}$$

$$\text{or} \quad \frac{m_e}{m_\alpha} = \frac{E_{K\alpha}}{E_{Ke}} \quad \text{where} \begin{bmatrix} m_e = \text{mass of electron} \\ m_\alpha = \text{mass of } \alpha\text{ - particle} \\ E_{Ke} = \text{K.E. of electron} \\ E_{K\alpha} = \text{K.E. of } \alpha\text{ - particle} \end{bmatrix}$$

As $m_\alpha > m_e \quad \therefore \text{K.E}_{Ke} > E_{K\alpha}$

Question 2.
Two lines, A and B, in the plot given below show the variation of de-Broglie wavelength, λ versus 1V√, Where V is the accelerating potential difference, for two particles carrying the same charge. Which one of two represents a particle of smaller mass ?



Answer:

According to de-Broglie wavelength, $\lambda = \frac{h}{\sqrt{2meV}}$

$$\frac{\lambda}{1/\sqrt{V}} = \frac{h}{\sqrt{2me}} \Rightarrow \frac{\lambda}{1/\sqrt{V}} = \frac{1}{\sqrt{m}} \times \frac{h}{\sqrt{2e}}$$

The slope is given by slope $\propto \frac{1}{\sqrt{m}}$

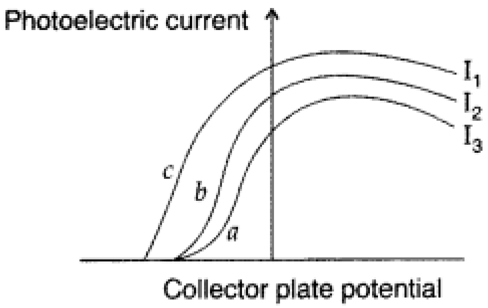
Slope of B > slope of A

$$\frac{1}{\sqrt{m}_B} > \frac{1}{\sqrt{m}_A} \Rightarrow \sqrt{m}_B < \sqrt{m}_A$$

$\therefore \quad m_B < m_A$

$\therefore$ **B represents a particle of smaller mass**

Question 3.
The figure shows a plot of three curves a, b, c, showing the variation of photocurrent vs. collector plate potential for three different intensities I_1, I_2 and I_3 having frequencies V_1, v_2 and v_3 respectively incident on a photosensitive surface.



Point out the two curves for which the incident radiations have same frequency but different intensities.
Answer:
Stopping potential will be same for the same frequency. So its curves 'a' and 'b' which have same frequency but different intensities. ($I_2 > I_3$)

Question 4.
The stopping potential in an experiment on photoelectric effect is 1.5 V. What is the maximum kinetic energy of the photoelectrons emitted?
Answer:
K.E. of the electron $e^- = 1.5$ eV

Question 5.
The maximum kinetic energy of a photoelectron is 3 eV. What is its stopping potential?
Answer:

Since $K_{max} = eV_0$

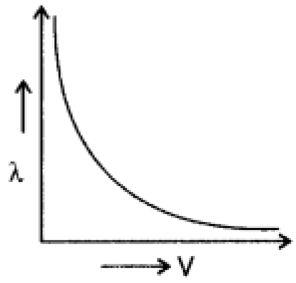
$\therefore$ Stopping potential $V_0 = \frac{K_{max}}{e} = $ **3 volt**

Question 6.
Show graphically, the variation of the de- Broglie wavelength (λ) with the potential (V) through which an electron is accelerated from rest.
Answer:

$$\lambda = \frac{h}{mv} = \frac{h}{m\sqrt{\frac{2eV}{m}}}$$

$$= \frac{h}{\sqrt{2meV}}$$

$$= \frac{12.27}{\sqrt{V}} \mathring{A}$$



Question 7.
Define the term 'stopping potential' in relation to photoelectric effect.
Answer:
The value of the retarding potential at which the photo electric current becomes zero is called cut off or stopping potential for the given frequency of the incident radiation.

Question 8.
State de-Broglie hypothesis.
Answer:
According to de-Broglie hypothesis, a particle of mass on moving with given velocity v must be associated with a matter waver of wavelength X given by:

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

Question 9.
A proton and an electron have same kinetic energy. Which one has greater de-Broglie wavelength and why? Answer:

Kinetic energy of a particle $E = \frac{1}{2}mv^2$

or $mv = \sqrt{2mE}$

de-Broglie wavelength associated with the particle is $\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}$

For a given value of E, $\lambda = \frac{1}{\sqrt{m}}$

Mass of electron < mass of proton

So, electron has greater de-Broglie wavelength.

Question 10.
A proton and an electron have same kinetic energy. Which one has smaller de-Broglie wavelength and why?
Answer:

K.E. of a particle, $K = \frac{1}{2}mv^2 = \frac{1}{2}\frac{(mv)^2}{m} = \frac{p^2}{m}$

$\therefore$ Linear momentum, $p = \sqrt{2mK}$

de-Broglie wavelength, $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}}$

For the particles possessing same kinetic energy,

$$\lambda \propto \frac{1}{\sqrt{m}}$$

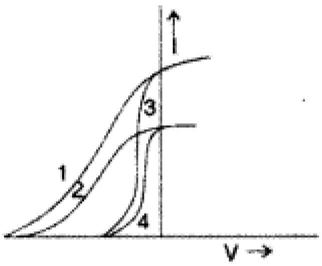
$me << mp \quad \therefore \lambda_e >> mp \quad \therefore \lambda_e >> h_p$

Proton has smaller de-Broglie wavelength.

Question 11.
Define 'intensity' of radiation in photon picture of light.
Answer:
It is the number of photo electrons emitted per second.

Question 12.
Why is photoelectric emission not possible at all frequencies?
Answer:
Photoelectric emission is possible only if the energy of the incident photon (hv) is greater than the work function ($\omega_0 = hv_0$) of the metal. Hence the frequency v of the incident radiation must be greater than the threshold frequency v_0.

Question 13.
The given graph shows the variation of photo-electric current (I) versus applied voltage (V) for two different photosensitive materials and for two different intensities of the incident radiation. Identify the pairs of curves that correspond to different materials but same intensity of incident radiation.

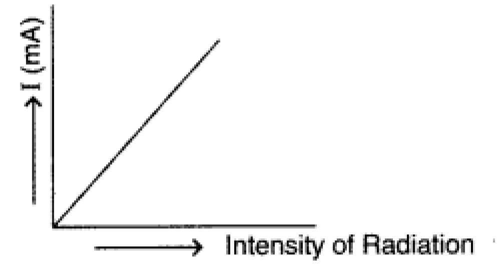


Answer:
The pairs (2, 4) and (1, 3) have same intensity but different material.

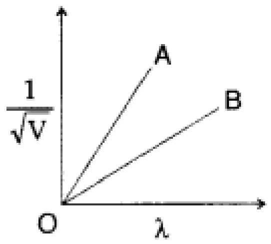
Question 14.
Write the expression for the de Broglie wavelength associated with a charged particle having charge ‘q’ and mass ‘m’, when it is accelerated by a potential V.
Answer:

$$\boxed{\lambda = \frac{h}{\sqrt{2mqV}}}$$

Question 15.
Show on a plot the nature of variation of photoelectric current with the intensity of radiation incident on a photosensitive surface.
Answer:



Question 16.
Figure shows a plot of 1V√, where V is the accelerating potential, vs. the de-Broglie wavelength ‘λ’ in the case of two particles having same charge ‘q’ but different masses m_1 and m_2. Which line (A or B) represents a particle of larger mass?



Answer:
B line represents particle of larger mass because slope ∝1m√.

Question 17.
Find the ratio of de-Broglie wavelengths associated with two electrons accelerated through 25 V and 36 V.
Answer:

$$\lambda \propto \frac{1}{\sqrt{V}} \qquad \frac{\lambda_1}{\lambda_2} = \sqrt{\frac{V_2}{V_1}} = \sqrt{\frac{36}{25}} = \frac{6}{5}$$

$$\therefore \quad \lambda_1 : \lambda_2 :: 6 : 5$$

Question 18.
Define intensity of radiation on the basis of photon picture of light. Write its S.I. unit.
Answer:
It is the number of photo-electrons emitted per second per unit area.
SI unit : $m^{-2}S^{-1}$

2 Mark Questions

Question 1.
An electron is accelerated through a potential difference of 64 volts. What is the de-Broglie wavelength associated with it? To which part of the electromagnetic spectrum does this value of wavelength correspond?
Answer:
According to de-Broglie wavelength,

$$\lambda = \frac{1.227}{\sqrt{V}} \text{ nm} = \frac{1.227}{\sqrt{64}} = \frac{1.227}{8} = 0.1533 \text{ nm}$$

This wavelength is associated with X-rays.

Question 2.
An a-particle and a proton are accelerated from rest by the same potential. Find the ratio of their de-Broglie wavelengths.
Answer:
de-Broglie wavelength of a charged (q)
Particle accelerated through a potential 'V' is

$$\lambda = \frac{h}{\sqrt{2mqV}}$$

Ratio of their de-Broglie wavelengths for an α-particle and a proton is $\frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{q_p m_p}{q_\alpha m_\alpha}}$

As $q_\alpha = 2\, q_p,\ m_\alpha = 4\, m_p$

$$\therefore \quad \frac{\lambda_\alpha}{\lambda_p} = \sqrt{\left(\frac{1}{2}\right)\left(\frac{1}{4}\right)} = \frac{1}{2\sqrt{2}}.$$

Question 3.
Write Einstein's photoelectric equation. State clearly the three salient features observed in photoelectric effect, which can be explained on the basis of the above equation.
Answer:
Einstein's photoelectric equation is $K_{max} = hv - \phi_0$
(i) We find K_{max} depends linearly on V only. It is independent of intensity of radiation.

(ii) Since K_{max} must be positive.

$h\nu > \phi_0 \quad \Rightarrow \nu > \nu_0 \qquad (\because \phi_0 = h\nu_0)$

So greater the work function (ϕ_0), higher is the minimum frequency (threshold frequency) required to emit photo electron.

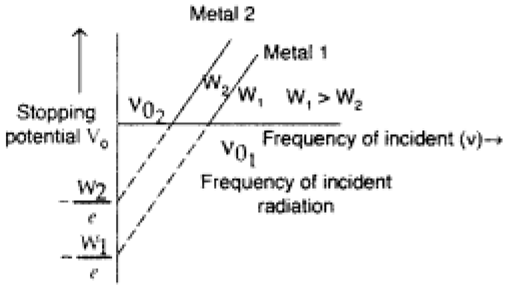
(iii) Greater the number of energy quanta, greater is the number of photoelectrons. So, photoelectric current is proportional to intensity.

Question 4.
Plot a graph showing the variation of stopping potential with the frequency of incident radiation for two different photosensitive materials having work functions W_1 and W_2 ($W_1 > W_2$). On what factors does the
(i) slope and
(ii) intercept of the lines depend?
Answer:

(i) As $eV_0 = hv - W_0 \qquad V_0 = \left(\frac{h}{e}\right)v - \frac{W_0}{e}$

$\therefore$ Slope of $V_0 - v$ graph $= \frac{h}{e}$

Slope depends on the Planck's constant and electronic charge (e).



(ii) Intercept $= \frac{\text{Work function}}{e} = \frac{-W_0}{e}$

Therefore, Intercept depends upon the work function (threshold frequency) and electronic charge (e).

Question 5.
A proton and a deuteron are accelerated through the same accelerating potential. Which one of the two has
(a) greater value of de-Broglie wavelength associated with it, and
(b) less momentum?
Give reasons to justify your answer.
Answer:
For proton and deuteron, charge (q) is the same, while the mass of deuteron is more than that of proton

(a) We know $\lambda = \frac{h}{\sqrt{2mqV}}$

Here q and V are the same for both,

Hence, $\lambda \propto \frac{1}{\sqrt{m}}$

∴ Proton will be associated with greater value of de-Broglie wavelength.

(b) $\because \frac{1}{2}mv^2 = qV$

Multiplying 'm' on both sides, we have

$\frac{1}{2}m^2v^2 = mqV$ or $\frac{1}{2}p^2 = mqV$

or $p = \sqrt{2mqV}$ $\therefore p \propto \sqrt{m}$

Proton will have less momentum.

Question 6.
A proton and an alpha particle are accelerated through the same potential. Which one of the two has
(i) greater value of de-Broglie wavelength associated with it, and
(ii) less kinetic energy.
Give reasons to justify your answer.
Answer:
Proton's mass is less than that of alpha particle, which contains 2 protons and 2 neutrons

Question 7.
A deuteron and an alpha particle are accelerated with the same accelerating potential. Which one of the two has
(1) greater value of de-Broglie wavelength, associated with it, and
(2) less kinetic energy? Explain.
Answer:
[A deuteron (consisting of one proton and one neutron) has less mass than alpha particle (consisting of 2 protons and 2 neutrons)]

Question 8.
(i) Monochromatic light of frequency 6.0×10^{14} Hz is produced by a laser. The power emitted is 2.0×10^{-3} W. Estimate the number of photons emitted per second on an average by the source.
(ii) Draw a plot showing the variation of photoelectric current versus the intensity of incident radiation on a given photosensitive surface.
Answer:

(*i*) Given : $\nu = 6.0 \times 10^{14}$ Hz, $P = 2.0 \times 10^{-3}$ W

Energy of one photon $= h\nu$

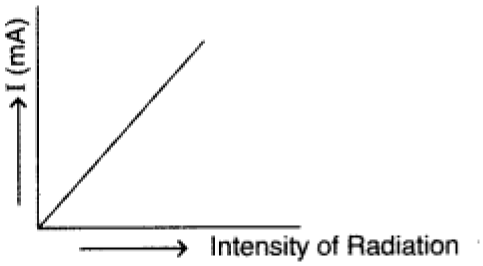
$= (6.6 \times 10^{-34}) \times (6.0 \times 10^{14})$

Number of photons emitted per sec

$$= \frac{\text{Power}}{\text{Energy of one photon}}$$

$$n = \frac{2\times10^{-3}}{(6.6\times10^{-34})\times(6.0\times10^{14})} \quad \therefore\ n = 5 \times 10^{15}$$

(ii)



Question 9.

Two monochromatic radiations of frequencies v^1 and v^2 ($V^1 > v^2$) and having the same intensity are, in turn, incident on a photosensitive surface to cause photoelectric emission. Explain, giving reason, in which case

(i) more number of electrons will be emitted and

(ii) maximum kinetic energy of the emitted photoelectrons will be more.

Answer:

(*i*) Intensity of incident radiation $I = nhv$

where [n is number of photons incident per unit time per unit area.
For same intensity of two monochromatic radiations of frequency v_1 and v_2]

$n_1hv_1 = n_2hv_2$

As $v_1 > v_2 \quad \Rightarrow n_2 > n_1$

$\therefore$ Number of electrons emitted for monochromatic radiation of frequency v_2, will be more than that for radiation of frequency v_1.

(*ii*) $hv = \phi_0 + K_{max}$

$\therefore$ For given ϕ_0 (work function of metal) K_{max} increases with v

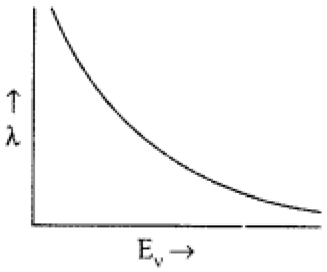
$\therefore$ Maximum kinetic energy of emitted photoelectrons will be more for monochromatic light of frequency v_1 (as $v_1 > v_2$).

Question 10.
X-rays fall on a photosensitive surface to cause photoelectric emission. Assuming that the work function of the surface can be neglected, find the relation between the de-Broglie wavelength (λ) of the electrons emitted to the energy (E_0) of the incident photons. Draw the nature of the graph for X as a function of E_v.
Answer:
(i) Relation $E_v = \phi_0 + K_{max}$

As $\phi_0 = 0$, $\quad \therefore E_v = K_{max} = \frac{p^2}{2m}$

$\because p = \sqrt{2m E_v} \quad \therefore \lambda = \frac{h}{p} = \frac{h}{\sqrt{2m E_v}}$

(ii)

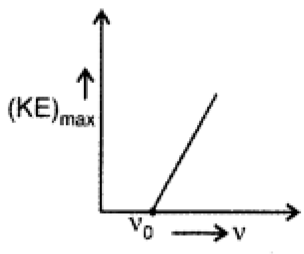


Question 11.
Write three basic properties of photons which are used to obtain Einstein's photoelectric equation. Use this equation to draw a plot of maximum kinetic energy of the electrons emitted versus the frequency of incident radiation.
Answer:
Properties.
Einstein's photoelectric equation is $K_{max} = h\nu - \phi_0$
(i) We find K_{max} depends linearly on V only. It is independent of intensity of radiation.
(ii) Since K_{max} must be positive.

$h\nu > \phi_0 \quad \Rightarrow \nu > \nu_0 \quad (\because \phi_0 = h\nu_0)$

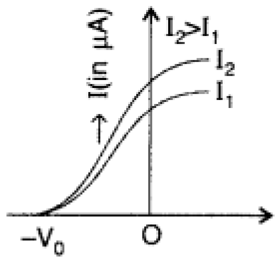
So greater the work function (ϕ_0), higher is the minimum frequency (threshold frequency) required to emit photo electron.
(iii) Greater the number of energy quanta, greater is the number of photoelectrons. So, photoelectric current is proportional to intensity.

Plot of maximum kinetic energy vs. frequency



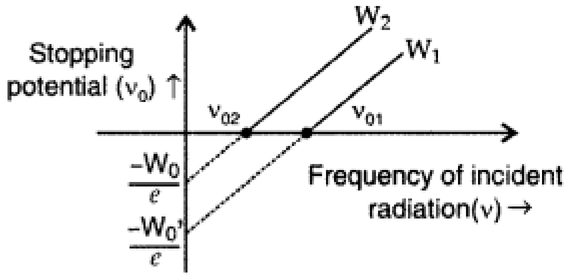
Question 12.
(i) Define the term 'threshold frequency' as used in photoelectric effect.
(ii) Plot a graph showing the variation of photoelectric current as a function of anode potential for two light beams having the same frequency but different intensities I_1 and I_2 ($I_1 > I_2$).
Answer:
(i) Threshold frequency. The minimum frequency v_0 which the incident light must possess so as to eject photoelectrons from a metal surface, is called threshold frequency of the metal.

(ii)



4 Mark Questions

Question 1.
Draw a graph showing the variation of stopping potential with frequency of incident radiation for two photosensitive materials having work functions W_1 and W_2 ($W_1 > W_2$).
Write two important conclusions that can be drawn from the study of these plots.
Answer:
$\because \quad W_1 = h\nu_{01}, \qquad W_2 = h\nu_{02}$
Given : $W_1 > W_2 \qquad \therefore \; \nu_{01} > \nu_{02}$
Conclusions:



(i) Threshold frequency of material having work function W_1 is more than that of material of work function W_2.
(ii) The slopes of the straight line graphs, in both the cases, have the same value.
(iii) For the same frequency of incident radiation (> v_{01}), the maximum kinetic energy of the electrons, emitted from the material of work function W_1 is < that of electrons emitted from material of work function W_2.(any two)

Question 2.
(a) Why photoelectric effect can not be explained on the basis of wave nature of light? Give reasons.
(b) Write the basic features of photon picture of electromagnetic radiation on which Einstein's photoelectric equation is based.
Answer:
(a) (i) The maximum kinetic energy of the emitted electron should be directly proportional to the intensity of incident radiations but it is not observed experimentally. Also maximum kinetic energy of the emitted electrons should not depend upon incident frequency according to wave theory, but it is not so.
(ii) According to wave theory, threshold frequency should not exist. Light of all frequencies should emit electrons provided intensity of light is sufficient for electrons to eject.
(iii) According to wave theory, photoelectric effect should not be instantaneous. Energy of wave cannot be transferred to a particular electron but will be distributed to all the electrons present in the illuminated portion. Hence, there has to be a time lag between incidence of radiation and emission of electrons.

(b) Basic features of photon picture of electromagnetic radiation :
(i) Radiation behaves as if it is made of particles like photons. Each photon has energy E = hv and momentum p = h/λ.
(ii) Intensity of radiation can be understood in terms of number of photons falling per second on the surface. Photon energy depends only on frequency and is independent of intensity.
(iii) Photoelectric effect can be understood as the result of one to one collision between an electron and a photon.
(iv) When a photon of frequency
(v) is incident on a metal surface, a part of its energy is used in overcoming the work function and other part is used in imparting kinetic energy, so KE = $h(v - v_0)$.

Question 3.
Write Einstein's photoelectric equation and point out any two characteristic properties of photons on which this equation is based. Briefly explain the three observed features which can be explained by this equation.
Answer:
Einstein's photoelectric equation

$$h\nu = h\nu_0 + \frac{1}{2}mv^2_{\max}$$

where $\left[\begin{array}{l} \nu = \text{frequency of incident radiation} \\ \frac{1}{2}mv^2_{\max} = \text{maximum kinetic energy} \\ \nu_0 = \text{threshold frequency} \end{array}\right.$

Two characteristics properties of photons on which equation is based.
1. Photoelectric emission will take place only if frequency of incident radiation is greater than or equal to threshold frequency.
2. When a photon collides with an electron, it gives all its energy to electron.

Three features :

(*i*) If $\nu > \nu_0$ the maximum K.E. is directly proportional to frequency of incident light. If on increasing intensity of light more photons fall on metal surface, it may result in ejection of greater number of electrons but their energy remains unchanged.

(*ii*) If $\nu > \nu_0$ then according to $h\nu - h\nu_0 = \frac{1}{2} mV^2_{max}$, K.E. depends on frequency of incident light.

(*iii*) If $\nu < \nu_0$, photoelectric emission does not take place for incident radiation below threshold frequency.

Question 4.
(a) State three important properties of photons which describe the particle picture of electromagnetic radiation.
(b) Use Einstein's photoelectric equation to define the terms
(i) stopping potential and
(ii) threshold frequency.
Answer:
(a)
Basic features of photon picture of electromagnetic radiation :
(i) Radiation behaves as if it is made of particles like photons. Each photon has energy E = hv and momentum p = h/λ.
(ii) Intensity of radiation can be understood in terms of number of photons falling per second on the surface. Photon energy depends only on frequency and is independent of intensity.
(iii) Photoelectric effect can be understood as the result of one to one collision between an electron and a photon.
(iv) When a photon of frequency
(v) is incident on a metal surface, a part of its energy is used in overcoming the work function and other part is used in imparting kinetic energy, so KE = h(v – v_0).

(b) (i) Stopping potential or cut-off potential. The minimum value of the negative potential 'V_0', which should be applied to the anode in a photo cell so that the photo electric current becomes zero, is called stopping potential.
The maximum kinetic energy (K_{max}) of photoelectrons is given by,

$$K_{max} = eV_0 \quad \text{or} \quad \frac{1}{2} mv^2_{max} = eV_0$$

(ii) Threshold frequency. The minimum frequency V_0, which the incident light must possess so as to eject photoelectrons from a metal surface, is called threshold frequency of the metal.

Mathematically $\phi_0 = h\upsilon_0$,

where [ϕ_0 is work function and h is plank's constant.]

Question 5.
An electron microscope uses electrons accelerated by a voltage of 50 kV. Determine the de-Broglie wavelength associated with the electrons. Taking other factors, such as numerical aperture etc. to be same, how does the resolving power of an electron microscope compare with that of an optical microscope which uses yellow light?
Answer:
Given : V = 50 kV = 50×10^3 volt
Kinetic energy of electron,

$$E_k = 50 \times 10^3 \text{ eV} = 50 \times 10^3 \times 1.6 \times 10^{-19} \text{ J} = 50 \times 1.6 \times 10^{-16} \text{ J}$$

de-Broglie wavelength of electron is

$$\lambda = \frac{h}{\sqrt{2mE_k}} = \frac{(6.63 \times 10^{-34})}{\sqrt{2 \times 9.11 \times 10^{-31} \times 50 \times 1.6 \times 10^{-16}}} = 5.5 \times 10^{-12} \text{ m}$$

For yellow light, wavelength X = 5.9×10^{-7} m Since resolving power (R.P.) is inversely proportional to wavelength, therefore, R.P. of an electron microscope is about 10^5 times more than optical microscope.

Question 6.
Write Einstein's photoelectric equation and mention which important features in photoelectric effect can be explained with the help of this equation.
The maximum kinetic energy of the photoelectrons gets doubled when the wavelength of light incident on the surface changes from λ_1 to λ_2. Derive the expressions for the threshold wavelength λ_0 and work function for the metal surface.
Answer:
(*i*) Einstein's Photoelectric equation,

$$h\nu = \phi_0 + k_{max}$$

$$\text{or } h\nu = h\nu_0 + k_{max} \qquad \textbf{where } k_{max} = \frac{1}{2} m v_{max}^2$$

(ii) Important features of photoelectric effect:
(a) Radiation behaves as if it is made of particles like photons. Each photon has energy E = hv and momentum p = h/λ.
(b) Intensity of radiation can be understood in terms of number of photons falling per second on the surface. Photon energy
depends only on frequency and is independent of intensity.
(c) Photoelectric effect can be understood as the result of the one to one collision between an electron and a photon.
(d) When a photon of frequency
(v) is incident on a metal surface, a part of its energy is used in overcoming the work function and other part

is used in imparting kinetic energy, so KE = $h(v - v_0)$

(iii) $h\nu = \phi_0 + k_{max}$ $\quad \because c = \nu\lambda$

$$\frac{hc}{\lambda_1} = \frac{hc}{\lambda_0} + k_{max} \qquad ...(i)$$

$$\frac{hc}{\lambda_2} = \frac{hc}{\lambda_0} + 2k_{max} \qquad ...(ii)$$

From (i) and (ii)

$$\frac{2hc}{\lambda_1} - \frac{hc}{\lambda_2} = \frac{hc}{\lambda_0} \qquad \frac{1}{\lambda_0} = \left(\frac{2}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$$\lambda_0 = \frac{\lambda_1\lambda_2}{2\lambda_2 - \lambda_1}$$

Work function, $\phi_0 = \frac{hc}{\lambda_0} = \frac{hc(2\lambda_2 - \lambda_1)}{\lambda_1\lambda_2}$

7 Marks Questions

Question 1.
(a) Describe briefly three experimentally observed features in the phenomenon of photoelectric effect.
(b) Discuss briefly how wave theory of light cannot explain these features.
Answer:
(a) Experimental features and observations of photoelectric effect :
(i) For a given photosensitive material and frequency of incident radiation (above the threshold frequency), the photoelectric current is directly proportional to the intensity of incident light.
(ii) For a given photosensitive material and frequency of incident radiation, saturation current is found to be proportional to the intensity of incident radiation whereas the stopping potential is independent of its intensity.
(iii) For a given photosensitive material, there exists a certain minimum cut-off frequency of the incident radiation, called the threshold frequency, below which no emission of photoelectrons takes place, no matter how intense the incident light is. Above the threshold frequency, the stopping potential or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiation, but is independent of its intensity.
(iv) The photoelectric emission is an instantaneous process without any apparent time lag ($\sim 10^{-9}$ s or less), even when the incident radiation is made exceedingly dim.

(b) Wave theory cannot explain photoelectric effect:
(i) According to the wave picture of light, the free electrons at the surface of the metal (over which the beam of radiation falls) absorb the radiant energy continuously. The greater the intensity of radiation, the greater are the amplitude of electric and magnetic fields. Consequently, the greater the intensity, the greater should be the energy absorbed by each electron. In this picture, the maximum kinetic energy of the photoelectrons on the surface is then expected to increase with increase in intensity. Also, no matter what the ‘ frequency of radiation is, a sufficiently intense beam of radiation (over sufficient time) should be able to impart enough energy to the electrons, so that they exceed the minimum energy needed to escape from the metal surface. A threshold frequency, therefore, should not exist. These expectations of the wave theory directly contradict observations (a) (i), (ii) and (iii) given above.

(ii) In the wave picture, the absorption of energy by electrons takes place continuously over the entire wavefront of the radiation. Since a large number of electrons absorb energy, the energy absorbed per electron per unit time turns out to be small. Explicit calculations estimate that it can take hours or more for a single electron to pick up sufficient energy to overcome the work function and come out of the metal. This conclusion is again in striking contrast to observation (iv) that the photoelectric emission is instantaneous. In short, the wave picture is unable to explain the most basic features of photoelectric emission.

Question 2.
(a) Write the important properties of photons which are used to establish Einstein's photoelectric equation.
(b) Use this equation to explain the concept of
(i) threshold frequency and
(ii) stopping potential.Write three characteristic features in photoelectric effect which cannot be explained on the basis of wave theory of light, but can be explained only using Einstein's equation.

Answer:
(a) Important properties of Photons :
(i) In interaction of radiation with matter, radiation behaves as if it is made up of particles called photons.
(ii) Each photon has energy E (= hv) and momentum p (= hv/c), and speed c, the speed of light.
(iii) All photons of light of a particular frequency v, or wavelength λ, have the same energy E (= hv = hc/λ) and momentum p (= hv/c = h/λ), whatever the intensity of radiation may be. By increasing the intensity of light of given wavelength, there is only an increase in the number of photons per second crossing a given area, with each photon having the same energy. Thus, photon energy is independent of intensity of radiation.
(iv) Photons are electrically neutral and are not deflected by electric and magnetic fields.
(v) In a photon-particle collision (such as photon-electron collision), the total energy and total momentum are conserved. However, the number of photons may not be conserved in a collision. The photon may be absorbed or a new photon may be created.
(b) Einstein's photoelectric equation is

$$K_{max} = h\nu - \phi_0 \quad \ldots(i)$$

(*i*) **Threshold frequency.** Since K_{max} must be non-negative, equation (*i*) implies that photoelectric emission is possible only if

$$h\nu > \phi_0 \quad \text{or} \quad \nu > \nu_0, \text{ where } \nu_0 = \frac{\phi_0}{h}$$

This equation shows that the greater the work function ϕ_0, higher the threshold frequency ν_0 needed to emit photoelectrons.
Thus, there exists a threshold frequency ν_0 (=ϕ_0/h the metal surface, below which no photoelectric emission is possible, no matter how intense the incident radiation may be or how long it falls on the surface.
(ii) Stopping potential. The minimum value of negative potential v_0, which should be applied to the anode in a photocell, so that the photoelectric current becomes zero, is called Stopping potential.

$$\because \quad K_{max} = \frac{1}{2} m v_{max}^2 = eV_0$$

$$eV_0 = h\nu - \phi_0;\ \text{for } \nu \geq \nu_0$$

$$\text{or} \quad V_0 = \left(\frac{h}{e}\right)\nu - \frac{\phi_0}{e}$$

V_0 is the stopping potential.

The maximum kinetic energy of the emitted electron should be directly proportional to the intensity of incident radiations but it is not observed experimentally. Also maximum kinetic energy of the emitted electrons should not depend upon incident frequency according to wave theory, but it is not so.
(ii) According to wave theory, threshold frequency should not exist. Light of all frequencies should emit electrons provided intensity of light is sufficient for electrons to eject.
(iii) According to wave theory, photoelectric effect should not be instantaneous. Energy of wave cannot be transferred to a particular electron but will be distributed to all the electrons present in the illuminated portion. Hence, there has to be a time lag between incidence of radiation and emission of electrons.

Fill in the blanks

1. The emission of electrons does not occur in which of the**---------------(X-Ray Emission)**

2. What happens to the kinetic energy of the emitted electrons when the light is incident on a metal surface is**---------------------(It varies with the speed of light)**

3. A photoelectric cell is a device which**--------------(Converts light energy into electricity)**

4. What does a cathode ray consist of**--------------(Electrons)**

Multiple choice questions

1. Who gave the theory of quantization of electric charge?

a. J.J Thomason
b. William Crookes
c. R.A Millikan
d. Wilhelm Hallwachs

Answer: (c) R.A Millikan

Explanation: R.A Millikan gave the theory of quantization of electric charge.

2. Which of the following metals is not sensitive to visible light?

a. Rubidium
b. Sodium
c. Caesium
d. Cadmium

Answer: (d) Cadmium

Explanation: Cadmium is not sensitive to visible light.

3. Which of the following does the wave theory of light not explain?

a. Diffraction
b. Photocurrent
c. Polarization
d. Interference

Answer: (b) Photocurrent

Explanation: Wave theory can explain diffraction, polarization and interference but could not explain the photoelectric effect. The photoelectric effect is explained by a quantum theory which treats light as a particle.

4. Photons are deflected by

a. Magnetic field only
b. Electric field only
c. Electromagnetic field
d. None of the above

Answer: (d) None of the above

Explanation: None of the given options deflect photons.

5. The photoelectric effect is based on the law of conservation of

a. Energy
b. Momentum
c. Mass
d. Angular momentum

Answer: (a) Energy

Explanation: The photoelectric effect is based on the law of conservation of energy.

6. Photon does not possess

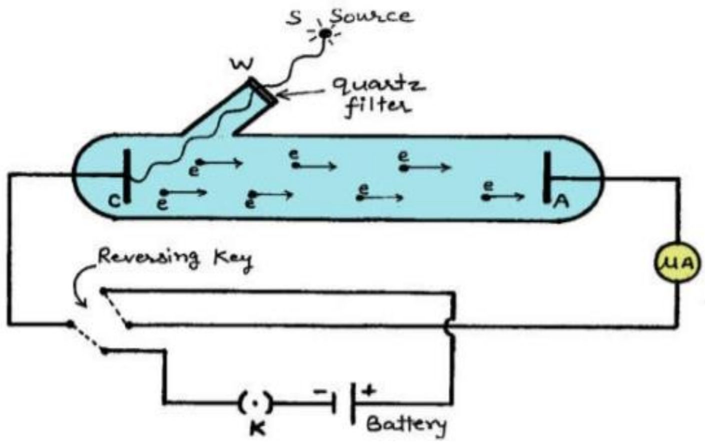
a. Energy
b. Momentum
c. Rest Mass
d. Frequency

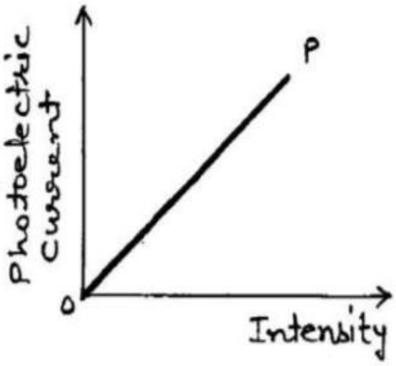
Answer: (c) Rest Mass

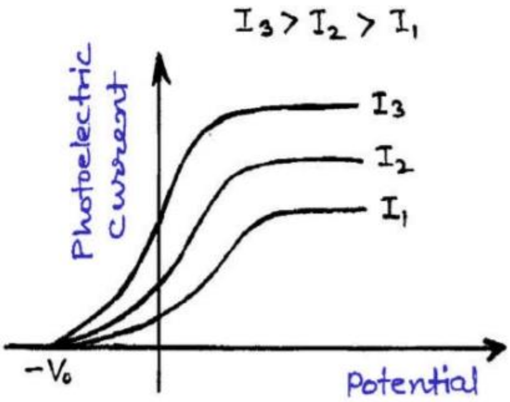
Explanation: Photon do not possess rest mass.

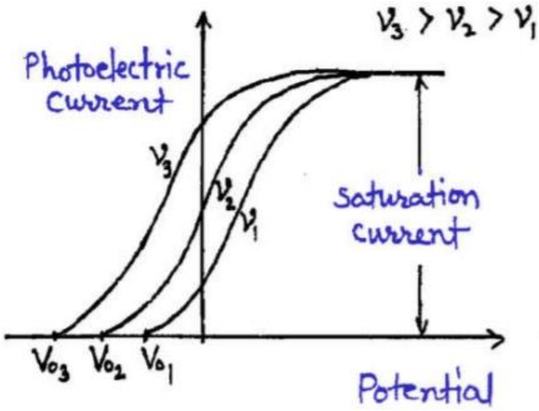
Diagrams

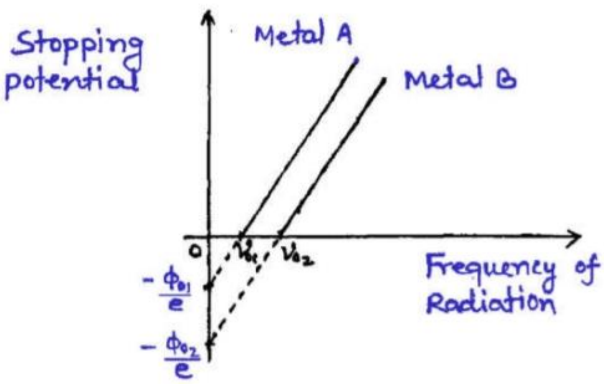
Experimental study of photoelectric Effect

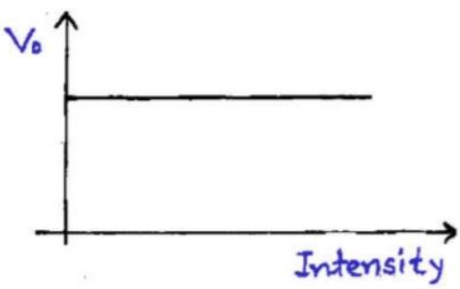




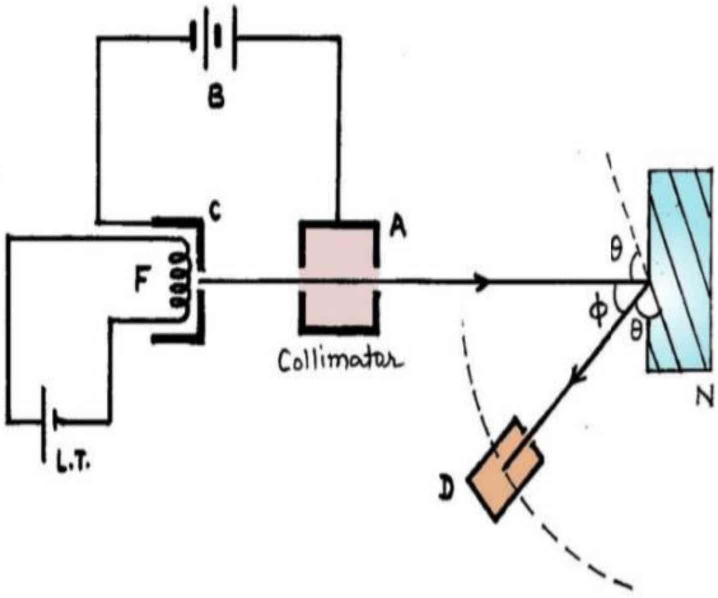


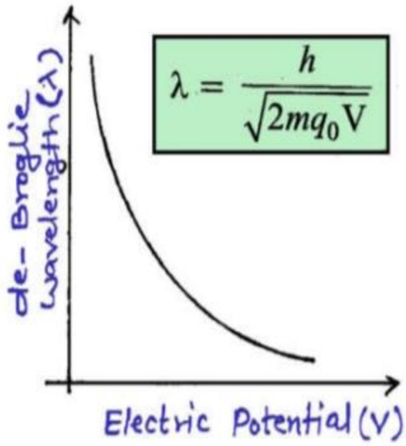






Experimental Demonstaration of ware nature of Electron





SUMMARY

- **Electric Discharge:**
  The passage of an electric current through a gas is called electric discharge.
- **Discharge Tube:**
  A hard glass tube along with the necessary arrangement, which is used to study the passage of electric discharge through gases at low pressure, is called a discharge tube.
- **Cathode Rays:**
  Cathode rays are the stream of negatively charged particles, electrons which are shot out at a high speed from the cathode of a discharge tube at pressure below 0.01 mm of Hg.
- **Work Function:**
  The minimum amount of energy required by an electron to just escape from the metal surface is known as work function of the metal.
  $$W_0 = \phi_0 = hv_0$$
- **Electron Emission:**
  The minimum amount of energy required by an electron to just escape from the metal surface is known as work function of the metal.
- **Thermionic Emission:**
  Here electrons are emitted from the metal surface with the help of thermal energy.
- **Field or Cold Cathode Emission:**
  Electrons are emitted from a metal surface by subjecting it to a very high electric field.
- **Photoelectric Emission:**
  Electrons emitted from a metal surface with the help of suitable electromagnetic radiations.
- **Secondary Emission:**
  Electrons are ejected from a metal surface by striking over its fast moving electrons.
- **Forces Experienced by an Electron in Electric and Magnetic Fields:**
  a) **Electric field:** The force FE experienced by an electron e in an electric field of strength (intensity) E is given by,
  $$FE = eE$$
  b) **Magnetic field**: The force experienced by an electron e in a magnetic field of strength B weber/m^2 is given by
  $$FB=Bev$$
  where v is the velocity with which the electron moves in the electric field and the magnetic field, perpendicular to the direction of motion.
  c) If the magnetic field is parallel to the direction of motion of electron, then, FB = 0.
- **Photoelectric Effect:**
  The phenomenon of emission of electrons from the surface of substances (mainly metals), when exposed to electromagnetic radiations of suitable frequency, is called

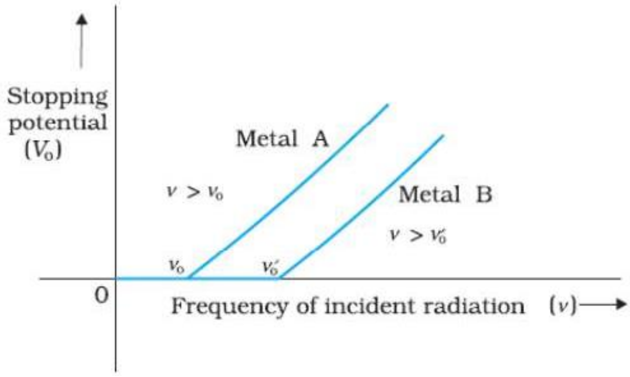
photoelectric effect and the emitted electrons are called photoelectrons.

- **Maximum K. E of the Photoelectrons Emitted from the Metal Surface:**

  $K_{max} = eV_0 = h\nu - \phi_0$ (Einstein's Photoelectric equation)

- **Cut Off or Stopping Potential:**

  The value of the retarding potential at which the photoelectric current becomes zero is called cut off or stopping potential for the given frequency of the incident radiation.



- **Threshold Frequency:**

  The minimum value of the frequency of incident radiation below which the photoelectric emission stops altogether is called threshold frequency.

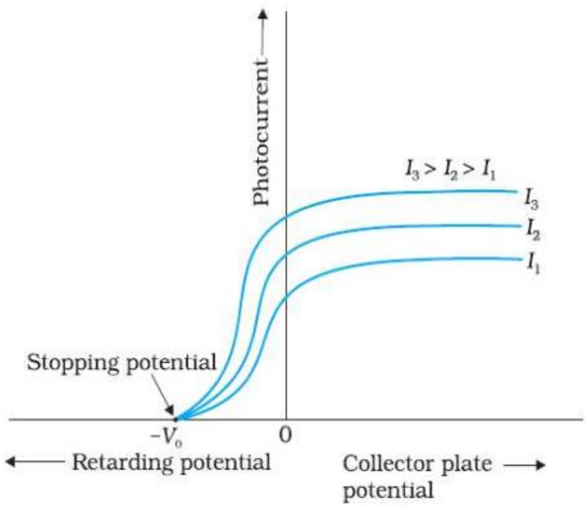
- **Laws of Photoelectric Effect:**

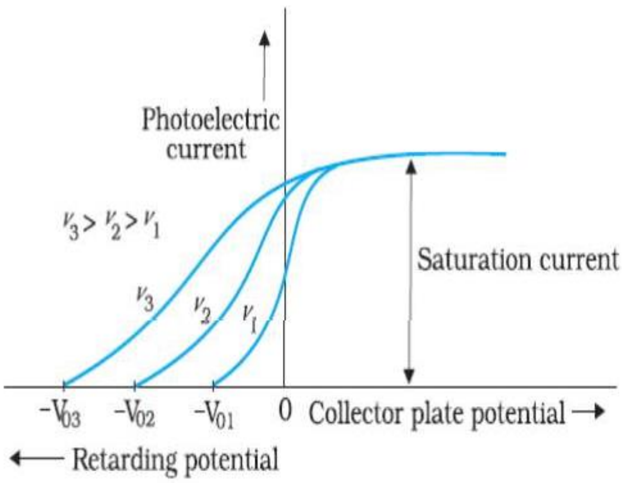
  a) For a given metal and a radiation of fixed frequency, the number of photoelectrons emitted is proportional to the intensity of incident radiation.

  b) For every metal, there is a certain minimum frequency below which no photoelectrons are emitted, howsoever high is the intensity of incident radiation. This frequency is called threshold frequency.

  c) For the radiation of frequency higher than the threshold frequency, the maximum kinetic energy of the photoelectrons is directly proportional to the frequency of incident radiation and is independent of the intensity of incident radiation.

  d) The photoelectric emission is an instantaneous process.





- **Einstein's Theory of Photoelectric Effect:**
  a) Einstein explained photoelectric effect with the help of Planck's quantum theory.
  b) When a radiation of frequency ν is incident on a metal surface, it is absorbed in the form of discrete packets of energy called quanta or photons.
  c) A part of energy $h\nu$ of the photon is used in removing the electrons from the metal surface and remaining energy is used in giving kinetic energy to the photoelectron.
  d) Einstein's photoelectric equation is,
  $$KE = \frac{1}{2}mv^2 = h\nu - w_0$$
  Where w_0 is the work function of the metal.
  e) If ν_0 is the threshold frequency, then $w_0 = h\nu_0$
  $$KE = \frac{1}{2}mv^2 = h(\nu - \nu_0)$$
  f) All the experimental observations can be explained on the basis Einstein's photoelectric equation.
- **Compton Shift:**
  It is the phenomenon of increase in the wavelength of X-ray photons which occurs when these radiations are scattered on striking an electron. The difference in the wavelength of scattered and incident photons is called Compton shift, which is given by
  $$\Delta\lambda = \frac{h}{m_0C}(1 - \cos\phi)$$
  Where ϕ is the angle of scattering of the X-ray photon and m_0 is the rest mass of the electron.
- **Charge and Mass of an Electron by Thompson's Method:**
  a) J. J. Thomson devised an experiment to determine the velocity (v) and the ratio of the charge (e) to the mass (m) i.e., $\frac{e}{m}$ of cathode rays.
  b) In this method, electric field $\vec{E}$ and magnetic field $\vec{B}$ are applied on the cathode rays.
  c) In the region where they are applied perpendicular to each other and to the direction of motion of cathode rays,
  Force due to electric field, FE = Force due to magnetic field FB,
  $$eE = Bev \Rightarrow V = \frac{E}{B}$$
  Also,
  $$\frac{e}{m} = \frac{E}{B^2R} = \frac{V/d}{B^2R} = \frac{Vx}{B^2lLd}$$
  Where V = Potential difference between the two electrodes (i.e., P and Q), d = distance between the two electrodes, R = radius of circular arc in the presence of magnetic field B, x = shift of the electron beam on the screen, l = length of the field

and L = distance between the centre of the field and the screen.

- **Milliken's Oil Drop Method:**
  a) This method helps to determine the charge on the electron.
  b) Let ρ be the density of oil, σ is the density of the medium in which oil drop moves and η the coefficient of viscosity of the medium, then the radius r of the drop is

$$r = \sqrt{\frac{9}{2}\frac{\eta V_0}{(\rho - \sigma)g}}$$

  Where v_0 is the terminal velocity of the drop under the effect of gravity alone.
  c) At the terminal velocity v_0, the force due to viscosity becomes equal to the electric weight of the body.
  d) The charge on oil drop is

$$q = \frac{18\pi\eta(V_1 + V_0)}{E}\sqrt{\frac{\eta V_0}{2(\rho - \sigma)g}}$$

  Where v_1 is the terminal velocity of the drop under the influence of electric field and gravity and E is the applied electric field.
- **Photocell:**
  a) It is an arrangement which converts light energy into electric energy.
  b) It works on the principle of photoelectric effect.
  c) It is used in cinematography for the reproduction of sound.
- **Dual Nature of Radiation:**
  Light has dual nature. It manifests itself as a wave in diffraction, interference, polarization, etc., while it shows particle nature in photoelectric effect, Compton scattering, etc.
- **Dual Nature of Matter:**
  a) As there is complete equivalence between matter (mass) and radiation (energy) and the principle of symmetry is always obeyed, de Broglie suggested that moving particles like protons, neutrons, electrons, etc., should be associated with waves known as de Broglie waves and their wavelength is called de Broglie wavelength.
  b) The de Broglie wavelength of a particle of mass m moving with velocity v is given by,

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

  Where h is Planck's constant.
- **Davison and Germer Experiment:**
  This experiment help to confirm the existence of de Broglie waves associated with electrons.
- **De Broglie Wavelength of an Electron:**
  The wavelength associated with an electron bean accelerated through a potential.

$$\lambda = \frac{h}{\sqrt{2meV}} = \frac{12.3}{\sqrt{V}}\overset{0}{A}$$

- de Broglie wavelength associated with the particle of momentum p is,

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

$$\lambda = \frac{1.22}{\sqrt{V}} nm$$

Where V is the magnitude of accelerating potential.

- **Heisenberg Uncertainty Principle:**

$$\Delta x . \Delta p \approx h / 2\pi$$

Where Δx is uncertainty in position & Δp is uncertainty in momentum

- **Electron Microscope**:
  a) It is a device which makes use of accelerated electron beams to study very minute objects like viruses, microbes and the crystal structure of solids.
  b) It has a magnification of $\sim 10^5$.
- **David-Germar Electron Diffraction Arrangement:**