Dual Nature of Matter and Radiation

basic concepts

1. Dual Nature of Radiations

It is well known that the phenomena of interference, diffraction and polarisation indicate that light has wave nature. But some phenomena like photoelectric effect, Compton effect, emission and absorption of radiation could not be explained by wave nature.

These were explained by particle (quantum) nature of light. Thus, light (radiation) has dual nature.

2. Quantum Nature of Light: Concept of a Photon

Some phenomena like photoelectric effect, Compton effect, Raman effect could not be explained by wave theory of light. Therefore, quantum theory of light was proposed by Einstein. According to quantum theory of light "light is propagated in bundles of small energy, each bundle being called a photon and possessing energy."

$$E = h\nu = \frac{hc}{\lambda} \qquad ...(i)$$

where ν is frequency, λ is wavelength of light and h is Planck's constant $= 6.62 \times 10^{-34}$ joule second and c = speed of light in vacuum $= 3 \times 10^8$ m/s.

Momentum of photon, $p = \frac{h\nu}{c} = \frac{h}{\lambda}$ ...(ii)

Rest mass of photon = 0

Dynamic or kinetic mass of photon, $m = \frac{h\nu}{c^2} = \frac{h}{c\lambda}$ ...(iii)

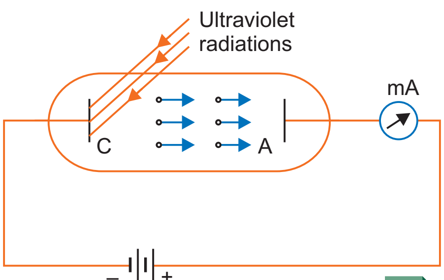
3. Photoelectric Effect

The phenomenon of emission of electrons from a metallic surface by the use of light (or radiant) energy is called *photoelectric effect*. The phenomenon was discovered by Lenard. For photoelectric emission, the metal used must have low work function, *e.g.*, alkali metals. *Caesium* is the best metal for photoelectric effect.

4. Hertz's Observations

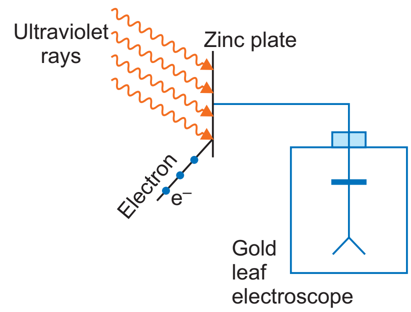
The phenomenon of photoelectric effect was discovered by Heinrich Hertz in 1887. While performing an experiment for production of electromagnetic waves by means of spark discharge, Hertz observed that sparks occurred more rapidly in the air gap of his transmitter when ultraviolet radiations was directed at one of the metal plates. Hertz could not explain his observations.

5. Lenard's Observations



Phillip Lenard observed that when ultraviolet radiations were made incident on the emitter plate of an evacuated glass tube enclosing two metal plates (called electrodes), current flows in the circuit, but as soon as ultraviolet radiation falling on the emitter plate was stopped, the current flow stopped. These observations indicate that when ultraviolet radiations fall on the emitter (cathode) plate C, the electrons are ejected from it, which are attracted towards anode plate A. The electrons flow through the evacuated glass tube, complete the circuit and current begins to flow in the circuit.

Hallwachs Exp.: Hallwachs studied further by taking a zinc plate and an electroscope. The zinc plate was connected to an electroscope. He observed that:



(*i*) When an uncharged zinc plate was irradiated by ultraviolet light, the zinc plate acquired positive charge.

(*ii*) When a positively charged zinc plate is illuminated by ultraviolet light, the positive charge of the plate was increased.

(*iii*) When a negatively charged zinc plate was irradiated by ultraviolet light, the zinc plate lost its charge.

All these observations show that when ultraviolet light falls on zinc plate, the negatively charged particles (electrons) are emitted.

Further study done by Hallwach's experiment shows that different metals emit electrons by different electromagnetic radiations. For example the alkali metals (*e.g.*, sodium, caesium, potassium etc.) emit electrons when visible light is incident on them. The heavy metals (such as zinc, cadmium, magnesium etc.) emit electrons when ultraviolet radiation is incident on them.

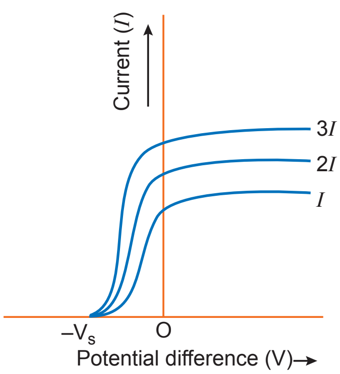
Caesium is the most sensitive metal for photoelectric emission. It can emit electrons with less-energetic infrared radiation.

In photoelectric effect the light energy is converted into electrical energy.

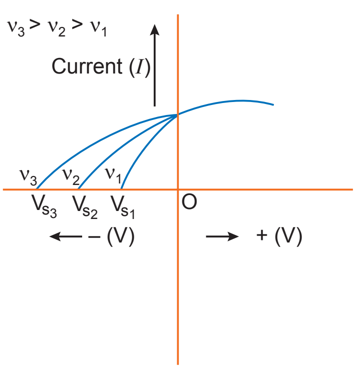
6. Characteristics of Photoelectric Effect

(*i*) Effect of Intensity: Intensity of light means the energy incident per unit area per second. For a given frequency, if intensity of incident light is increased, the photoelectric current increases and with decrease of intensity, the photoelectric current decreases; but the stopping potential remains the same.

Intensity of radiations can be increased/decreased by varying the distance between source and metal plate (or emitter).



(*a*)



(*b*)

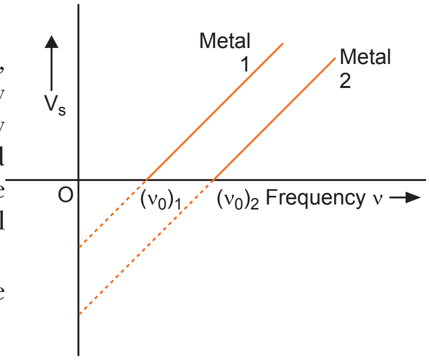
This means that the *intensity of incident light affects the photoelectric current but the maximum kinetic energy of photoelectrons remains unchanged as shown in fig (b).*

(*ii*) Effect of Frequency: When the intensity of incident light is kept fixed and frequency is increased, the photoelectric current remains the same; but the stopping potential increases.

If the frequency is decreased, the stopping potential decreases and at a particular frequency of incident light, the stopping potential becomes zero. This value of frequency of incident light for which the stopping potential is zero is called *threshold frequency* ν_0. If the frequency of incident light (ν) is less than the threshold frequency (ν_0) no photoelectric emission takes place.

Thus, *the increase of frequency increases the maximum kinetic energy of photoelectrons but the photoelectric current remain unchanged*.

(*iii*) **Effect of Photometal:** When frequency and intensity of incident light are kept fixed and photometal is changed, we observe that stopping potential (VS) versus frequency (ν) graphs are parallel straight lines, cutting frequency axis at different points (Fig.). This shows that threshold frequencies are different for different metals, the slope (V_S / ν) for all the metals is same and hence a universal constant.



(*iv*) **Effect of Time:** There is no time lag between the incidence of light and the emission of photoelectrons.

7. Some Definitions

Work Function: The minimum energy required to free an electron from its metallic bonding is called work function. It is denoted by W or ϕ and is usually expressed in electron volt (1 eV = 1.6×10^{-19} J).

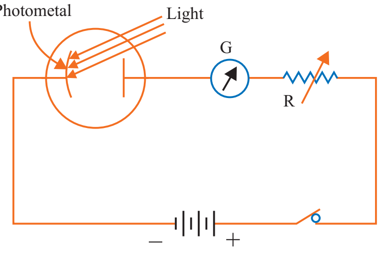
Threshold Frequency: The minimum frequency of incident light which is just capable of ejecting electrons from a metal is called the threshold frequency. It is denoted by ν_0. It is different for different metal.

Stopping Potential: The minimum retarding potential applied to anode of a photoelectric tube which is just capable of stopping photoelectric current is called the stopping potential. It is denoted by V_0 (or V_S)

8. Einstein's Explanation of Photoelectric Effect: Einstein's Photoelectric Equation

Einstein extended Planck's quantum idea for light to explain photoelectric effect.

The assumptions of Einstein's theory are:



1. The photoelectric effect is the result of collision of a photon of incident light and an electron of photometal.
2. The electron of photometal is bound with the nucleus by coulomb attractive forces. The minimum energy required to free an electron from its bondage is called work function (W).
3. The incident photon interacts with a single electron and loses its energy in two parts:
   (*i*) in releasing the electron from its bondage, and
   (*ii*) in imparting kinetic energy to emitted electron.

Accordingly, if $h\nu$ is the energy of incident photon, then from law of conservation of energy

$$h\nu = W + E_k$$

or maximum kinetic energy of photoelectrons, $E_k = \frac{1}{2}mv^2_{max} = h\nu - W$ ...(*i*)

where W is work function. This equation is referred as *Einstein's photoelectric equation* and explains all experimental results of photoelectric effect. If V_s is stopping potential, then

$$E_k = \frac{1}{2}mv^2_{max} = eV_S \quad \ldots(ii)$$

Stopping potential, $V_s = \frac{h}{e}\nu - \frac{W}{e}$ ...(*iii*)

The slope of E_k versus ν graph is h.

The slope of V_S versus ν graph is $\frac{h}{e}$.

9. Photocell

A photocell is a device which converts light energy into electrical energy. It is also called electric eye.

10. Matter Waves: Wave Nature of Particles

Light exhibits particle aspects in certain phenomena (*e.g.*, photoelectric effect, emission and absorption of radiation), while wave aspects in other phenomena (*e.g.*, interference, diffraction and polarisation). That is, light has dual nature. In analogy with dual nature of light, de Broglie thought in terms of dual nature of matter.

11. de Broglie Hypothesis

Louis de Broglie postulated that the **material particles** (*e.g.*, electrons, protons, α-particles, atoms, etc.) may exhibit wave aspect. Accordingly, *a moving material particle behaves as wave and the wavelength associated with material particle is*

$$\lambda = \frac{h}{p} = \frac{h}{mv}, \quad \text{where } p \text{ is momentum.}$$

If E_k is kinetic energy of moving material particle, then $p = \sqrt{2mE_k}$

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

i.e.,
$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE_k}}$$

The wave associated with material particle is called the ***de-Broglie wave or matter wave***. The de-Broglie hypothesis has been confirmed by diffraction experiments.

For charged particles associated through a potential of V volt,

$$E_k = qV$$

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

For electrons, $q = e = 1.6 \times 10^{-19}$ C, $m = 9 \times 10^{-31}$ kg

$$\lambda = \frac{12.27}{\sqrt{V}} \times 10^{-10} \text{m} = \frac{12.27}{\sqrt{V}} \text{Å} \quad \text{(Only for electrons)}$$

For electron orbiting in an atom, de Broglie wavelength is given as $\lambda = \frac{h}{p} = \frac{h}{mv}$

For neutral particles in thermal equilibrium at absolute temperature T, $E_k = kT$

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

12. Davisson and Germer Experiment

This experiment gave the first experimental evidence for the wave nature of slow electrons. Later on, it was shown that all material particles in motion behave as waves.

Selected NCERT Textbook Questions

Photoelectric Effect

Q. 1. Find the (*a*) maximum frequency and (*b*) minimum wavelength of *X*-rays produced by 30 kV electrons.

Ans. Given $V = 30$ kV $= 30 \times 10^3$ volt

Energy, $E = eV = 1.6 \times 10^{-19} \times 30 \times 10^3 = 4.8 \times 10^{-15}$ joule

(*a*) Maximum frequency ν_{max} is given by, $E = h\nu_{max}$

$$\nu_{max} = \frac{E}{h} = \frac{4.8 \times 10^{-15}}{6.63 \times 10^{-34}} = \mathbf{7.24 \times 10^{18}\ Hz}$$

(*b*) Minimum wavelength, $\lambda_{min} = \frac{c}{\nu_{max}} = \frac{3 \times 10^8}{7.24 \times 10^{18}} = 4.1 \times 10^{-11}$ m $=$ **0.041 nm**

Q. 2. The work function of caesium metal is 2.14 eV. When light of frequency 6×10^{14} Hz is incident on the metal surface, photoemission of electrons occurs. What is the

(*a*) maximum kinetic energy of the emitted electrons?

(*b*) stopping potential and (*c*) maximum speed of emitted electrons?

Ans. Given $\phi_0 = 2.14$ eV, $\nu = 6\times10^{-14}$ Hz

(*a*) Maximum kinetic energy of emitted electron

$$E_k = h\nu - \phi_0 = 6.63 \times 10^{-34} \times 6 \times 10^{14} - 2.14 \times 1.6 \times 10^{-19}$$

$$= 0.554 \times 10^{-19}\text{ J} = \frac{0.554 \times 10^{-19}}{1.6 \times 10^{-19}}\text{ eV} = \mathbf{0.34\ eV}$$

(*b*) Stopping potential V_0 is given by

$$E_k = eV_0 \Rightarrow V_0 = \frac{E_k}{e} = \frac{0.34\text{ eV}}{e} = \mathbf{0.34\ V}$$

(*c*) Maximum speed (v_{max}) of emitted electrons is given by

$$\frac{1}{2}mv_{max}^2 = E_k$$

or $$v_{max} = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 0.554 \times 10^{-19}}{9.1 \times 10^{-31}}} = \mathbf{3.48\times10^5\ m/s}$$

Q. 3. The photoelectric cut-off voltage in a certain photoelectric experiment is 1.5 V. What is the maximum kinetic energy of photoelectrons emitted?

Ans. Cut-off voltage, $V_0 = 1.5$ V

Maximum kinetic energy of photoelectrons

$$E_k = eV_0 = 1.5\text{ eV} = 1.5 \times 1.6 \times 10^{-19}\text{ J} = \mathbf{2.4\times 10^{-19}\ J}$$

Q. 4. The energy flux of sunlight reaching the surface of earth is 1.388×10^3 W/m^2. How many photons (nearly) per square metre are incident on the earth per second? Assume that the photons in the sunlight have an average wavelength of 550 nm.

Ans. Energy of each photon $E = \dfrac{hc}{\lambda} = \dfrac{6.63 \times 10^{-34} \times 3 \times 10^8}{550 \times 10^{-9}} = 3.62 \times 10^{-19}$ J

Number of photons incident on earth's surface per second per square metre

$$= \frac{\text{Total energy per square metre per second}}{\text{Energy of one photon}}$$

$$= \frac{1.388 \times 10^3}{3.62 \times 10^{-19}} = \mathbf{3.8 \times 10^{21}}$$

Q. 5. In an experiment of photoelectric effect, the slope of cut-off voltage versus frequency of incident light is found to be 4.12×10^{-15} Vs. Calculate the value of Planck's constant.

Ans. Einstein's photoelectric equation is $E_k = h\nu - \phi_0$

or $eV_0 = h\nu - \phi_0$

or $V_0 = \dfrac{h}{e}\nu - \dfrac{\phi_0}{e}$

Clearly slope of $V_0 - \nu$ curve is $\dfrac{h}{e}$

Give $\dfrac{h}{e} = 4.12\times10^{-15}$ Vs $\Rightarrow$ $h = 4.12\times10^{-15}$ eVs

$$= 4.12\times10^{-15} \times 1.6 \times 10^{-19}$$

$$= \mathbf{6.59\times10^{-34}\ Js}$$

Q. 6. A 100 W sodium lamp radiates energy uniformly in all directions. The lamp is located at the centre of a large sphere that absorbs all the sodium light which is incident on it. The wavelength of the sodium light is 589 nm.

(*a*) What is the energy associated per photon with sodium light?

(*b*) At what rate are the photons delivered to the sphere?

Ans. Given $P = 100$ W, $\lambda = 589$ nm $= 589\times 10^{-9}$ m

(*a*) Energy of one photon $E = \dfrac{hc}{\lambda} = \dfrac{6.63\times 10^{-34}\times 3\times 10^{8}}{589\times 10^{-9}} = \mathbf{3.38\times 10^{-19}\ J}$

(*b*) Number of photons (n) delivered to the sphere per second is given by

$$P = nE \quad \Rightarrow \quad n = \frac{P}{E} = \frac{100}{3.38\times 10^{-19}} = \mathbf{3.0\times 10^{20}\ photons/second}$$

Q. 7. The threshold frequency for a certain metal is 3.3×10^{14} Hz. If light of frequency 8.2×10^{14} Hz is incident on the metal, predict the cut-off voltage for photoelectric emission.

Ans. Einstein's photoelectric equation is

$$h\nu = h\nu_0 + E_k \qquad \text{or} \qquad h\nu = h\nu_0 + eV_0$$

$$eV_0 = h(\nu - \nu_0) = 6.63\times10^{-34}\,(8.2\times10^{14} - 3.3\times10^{14})\ \text{joule}$$

or cut-off voltage $V_0 = \dfrac{6.63\times 4.9\times 10^{-20}}{e} = \dfrac{6.63\times 4.9\times 10^{-20}}{1.6\times 10^{-19}}\text{V} = \mathbf{2.03\ V}$

Q. 8. The work function of a certain metal is 4.2 eV. Will this metal give photoelectric emission for incident radiation of wavelength 330 nm?

Ans. The energy of incident radiations

$$E = \frac{hc}{\lambda} = \frac{6.63\times 10^{-34}\times 3\times 10^{8}}{330\times 10^{-9}}\text{joule} = 6.03\times10^{-19}\ \text{joule}$$

$$= \frac{6.03\times 10^{-19}}{1.6\times 10^{-19}}\text{eV} = 3.77\ \text{eV}$$

The work function of photometal, $\phi_0 = 4.2$ eV

As energy of incident photon is less than work function, **photoemission is not possible.**

Q. 9. Light of frequency 7.21×10^{14} Hz is incident on a metal surface. Electrons with a maximum speed of 6.0×10^{5} ms^{-1} are ejected from the surface. What is the threshold frequency for photoemission of electrons? (Planck's constant $h = 6.62\times10^{-34}$ Js)

Ans. Given $\nu = 7.21\times10^{14}$ Hz, $v_{max} = 6.0\times10^{5}$ ms^{-1}

From Einstein's photoelectric equation

$E_k = h\nu - h\nu_0$, where ν_0 is the threshold frequency

$$\nu_0 = \frac{h\nu - E_k}{h} = \left(\nu - \frac{E_k}{h}\right) = \nu - \frac{\frac{1}{2}mv^2_{max}}{h}$$

$$= 7.21\times 10^{14} - \frac{9.1\times 10^{-31}\times(6.0\times 10^{5})^2}{2\times 6.62\times 10^{-34}}$$

$$= 7.21\times 10^{14} - 2.47\times 10^{14} = \mathbf{4.74\times10^{14}\ Hz}$$

Q. 10. Light of wavelength 488 nm is produced by an Argon Laser which is used in the photoelectric effect. When light from this spectral line is incident on the cathode the stopping potential of photoelectrons is 0.38 V. Find the work function of the cathode material.

Ans. Given $\lambda = 488$ nm $= 488 \times 10^{-9}$ m, $V_0 = 0.38$ V, $\phi_0 = ?$

Energy of incident photon $E = \dfrac{hc}{\lambda}$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{488 \times 10^{-9}} = 4.08 \times 10^{-19}\,\text{J}$$

$$= \frac{4.08 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.55\,\text{eV}$$

From Einstein's photoelectric equation $\dfrac{hc}{\lambda} = \phi_0 + eV_0$

Work function $\phi_0 = \dfrac{hc}{\lambda} - eV_0 = 2.55\,\text{eV} - 0.38\,\text{eV} = \mathbf{2.17\,eV}$

Q. 11. The work function of the following metals is given:

Na = 2.75 eV; K = 2.30 eV, Mo = 4.17 eV, Ni = 5.15 eV.

Which of these metals will not give a photoelectric emission for a radiation of wavelength 3300 Å from a He–Cd laser placed 1 m away from the photocell? What happens if the laser is brought nearer and placed 50 cm away?

Ans. Energy of incident photon, $E = \dfrac{hc}{\lambda}$

Here $\lambda = 3300$ Å $= 3300 \times 10^{-10}$ m $= 3.3 \times 10^{-7}$ m

$$E = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{3.3 \times 10^{-7}}\,\text{joule}$$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{3.3 \times 10^{-7} \times 1.6 \times 10^{-19}}\,\text{eV} = \mathbf{3.76\,eV}$$

Photoelectric emission is only possible if energy of incident photon is equal to or greater than the work function. For Na and K this condition is satisfied, hence photoelectric emission is possible; but in the case of Mo and Ni, the energy of incident photon is less than the work function; hence photoelectric emission is not possible.

If source is brought nearer, then the intensity of incident radiation increases but frequency of a photon remains the same; therefore Mo and Ni will still not show photoelectric effect; however in the case of Na and K the current will increase in same proportion as the increase in intensity takes place.

de Broglie Waves

Q. 12. Calculate the (*a*) momentum and (*b*) de Broglie wavelength of the electrons accelerated through a potential difference of 56 V.

Ans. For electron, mass $m = 9.1 \times 10^{-31}$ kg

(*a*) Momentum $p = \sqrt{2mE_k} = \sqrt{2meV}$

$$= \sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times 56} = \mathbf{4.04 \times 10^{-24}\,kg\,ms^{-1}}$$

(*b*) de Broglie wavelength $\lambda = \dfrac{h}{p} = \dfrac{6.63 \times 10^{-34}}{4.04 \times 10^{-24}} = 1.64 \times 10^{-10}\,\text{m} = \mathbf{0.164\,nm}$

Q. 13. What is the (*a*) momentum (*b*) speed and (*c*) de Broglie wavelength of an electron with kinetic energy of 120 eV?

(mass of electron $m_e = 9.1 \times 10^{-31}$ kg, $h = 6.63 \times 10^{-34}$ Js)

Ans. Given kinetic energy, $E_k = 120$ eV $= 120 \times 1.6 \times 10^{-19}$ J $= 1.92 \times 10^{-17}$ J

(*a*) Momentum of electron, $p = \sqrt{2m_eE_k}$

$$= \sqrt{2 \times 9.1 \times 10^{-31} \times 1.92 \times 10^{-17}} = \mathbf{5.91 \times 10^{-24}\,kg\,ms^{-1}}$$

(*b*) Speed of electron, $v = \frac{p}{m} = \frac{5.91 \times 10^{-24}}{9.1 \times 10^{-31}} = \mathbf{6.5 \times 10^6\, m/s}$

(*c*) de Broglie wavelength, $\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{5.91 \times 10^{-24}} = 1.12 \times 10^{-10}\text{m} = \mathbf{0.112\ nm}$

Q. 14. The wavelength of light from the spectral emission line of sodium is 589 nm. Find the kinetic energy at which (*a*) an electron and (*b*) a neutron, would have the same de Broglie wavelength.

[*CBSE Guwahati 2015*]

Ans. Given $\lambda = 589\text{ nm} = 5.89 \times 10^{-7}\text{ m}$

The de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE_k}} \quad \Rightarrow \quad \lambda^2 = \frac{h^2}{2mE_k}$

$\therefore$ Kinetic energy $E_k = \frac{h^2}{2m\lambda^2}$

(*a*) For electron $E_k = \frac{h^2}{2m\lambda^2}$

$$\therefore \quad E_k = \frac{(6.63 \times 10^{-34})^2}{2 \times 9.1 \times 10^{-31} \times (5.89 \times 10^{-7})^2} = \mathbf{6.96 \times 10^{-25}\ J}$$

(*b*) For neutron $m = 1.67 \times 10^{-27}$ kg

$$E_k = \frac{(6.63 \times 10^{-34})^2}{2 \times 1.67 \times 10^{-27} \times (5.89 \times 10^{-7})^2} = \mathbf{3.79 \times 10^{-28}\ J}$$

Q. 15. What is the de Broglie wavelength of:

(*a*) a bullet of mass 0.040 kg travelling at a speed of 1.0 km/s.

(*b*) a ball of mass 0.060 kg moving at a speed of 1.0 m/s.

(*c*) a dust particle of mass 1.0×10^{-9} kg drifting with a speed of 2.2 m/s.

Ans. (*a*) $\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{0.040 \times 1.0 \times 10^3} = \mathbf{1.66 \times 10^{-35}\ m}$

(*b*) $\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{0.060 \times 1.0} = \mathbf{1.1 \times 10^{-32}\ m}$

(*c*) $\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{1.0 \times 10^{-9} \times 2.2} = \mathbf{3.01 \times 10^{-25}\ m}$

Obviously de Broglie wavelength decreases with increase of momentum.

Q. 16. An electron and a photon, each has a wavelength of 1.00 nm. Find (*a*) their momenta (*b*) the energy of the photon and (*c*) the kinetic energy of electron.

[*CBSE Delhi 2011*]

Ans. Given $\lambda = 1.00\text{ nm} = 1.00 \times 10^{-9}\text{ m}$

(*a*) Momenta of electron and photon are equal; given by

$$p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{1.00 \times 10^{-9}} = \mathbf{6.63 \times 10^{-25}\, kg\ ms^{-1}}$$

(*b*) Energy of photon, $E = h\nu = h.\frac{c}{\lambda} = \frac{h}{\lambda}c$

$$= pc = 6.63 \times 10^{-25} \times 3 \times 10^8\text{ J} = 19.89 \times 10^{-17}\text{ J}$$

$$= \frac{19.89 \times 10^{-17}}{1.6 \times 10^{-19}}\text{eV} = 1.24 \times 10^3\text{eV} = \mathbf{1.24\ keV}$$

(*c*) Kinetic energy of electron $E_k = \frac{1}{2}m_e v^2 = \frac{p^2}{2m_e}$

$$= \frac{(6.63 \times 10^{-25})^2}{2 \times 9.1 \times 10^{-31}} \text{J}$$

$$= 2.42 \times 10^{-19} \text{J} = \frac{2.42 \times 10^{-19}}{1.6 \times 10^{-19}} \text{eV} = \mathbf{1.51\ eV}$$

Q. 17. (*a*) For what kinetic energy of a neutron will the associated de Broglie wavelength be 1.40×10^{-10} m.

(*b*) Also find the de Broglie wavelength of a neutron, in thermal equilibrium with matter, having an average kinetic energy $\frac{3}{2}$ kT at 300 K. [Mass of neutron=1.67×10^{-27} kg]

Ans. (*a*) de Broglie's wavelength $\lambda = \frac{h}{\sqrt{2mE_k}}$

Kinetic energy $E_k = \frac{h^2}{2m\lambda^2} = \frac{(6.63\times10^{-34})^2}{2\times1.67\times10^{-27}\times(1.40\times10^{-10})^2} = \mathbf{6.7\times10^{-21}\,J}$

(*b*) $\lambda = \frac{h}{\sqrt{2mE_k}} = \frac{h}{\sqrt{2m\times\frac{3}{2}kT}} = \frac{h}{\sqrt{3mkT}}$

$$= \frac{6.63\times10^{-34}}{\sqrt{3\times1.67\times10^{-27}\times1.38\times10^{-23}\times300}}$$

$$= \frac{6.63\times10^{-34}}{4.55\times10^{-24}} = 1.46\times10^{-10} \text{ m} = \mathbf{0.146\ nm}$$

Q. 18. Show that the wavelength of electromagnetic radiation is equal to the de Broglie wavelength of its quantum (photon).

Ans. Momentum of a photon of frequency ν (wavelength λ) is given by

$$p = \frac{h\nu}{c} = \frac{h}{\lambda}$$

∴ Wavelength of electromagnetic radiation

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

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

Thus wavelength of electromagnetic radiation is equal to de Broglie wavelength of its quantum.

Q. 19. What is the de Broglie wavelength of a nitrogen molecule in air at 300 K? Assume that the molecule is moving with the root mean square speed of molecules at this temperature. Atomic mass of nitrogen = 14.0076 u.

Ans. Root mean square speed, $v_{rms} = \sqrt{\frac{3kT}{m}}$

Mass of nitrogen molecule, $m = 2\times14.0076 = 28.0152 \text{ u} = 28.0152\times1.66\times10^{-27}$ kg

de Broglie wavelength, $\lambda = \frac{h}{mv_{rms}} = \frac{h}{m.\sqrt{\frac{3kT}{m}}} = \frac{h}{\sqrt{3mkT}}$

$$= \frac{6.63 \times 10^{-34}}{\sqrt{3 \times 28.0152 \times 1.66 \times 10^{-27} \times 1.38 \times 10^{-23} \times 300}}$$

$$= \frac{6.63 \times 10^{-34}}{2.40 \times 10^{-23}} = 2.76 \times 10^{-11} \text{m} = \mathbf{0.276\ Å}$$

Q. 20. An electron microscope uses electrons accelerated by a voltage of 50 kV. Determine the de Broglie wavelength associated with the electrons. If other factors (such as numerical aperture, etc.) are taken to be roughly the same, how does the resolving power of an electron microscope compare with that of an optical microscope which uses yellow light ($\lambda_y = 5.9 \times 10^{-7}$ m)? *[CBSE (AI) 2014]*

Ans. de Broglie wavelength associated with electron

$$\lambda = \frac{12.27}{\sqrt{V}} \times 10^{-10} \text{m}$$

Here $V = 50$ kV $= 50 \times 10^3$ V

$$\therefore \quad \lambda = \frac{12.27}{\sqrt{50 \times 10^3}} \times 10^{-10} = \mathbf{5.5 \times 10^{-12}\ m}$$

Wavelength of yellow light, $\lambda_y = 5.9 \times 10^{-7}$ m

The resolving power of an electron microscope is given by

$$RP = \frac{1}{d_{\min}} = \frac{2\mu \sin \beta}{1.22\lambda}$$

Where $d_{\min}$ = minimum separation

For constant numerical aperture

Resolving power of microscope $\propto \frac{1}{\lambda}$

$$\therefore \quad \frac{\text{Resolving power of electron microscope}}{\text{Resolving power of optical microscope}} = \frac{\lambda_y}{\lambda} = \frac{5.9 \times 10^{-7}}{5.5 \times 10^{-12}} \approx \mathbf{10^5}$$

That is, resolving power of electron microscope is 10^5 times the resolving power of optical microscope.

Multiple Choice Questions [1 mark]

Choose and write the correct option(s) in the following questions.

1. **A particle is dropped from a height H. The de Broglie wavelength of the particle as a function of height is proportional to** *[NCERT Exemplar]*

   (*a*) H (*b*) $H^{1/2}$

   (*c*) H^0 (*d*) $H^{-1/2}$

2. **The wavelength of a photon needed to remove a proton from a nucleus which is bound to the nucleus with 1 MeV energy is nearly** *[NCERT Exemplar]*

   (*a*) 1.2 nm (*b*) 1.2×10^{-3} nm

   (*c*) 1.2×10^{-6} nm (*d*) 1.2×10^{1} nm

3. **Consider a beam of electrons (each electron with energy E_0) incident on a metal surface kept in an evacuated chamber. Then** *[NCERT Exemplar]*

   (*a*) no electrons will be emitted as only photons can emit electrons.

   (*b*) electrons can be emitted but all with an energy, E_0.

   (*c*) electrons can be emitted with any energy, with a maximum of $E_0 - \phi$ (ϕ is the work function).

   (*d*) electrons can be emitted with any energy, with a maximum of E_0.

4. **The threshold wavelength for photoelectric emission from a material is 5200 Å. Photoelectrons will be emitted when this material is illuminated with monochromatic radiation from a:**

   (*a*) 50 watt infrared lamp (*b*) 1000 watt infrared lamp

   (*c*) 1 watt ultraviolet lamp (*d*) 1 watt infrared lamp

5. A photoelectric cell is illuminated by a point source of light 1 m away. The plate emits electrons having stopping potential *V*. Then:

(*a*) *V* decreases as distance increase

(*b*) *V* increases as distance increase

(*c*) *V* is independent of distance (r)

(*d*) *V* becomes zero when distance increases or decreases

6. In a photoelectric experiment, the stopping- potential for the incident light of wavelength 4000 Å is 2 volt. If the wavelength be changed to 3000 Å, the stopping-potential will be:

(*a*) 2 volt (*b*) less than 2 volt

(*c*) zero (*d*) more than 2 volt.

7. The work-function for a metal is 3 eV. To emit a photoelectron of energy 2 eV from the surface of this metal, the wavelength of the incident light should be:

(*a*) 6187 Å (*b*) 4125 Å

(*c*) 12375 Å (*d*) 2486 Å

8. In the Davisson and Germer experiment, the velocity of electrons emitted from the electron gun can be increased by

(*a*) increasing the potential difference between the anode and filament

(*b*) increasing the filament current

(*c*) decreasing the filament current

(*d*) decreasing the potential difference between the anode and filament

9. The work-function of a surface of a photosensitive material is 6.2 eV. The wavelength of incident radiation for which the stopping potential is 5 V lies in:

(*a*) ultraviolet region (*b*) visible region

(*c*) infrared region (*d*) X-ray region

10. A proton, a neutron, an electron and an α-particle have same energy. Then their de Broglie wavelengths compare as [*NCERT Exemplar*]

(*a*) $\lambda_p = \lambda_n > \lambda_e > \lambda_\alpha$ (*b*) $\lambda_\alpha < \lambda_p = \lambda_n > \lambda_e$

(*c*) $\lambda_e < \lambda_p = \lambda_n > \lambda_\alpha$ (*d*) $\lambda_e = \lambda_p = \lambda_n = \lambda_\alpha$

11. The number of photoelectrons emitted for light of frequency ν (higher than the threshold frequency ν_0) is proportional to:

(*a*) threshold frequency (*b*) intensity of light

(*c*) frequency of light (*d*) $\nu - \nu_0$

12. Relativistic corrections become necessary when the expression for the kinetic energy $\frac{1}{2}mv^2$, becomes comparable with mc^2, where *m* is the mass of the particle. At what de Broglie wavelength will relativistic corrections become important for an electron? [*NCERT Exemplar*]

(*a*) λ = 10 nm (*b*) $\lambda = 10^{-1}$ nm

(*c*) $\lambda = 10^{-4}$ nm (*d*) $\lambda = 10^{-6}$ nm

13. Monochromatic light of wavelength 667 nm is produced by a helium neon laser. The power emitted is 9 mW. The number of photons arriving per second on the average at a target irradiated by this beam is:

(*a*) 3×10^{16} (*b*) 9×10^{15} (*c*) 3×10^{19} (*d*) 9×10^{17}

14. Electrons used in an electron microscope are accelerated by a voltage of 25 kV. If the voltage is increased to 100 kV then the de-Broglie wavelength associated with the electrons would

(*a*) increase by 2 times (*b*) decrease by 2 times

(*c*) decrease by 4 times (*d*) increase by 4 times

15. **Two particles A_1 and A_2 of masses m_1, m_2 ($m_1 > m_2$) have the same de Broglie wavelength. Then** [*NCERT Exemplar*]

(*a*) their momenta are the same

(*b*) their energies are the same

(*c*) energy of A_1 is less than the energy of A_2

(*d*) energy of A_1 is more than the energy of A_2

16. **An electron (mass m) with an initial velocity $\vec{v} = v_0\hat{i}$ is in an electric field $\vec{E} = E_0\hat{j}$. If $\lambda_0 = h/mv_0$, it's de Breoglie wavelength at time t is given by** [*NCERT Exemplar*]

(*a*) λ_0 (*b*) $\lambda_0\sqrt{1+\frac{e^2E_0^2t^2}{m^2v_0^2}}$ (*c*) $\frac{\lambda_0}{\sqrt{1+\frac{e^2E_0^2t^2}{m^2v_0^2}}}$ (*d*) $\frac{\lambda_0}{\left(1+\frac{e^2E_0^2t^2}{m^2v_0^2}\right)}$

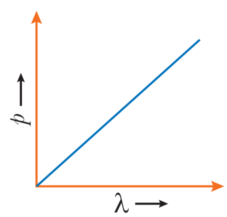
17. **If an electron and a photon propagate in the form of waves having same wavelength, it implies that they have same:**

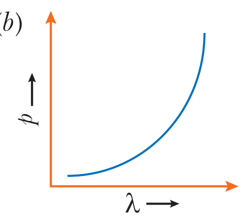
(*a*) speed (*b*) momentum (*c*) energy (*d*) all the above

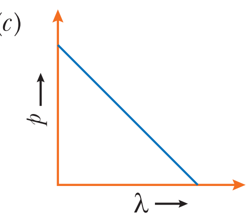
18. **A particle of mass 1 mg has the same wavelength as an electron moving with a velocity of 3×10^6 ms^{-1}. The velocity of the particle is (mass of electron = 9.1×10^{-31} kg)**

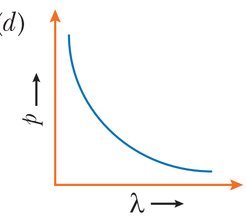
(*a*) 2.7×10^{-18} ms^{-1} (*b*) 9×10^{-2} ms^{-1} (*c*) 3×10^{-31} ms^{-1} (*d*) 2.7×10^{-21} ms^{-1}

19. **Which of the following figures represent the variation of particle momentum and the associated de-Broglie wavelength?**

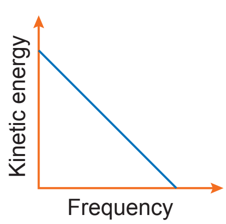
(*a*)


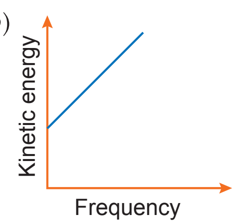
(*b*)


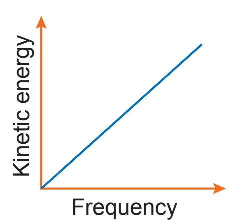
(*c*)


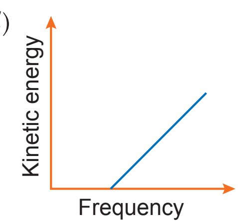
(*d*)


20. **According to Einstein's photoelectric equation, the graph between the kinetic energy of photoelectrons ejected and the frequency of incident radiation is**

(*a*)


(*b*)


(*c*)


(*d*)


Answers

1. (*d*)	**2.** (*b*)	**3.** (*d*)	**4.** (*c*)	**5.** (*c*)	**6.** (*d*)
7. (*d*)	**8.** (*a*)	**9.** (*a*)	**10.** (*b*)	**11.** (*b*)	**12.** (*c*), (*d*)
13. (*a*)	**14.** (*b*)	**15.** (*a*), (*c*)	**16.** (*c*)	**17.** (*b*)	**18.** (*a*)
19. (*d*)	**20.** (*d*)				

Fill in the Blanks [1 mark]

1. The minimum energy required by a free electron to just escape from the metal surface is called as ________________.
2. The maximum kinetic energy of emitted photoelectrons depends on the ________________ of incident radiation and the nature of material.
3. The velocity of photon in different media is ________________.
4. The main aim of Davisson-Germer experiment is to verify the ________________ nature of moving electrons.
5. The minimum frequency required to eject an electron from the surface of a metal surface is called ________________ frequency.
6. In photoelectric effect, saturation current is not affected on decreasing the ________________ of incident radiation provided its intensity remains unchanged.
7. The intensity of radiation also depends upon the number of ________________.
8. Momentum of photon in different media is ________________.
9. Davisson and Germer experiment established the ________________.
10. Matter wave are associated with ________________ particle.

Answers

1. work function	2. frequency	3. different	4. wave
5. threshold	6. wavelength/frequency	7. photons	8. different
9. wave nature	10. moving		

Very Short Answer Questions [1 mark]

Q. 1. Name the phenomenon which shows the quantum nature of electromagnetic radiation. *[CBSE (AI) 2017]*

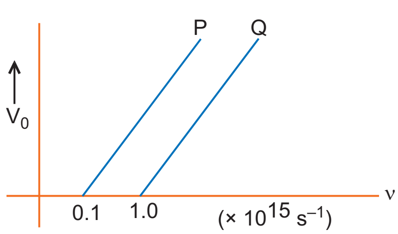
Ans. "Photoelectric effect" shows the quantum nature of electromagnetic radiation.

Q. 2. Define intensity of radiation on the basis of photon picture of light. Write its SI unit. *[CBSE (AI) 2014; 2019 (55/1/1)]*

Ans. The amount of light energy or photon energy incident per metre square per second is called intensity of radiation.

SI unit: $\frac{W}{m^2}$ or $J/s-m^2$

Q. 3. The figure shows the variation of stopping potential V_0 with the frequency ν of the incident radiations for two photosensitive metals P and Q. Which metal has smaller threshold wavelength? Justify your answer. *[CBSE 2019 (55/4/1)]*



Ans. Since $\lambda_0 = \frac{c}{\nu_0}$, metal Q has smaller threshold wavelength.

Q. 4. Write the basic features of photon picture of electromagnetic radiation on which Einstein's photoelectric equation is based. *[CBSE Delhi 2013]*

Ans. Features of the photons:

(*i*) Photons are particles of light having energy $E = h\nu$ and momentum $p = \frac{h}{\lambda}$, where h is Planck constant.

(*ii*) Photons travel with the speed of light in vacuum, independent of the frame of reference.

(*iii*) Intensity of light depends on the number of photons crossing unit area in a unit time.

Q. 5. Define the term 'stopping potential' in relation to photoelectric effect. [*CBSE (AI) 2011*]

Ans. The minimum retarding (negative) potential of anode of a photoelectric tube for which photoelectric current stops or becomes zero is called the stopping potential.

Q. 6. Define the term 'threshold frequency' in relations to photoelectric effects. [*CBSE (F) 2011*, 2019 (55/1/1)]

Ans. Threshold frequency is defined as the minimum frequency of incident radiation which can cause photoelectric emission. It is different for different metal.

Q. 7. In photoelectric effect, why should the photoelectric current increase as the intensity of monochromatic radiation incident on a photosensitive surface is increased? Explain. [*CBSE (F) 2014*]

Ans. The photoelectric current increases proportionally with the increase in intensity of incident radiation. Larger the intensity of incident radiation, larger is the number of incident photons and hence larger is the number of electrons ejected from the photosensitive surface.

Q. 8. 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*. [*CBSE (AI) 2013*]

Ans. de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mqV}}$

Hint: $W = K = qV = \frac{p^2}{2m}$ or $p = \sqrt{2mqV}$

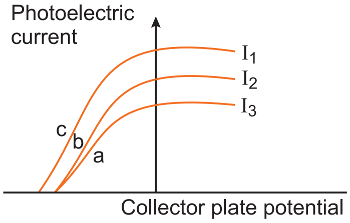
Q. 9. State de-Broglie hypothesis. [*CBSE Delhi 2012*]

Ans. According to hypothesis of de Broglie "The atomic particles of matter moving with a given velocity, can display the wave like properties."

i.e., $\lambda = \frac{h}{mv}$ (mathematically)

Q. 10. 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 ν_1, ν_2 and ν_3 respectively incident on a photosenitive surface.

Point out the two curves for which the incident radiations have same frequency but different intensities. [*CBSE Delhi 2009*]



Ans. Curves *a* and *b* have different intensities but same stopping potential, so curves '*a*' and '*b*' have same frequency but different intensities.

Q. 11. The stopping potential in an experiment on photoelectric effect is 1.5 V. What is the maximum kinetic energy of the photoelectrons emitted? [*CBSE (AI) 2009*]

Ans. $K_{max} = eV_s = e\,(1.5V) = 1.5$ eV

$= 1.5 \times 1.6 \times 10^{-19}$ J $= 2.4 \times 10^{-19}$ J

Q. 12. The maximum kinetic energy of a photoelectron is 3 eV. What is its stopping potential? [*CBSE (AI) 2009*]

Ans. $(E_k)_{max} = eV_s$

Stopping potential, $V_s = \frac{(E_k)_{max}}{e} = \frac{3\,eV}{e} = 3$ V

Q. 13. The stopping potential in an experiment on photoelectric effect is 2 V. What is the maximum kinetic energy of the photoelectrons emitted? [*CBSE (AI) 2009*]

Ans. Maximum kinetic energy, $(E_k)_{max} = eV_s$

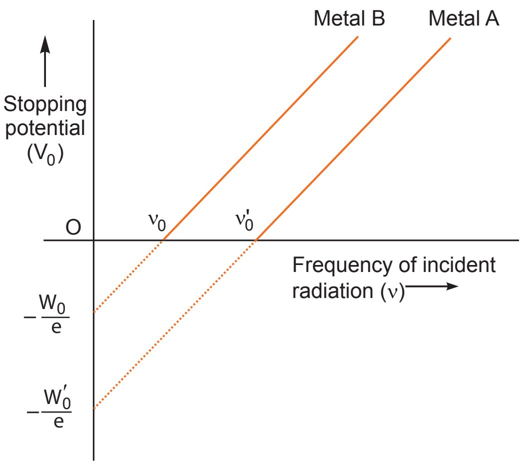
$= e(2V) = 2$ eV

Q. 14. What is the stopping potential of a photocell, in which electrons with a maximum kinetic energy of 6 eV are emitted ? [*CBSE (AI) 2008*]

Ans. $E_k = eV_0 \Rightarrow 6$ eV $= eV_0 \Rightarrow V_0 = 6$ V

The stopping potential $V_0 = 6$ volt (Negative).

Q. 15. The graph shows the variation of stopping potential with frequency of incident radiation for two photosensitive metals *A* and *B*. Which one of the two has higher value of work-function? Justify your answer. [*CBSE (AI) 2014*]



Ans. Metal *A*

Since work function $W = h\nu_0$

and $\nu'_0 > \nu_0$ so work function of metal *A* is more.

Aliter:

On stopping potential axis $-\frac{W'_0}{e} > -\frac{W_0}{e}$.

Hence work function W'_0 of metal *A* is more.

Q. 16. An electron and a proton have the same kinetic energy. Which one of the two has the larger de Broglie wavelength and why? [*CBSE (AI) 2012*]

Ans. An electron has the larger wavelength.

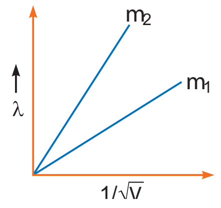
Reason: de-Broglie wavelength in terms of kinetic energy is $\lambda = \frac{h}{\sqrt{2mE_k}} \propto \frac{1}{\sqrt{m}}$ for the same kinetic energy.

As an electron has a smaller mass than a proton, *an electron has larger de Broglie wavelength than a proton for the same kinetic energy*.

Q. 17. Plot a graph showing variation of de-Broglie wavelength λ versus $\frac{1}{\sqrt{V}}$, where *V* is accelerating potential for two particles *A* and *B* carrying same charge but of masses m_1, m_2 ($m_1 > m_2$). Which one of the two represents a particle of smaller mass and why? [*CBSE Delhi 2016*] [*HOTS*]

Ans. As, $\lambda = \frac{h}{\sqrt{2mqV}}$ or $\lambda = \left(\frac{h}{\sqrt{2q}}\cdot\frac{1}{\sqrt{m}}\right)\frac{1}{\sqrt{V}}$

or $\frac{\lambda}{\frac{1}{\sqrt{V}}} = \frac{h}{\sqrt{2q}}\cdot\frac{1}{\sqrt{m}}$



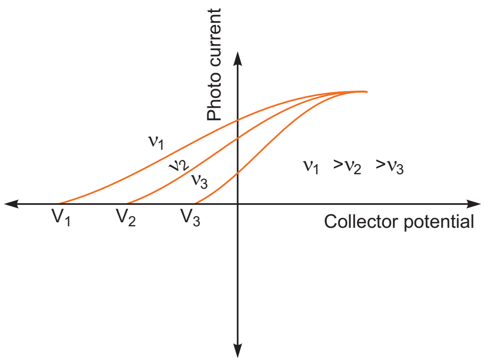
As the charge on two particles is same, we get

$$\text{Slope} \propto \frac{1}{\sqrt{m}}$$

Hence, particle with lower mass (m_2) will have greater slope.

Q. 18. Show the variation of photocurrent with collector plate potential for different frequencies but same intensity of incident radiation. [*CBSE (F) 2011*] [*HOTS*]

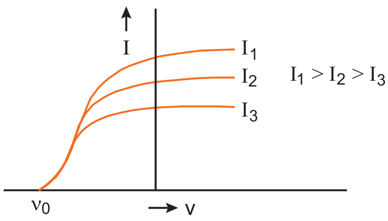
Ans.



Q. 19. **(*a*) Draw a graph showing variation of photo-electric current (*I*) with anode potential (*V*) for different intensities of incident radiation. Name the characteristic of the incident radiation that is kept constant in this experiment.**

(*b*) If the potential difference used to accelerate electrons is doubled, by what factor does the de-Broglie wavelength associated with the electrons change? *[CBSE (F) 2009]*

Ans. (*a*) The frequency of incident radiation was kept constant.



(*b*) de-Broglie wavelength,

$$\lambda = \frac{h}{\sqrt{2mqV}} \propto \frac{1}{\sqrt{V}}$$

If potential difference V is doubled, the de-Broglie wavelength is decreased to $\frac{1}{\sqrt{2}}$ times.

Q. 20. **(*a*) Define the term 'intensity of radiation' in photon picture.**

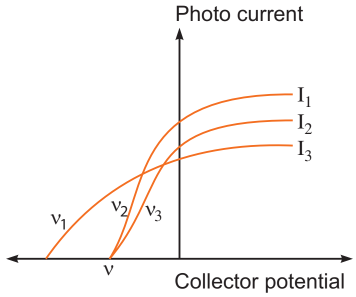
(*b*) Plot a graph showing the variation of photo current vs collector potential for three different intensities $I_1 > I_2 > I_3$, two of which (I_1 and I_2) have the same frequency ν and the third has frequency $\nu_1 > \nu$.

(*c*) Explain the nature of the curves on the basis of Einstein's equation.

[CBSE South 2016] [HOTS]

Ans. (*a*) The amount of light energy or photon energy incident per metre square per second is called intensity of radiation.

(*b*) $\nu_2 = \nu_3 = \nu$

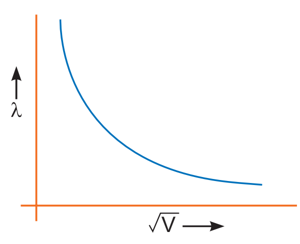


(*c*) As per Einstein's equation,

(*i*) The stopping potential is same for I_1 and I_2 as they have the same frequency.

(*ii*) The saturation currents are as shown in figure because $I_1 > I_2 > I_3$.

Q. 21. **Show on a graph the variation of the de Broglie wavelength (λ) associated with an electron, with the square root of accelerating potential (V).** *[CBSE (F) 2012] [HOTS]*



Ans. We know $\lambda = \frac{12.27}{\sqrt{V}}$ Å

$\therefore \quad \lambda\sqrt{V} = \text{constant}$

The nature of the graph between λ and $\sqrt{V}$ is hyperbola.

Q. 22. **Two metals *A* and *B* have work functions 4 eV and 10 eV respectively. Which metal has the higher threshold wavelength?**

Ans. Work function $W = h\nu_0 = \frac{hc}{\lambda_0}$

$\Rightarrow \quad \lambda_0 \propto \frac{1}{W}$

As $\quad W_A < W_B; \; (\lambda_0)_A > (\lambda_0)_B$

i.e., threshold wavelength of metal *A* is higher.

Q. 23. de Broglie wavelength associated with an electron accelerated through a potential difference V is λ What will be the de Broglie wavelength when the accelerating potential is increased to $4V$?

Ans. $\frac{\lambda}{2}$

Reason: de Broglie wavelength associated with electron is

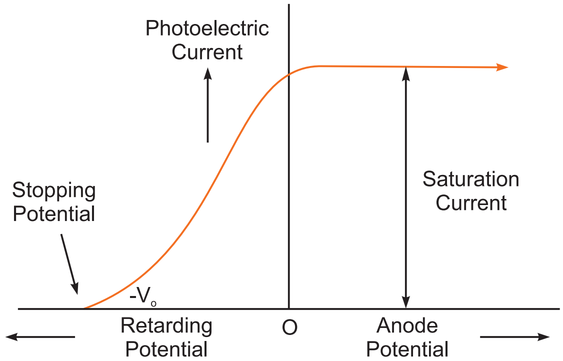
$$\lambda = \frac{h}{\sqrt{2meV}} \quad \Rightarrow \quad \lambda \propto \frac{1}{\sqrt{V}}$$

Obviously when accelerating potential becomes $4V$, the de-Broglie wavelength reduces to half.

Q. 24. (*a*) Draw a graph showing variation of photocurrent with anode potential for a particular intensity of incident radiation. Mark saturation current and stopping potential.

(*b*) How much would stopping potential for a given photosensitive surface go up if the frequency of the incident radiations were to be increased from 4×10^{15} Hz to 8×10^{15} Hz?

Ans. (*a*)



Intercept of the graph with potential axis gives the stopping potential.

(*b*) We have, $h\nu_{in} = eV$

$$\Rightarrow \quad \Delta V = \frac{h(\nu_2 - \nu_1)}{e}$$

$$= \frac{6.62\times10^{-34}\times(8\times10^{15} - 4\times10^{15})}{1.6\times10^{-19}}$$

$$= \frac{6.62\times4\times10^{15}\times10^{-34}}{1.6\times10^{-19}}\text{V}$$

= 16.55 V

Q. 25. There are materials which absorb photons of shorter wavelength and emit photons of longer wavelength. Can there be stable substances which absorb photons of larger wavelength and emit light of shorter wavelength? ***[NCERT Exemplar]***

Ans. In the first case, energy given out is less than the energy supplied. In the second case, the material has to supply the energy as the emitted photon has more energy. This cannot happen for stable substances.

Q. 26. Do all the electrons that absorb a photon come out as photoelectrons? ***[NCERT Exemplar] [HOTS]***

Ans. No, most electrons get scattered into the metal. Only a few come out of the surface of the metal.

Q. 27. Electrons are emitted from a photosensitive surface when it is illuminated by green light but electron emission does not take place by yellow light. Will the electrons be emitted when the surface is illuminated by (*i*) red light, and (*ii*) blue light? ***[HOTS]***

Ans. (*i*) No (*ii*) Yes.

Reason: According to colour sequence VIBGYOR, the frequency of red light photons is less than threshold frequency of photometal but frequency of blue light photons is more than threshold frequency of photometal; so (*i*) electrons will not be emitted by red light and (*ii*) electrons will be emitted by blue light.

Q. 28. In a photoelectric effect, the yellow light is just able to emit electrons, will green light emit photoelectrons? What about red light? [*HOTS*]

Ans. Energy of photon $E = \frac{hc}{\lambda} \propto \frac{1}{\lambda}$

As $\lambda_{green} < \lambda_{yellow}$ so green light photon has more energy than yellow light photon, so green light will eject electron.

As $\lambda_{red} > \lambda_{yellow}$ so red light photon has lesser energy than yellow light photon, so red light will not be able to eject electrons.

Q. 29. Work function of aluminium is 4.2 eV. If two photons, each of energy 2.5 eV, are incident on its surface, will the emission of electrons take place? Justify your answer. [*HOTS*]

Ans. In photoelectric effect, a single photon interacts with a single electron. As individual photon has energy (2.5 eV) which is less than work function, hence emission of electron will not take place.

Short Answer Questions–I [2 marks]

Q. 1. Write Einstein's photoelectric equation and point out any two characteristic properties of photons on which this equation is based. [*CBSE (AI) 2013*]

Ans. If radiation of frequency (ν) greater than threshold frequency (ν_0) irradiate the metal surface, electrons are emitted out from the metal. So Einstein's photoelectric equation can be given as

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

Characteristic properties of photons:

(*i*) Energy of photon is directly proportional to the frequency (or inversely proportional to the wavelength).

(*ii*) In photon-electron collision, total energy and momentum of the system of two constituents remains constant.

(*iii*) In the interaction of photons with the free electrons, the entire energy of photon is absorbed.

Q. 2. 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. [*CBSE Delhi 2016*]

Ans. The three characteristic features which cannot be explained by wave theory are:

(*i*) Kinetic energy of emitted electrons is found to be independent of the intensity of incident light.

(*ii*) There is no emission of electrons if frequency of incident light is below a certain frequency (threshold frequency).

(*iii*) Photoelectric effect is an instantaneous process.

Q. 3. A proton and an electron have same velocity. Which one has greater de Broglie wavelength and why? [*CBSE (AI) 2012*]

Ans. de Broglie wavelength (λ) is given as $\lambda = \frac{h}{mv}$

Given $v_p = v_e$

where v_p = velocity of proton and v_e = velocity of electron

Since $m_p > m_e$

From the given relation

$$\lambda \propto \frac{1}{m}, \text{ hence } \lambda_p < \lambda_e$$

Thus, electron has greater de Broglie wavelength, if accelerated with same speed.

Q. 4. What is meant by work function of a metal? How does the value of work function influence the kinetic energy of electrons liberated during photoelectron emission?

[*CBSE Delhi 2013; (AI) 2013*]

Ans. **Work Function:** The minimum energy required to free an electron from metallic surface is called the work function.

Smaller the work function, larger the kinetic energy of emitted electron.

Q. 5. Monochromatic light of frequency 6×10^{14} Hz is produced by a laser. The power emitted is 2.0×10^{-3} W. How many photons per second on an average are emitted by the source?

[*CBSE Guwahati 2015*]

Ans. Power of radiation, $P = \frac{nh\nu}{t} = Nh\nu$, where N is number of photons per sec.

or
$$N = \frac{P}{h\nu}$$
$$= \frac{2.0 \times 10^{-3}}{6.63 \times 10^{-34} \times 6 \times 10^{14}}$$
$$= \mathbf{5 \times 10^{15}} \textbf{ photons per second}$$

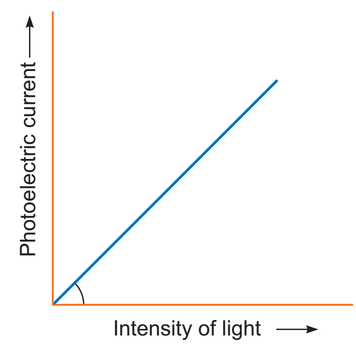
Q. 6. Plot a graph showing the variation of photoelectric current with intensity of light. The work function for the following metals is given:

Na: 2.75 eV and Mo: 4.175 eV.

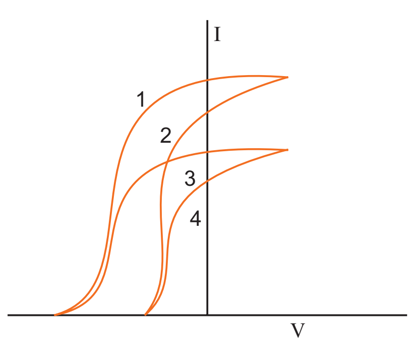
Which of these will not give photoelectron emission from a radiation of wavelength 3300 Å from a laser beam? What happens if the source of laser beam is brought closer? **[*CBSE (F) 2016*]**

Ans. Energy of photon $E = \frac{hc}{\lambda}$ Joule
$$= \frac{hc}{e\lambda}\text{eV}$$
$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.6 \times 10^{-19} \times 3.3 \times 10^{-7}}\text{ eV} = \mathbf{3.76\ eV}$$

Since W_0 of Mo is greater than E, $\therefore$ Mo will not give photoemission. There will be no effect of bringing source closer in the case of Mo. In case of Na, photocurrent will increase.



Q. 7. The given graph shows the variation of photo-electric current (*I*) with the applied voltage (*V*) for two different materials and for two different intensities of the incident radiations. Identify and explain using Einstein's photo electric equation for the pair of curves that correspond to (*i*) different materials but same intensity of incident radiation, (*ii*) different intensities but same materials. **[*CBSE East 2016*]**



Ans. (*a*) 1 and 2 correspond to same intensity but different material.

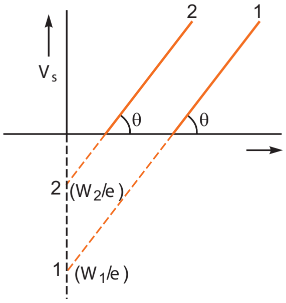
(*b*) 3 and 4 correspond to same intensity but different material.

This is because the saturation currents are same and stopping potentials are different.

(*a*) 1 and 3 correspond to different intensity but same material.
(*b*) 2 and 4 correspond to different intensity but same material.

This is because the stopping potentials are same but saturation currents are different.

Q. 8. 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? [*CBSE Delhi 2010*]



Ans. The graph of stopping potential V_s and frequency (ν) for two photosensitive materials 1 and 2 is shown in fig.

(*i*) Slope of graph $\tan\theta = \dfrac{h}{e}$ = universal constant.

(*ii*) Intercept of lines depend on the work function.

Q. 9. An electron is accelerated through a potential difference of 100 V. What is the de Broglie wavelength associated with it? To which part of the electromagnetic spectrum does this value of wavelength correspond? [*CBSE Delhi 2010*]

Ans. de Broglie wavelength, $\lambda\left(=\dfrac{h}{p}\right)=\dfrac{h}{\sqrt{2meV}}$

$$=\frac{6.63\times10^{-34}}{\sqrt{2\times9.1\times10^{-31}\times1.6\times10^{-19}\times100}}$$

$$=1.227\times10^{-10}\text{ m}=\mathbf{1.227\ \text{Å}}$$

This wavelength belongs to X-ray spectrum.

Q. 10. An electromagnetic wave of wavelength λ_1 is incident on a photosensitive surface of negligible work function. If the photo-electrons emitted from this surface have the de-Broglie wavelength prove that $\lambda=\left(\dfrac{2mc}{h}\right)\lambda_1^2$ [*CBSE Delhi 2008*]

Ans. Kinetic energy of electrons, E_k = energy of photon of EM wave

$$=\frac{hc}{\lambda} \qquad \ldots(i)$$

de Broglie wavelength, $\lambda_1=\dfrac{h}{\sqrt{2mE_k}}$ or $\lambda_1^2=\dfrac{h^2}{2mE_k}$

Using (*i*), we get

$$\lambda_1^2=\frac{h^2}{2m\left(\dfrac{hc}{\lambda}\right)} \quad\Rightarrow\quad \lambda=\left(\frac{2mc}{h}\right)\lambda_1^2$$

Q. 11. An α-particle and a proton of the same kinetic energy are in turn allowed to pass through a magnetic field $\vec{B}$, acting normal to the direction of motion of the particles. Calculate the ratio of radii of the circular paths described by them. [*CBSE 2019 (55/1/1)*]

Ans. Radius $r=\dfrac{mv}{qB}=\dfrac{\sqrt{2mK}}{qB}$

$$K_\alpha=K_{\text{proton}}$$
$$M_\alpha=4\,M_P$$
$$q_\alpha=2q_P$$

$$\frac{r_\alpha}{r_p} = \frac{\dfrac{\sqrt{2m_\alpha K}}{q_\alpha B}}{\dfrac{\sqrt{2m_p K}}{q_p B}}$$

$$= \sqrt{\frac{m_a}{m_p}} \times \frac{q_p}{q_\alpha}$$

$$= \sqrt{4} \times \frac{1}{2} = \mathbf{1}$$

Q. 12. There are two sources of light, each emitting with a power 100W. One emits X-rays of wavelength 1 nm and the other visible light at 500 nm. Find the ratio of number of photons of X-rays the photons of visible light of the given wavelength. [*NCERT Exemplar*]

Ans. Total E is constant.

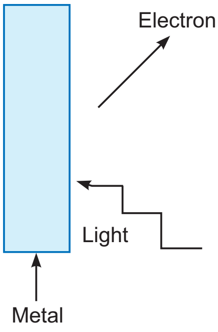
Let n_1 and n_2 be the number of photons of X-rays and visible region.

$$n_1 E_1 = n_2 E_2 \quad \Rightarrow \quad n_1 \frac{hc}{\lambda_1} = n_2 \frac{hc}{\lambda_2}$$

$$\frac{n_1}{n_2} = \frac{\lambda_1}{\lambda_2} \quad \Rightarrow \quad \frac{n_1}{n_2} = \frac{\mathbf{1}}{\mathbf{500}}$$

Q. 13. Consider Fig. for photoemission.

How would you reconcile with momentum-conservation? No light (Photons) have momentum in a different direction than the emitted electrons. [*NCERT Exemplar*]



Ans. The momentum is transferred to the metal. At the microscopic level, atoms absorb the photon and its momentum is transferred mainly to the nucleus and electrons. The excited electron is emitted. Conservation of momentum needs to be accounted for the momentum transferred to the nucleus and electrons.

Q. 14. A photon and a proton have the same de-Broglie wavelength λ. Prove that the energy of the photon is $(2m\lambda c/h)$ times the kinetic energy of the proton. [*CBSE 2019 (55/2/1)*]

Ans. Energy of photon $E_P = \dfrac{hc}{\lambda}$

For proton $\lambda = \dfrac{h}{mv}$

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

Kinetic energy of proton $E_k = \dfrac{1}{2}mv^2$

$$E_k = \frac{1}{2}\frac{h^2}{m\lambda^2}$$

$$E_P = \left(\frac{2m\lambda c}{h}\right) E_k$$

Q. 15. If light of wavelength 412·5 nm is incident on each of the metals given below, which ones will show photoelectric emission and why? [*CBSE 2018*]

Metal	Work Function (eV)
Na	1.92
K	2.15
Ca	3.20
Mo	4.17

Ans. The energy of the incident photon,

$$E = h\nu = \frac{hc}{\lambda}$$

$$= \frac{6.63\times10^{-34}\times3\times10^{8}}{412.5\times10^{-9}}\text{ J}$$

$$= \frac{0.048\times10^{-17}}{1.6\times10^{-19}}\text{ eV} = \mathbf{3\ eV}$$

Metals having work function less than energy of the incident photon will show photoelectric effect. Hence, only Na and K will show photoelectric emission.

Short Answer Questions–II [3 marks]

Q. 1. Explain briefly the reasons why wave theory of light is not able to explain the observed features of photo-electric effect. [*CBSE Delhi 2013; (AI) 2013; (F) 2010; 2019 (55/2/1)*]

Ans. The observed characteristics of photoelectric effect could not be explained on the basis of wave theory of light due to the following reasons.

(*i*) According to wave theory, the light propagates in the form of wavefronts and the energy is distributed uniformly over the wavefronts. With increase of intensity of light, the amplitude of waves and the energy stored by waves will increase. These waves will then, provide more energy to electrons of metal; consequently, the energy of electrons will increase.

Thus, ***according to wave theory, the kinetic energy of photoelectrons must depend on the intensity of incident light; but according to experimental observations, the kinetic energy of photoelectrons does not depend on the intensity of incident light.***

(*ii*) According to wave theory, the light of any frequency can emit electrons from metallic surface provided the intensity of light be sufficient to provide necessary energy for emission of electrons, but according to experimental observations, the light of frequency less than threshold frequency cannot emit electrons; whatever the intensity of incident light may be.

(*iii*) According to wave theory, the energy transferred by light waves will not go to a particular electron, but it will be distributed uniformly to all electrons present in the illuminated surface. Therefore, electrons will take some time to collect the necessary energy for their emission. The time for emission will be more for light of less intensity and vice versa. But experimental observations show that the emission of electrons take place instantaneously after the light is incident on the metal; whatever the intensity of light may be.

Q. 2. Write Einstein's photoelectric equation. State clearly the three salient features observed in photoelectric effect which can explain on the basis 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. [*CBSE Delhi 2015; (AI) 2010*]

Ans. Einstein's photoelectric equation:

$$h\nu = h\nu_0 + eV_0$$

where ν = incident frequency, ν_0 = threshold frequency, V_0 = stopping potential

(*i*) Incident energy of photon is used in two ways (*a*) to liberate electron from the metal surface (*b*) rest of the energy appears as maximum energy of electron.

(*ii*) Only one electron can absorb energy of one photon. Hence increasing intensity increases the number of electrons hence current.

(*iii*) If incident energy is less than work function, no emission of electron will take place.

(*iv*) Increasing ν (incident frequency) will increase maximum kinetic energy of electrons but number of electrons emitted will remain same.

For wavelength λ_1

$$\frac{hc}{\lambda_1} = \phi_0 + K = \phi_0 + eV_0 \qquad \ldots(i) \text{ where } K = eV_0$$

For wavelength λ_2

$$\frac{hc}{\lambda_2} = \phi_0 + 2eV_0 \qquad \ldots(ii) \text{ (because } KE \text{ is doubled)}$$

From equation (*i*) and (*ii*), we get

$$\frac{hc}{\lambda_2} = \phi_0 + 2\left(\frac{hc}{\lambda_1} - \phi_0\right) = \phi_0 + \frac{2hc}{\lambda_1} - 2\phi_0$$

$$\Rightarrow \qquad \phi_0 = \frac{2hc}{\lambda_1} - \frac{hc}{\lambda_2}$$

For threshold wavelength λ_0 kinetic energy, $K = 0$, and work function $\phi_0 = \frac{hc}{\lambda_0}$

$$\therefore \qquad \frac{hc}{\lambda_0} = \frac{2hc}{\lambda_1} - \frac{hc}{\lambda_2}$$

$$\Rightarrow \qquad \frac{1}{\lambda_0} = \frac{2}{\lambda_1} - \frac{1}{\lambda_2} \quad \Rightarrow \quad \lambda_0 = \frac{\lambda_1\lambda_2}{2\lambda_2 - \lambda_1}$$

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

Q. 3. Using photon picture of light, show how Einstein's photoelectric equation can be established. Write two features of photoelectric effect which cannot be explained by wave theory.

[*CBSE (AI) 2017*]

Ans. In the photon picture, energy of the light is assumed to be in the form of photons each carrying energy.

When a photon of energy '$h\nu$' falls on a metal surface, the energy of the photon is absorbed by the electrons and is used in the following two ways:

(*i*) A part of energy is used to overcome the surface barrier and come out of the metal surface. This part of energy is known as a work function and is expressed as $\phi_0 = h\nu_0$.

(*ii*) The remaining part of energy is used in giving a velocity 'v' to the emitted photoelectron which is equal to the maximum kinetic energy of photo electrons $\left(\frac{1}{2}mv^2_{max}\right)$.

(*iii*) According to the law of conservation of energy,

$$h\nu = \phi_0 + \frac{1}{2}mv^2_{max}$$

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

$$\Rightarrow \qquad KE_{max} = h\nu - h\nu_0$$

$$\text{or} \qquad KE_{max} = h\nu - \phi_0$$

This equation is called Einstein photoelectric equation.

Features which cannot be explained by wave theory:

(*i*) The process of photoelectric emission is instantaneous in nature.

(*ii*) There exists a 'threshold frequency' for each photosensitive material.

(*iii*) Maximum kinetic energy of emitted electrons is independent of the intensity of incident light.

Q. 4. 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. **[*CBSE North 2016, Delhi 2014*]**

Ans. (*i*) de Broglie wavelength

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

For same $V, \lambda \propto \frac{1}{\sqrt{mq}}$

$$\frac{\lambda_p}{\lambda_\alpha} = \sqrt{\frac{m_\alpha q_\alpha}{m_p q_p}} = \sqrt{\frac{4m_p}{m_p} \cdot \frac{2e}{e}}$$

$$= \sqrt{8} = 2\sqrt{2}$$

Clearly, $\lambda_p > \lambda_\alpha$.

Hence, proton has a greater de-Broglie wavelength.

(*ii*) Kinetic energy, $K = qV$

For same V, $K \propto q$

$$\frac{K_p}{K_\alpha} = \frac{q_p}{q_\alpha} = \frac{e}{2e} = \frac{1}{2}$$

Clearly, $K_p < K_\alpha$.

Hence, proton has less kinetic energy.

Q. 5. Define the terms (*i*) 'cut-off voltage' and (*ii*) 'threshold frequency' in relation to the phenomenon of photoelectric effect.

Using Einstein's photoelectric equation show how the cut-off voltage and threshold frequency for a given photosensitive material can be determined with the help of a suitable plot/graph.

[CBSE (AI) 2012]

Ans. (*i*) Cut off or stopping potential is that minimum value of negative potential at anode which just stops the photo electric current.

(*ii*) For a given material, there is a minimum frequency of light below which no photo electric emission will take place, this frequency is called as threshold frequency.

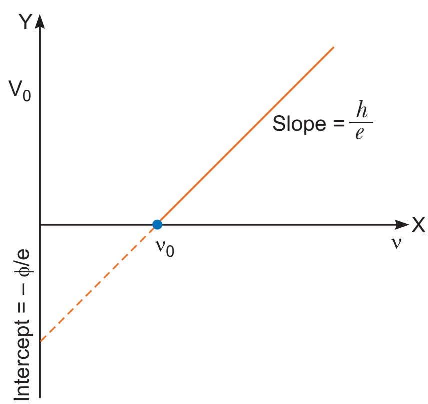
By Einstein's photo electric equation

$$KE_{max} = \frac{hc}{\lambda} - \phi = h\nu - h\nu_0$$

$$eV_0 = h\nu - h\nu_0$$

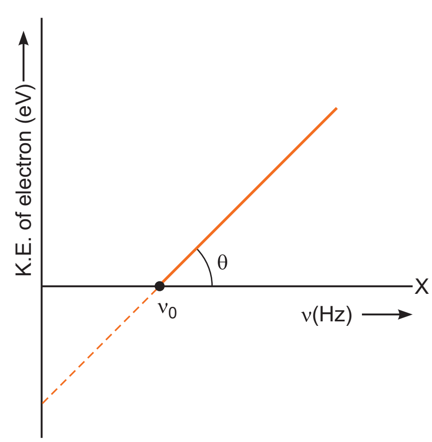
$$V_0 = \frac{h}{e}\nu - \frac{h}{e}\nu_0$$

Clearly, $V_0 - \nu$ graph is a straight line.



Q. 6. Write two characteristic features observed in photoelectric effect which support the photon picture of electromagnetic radiation.

Draw a graph between the frequency of incident radiation (ν) and the maximum kinetic energy of the electrons emitted from the surface of a photosensitive material. State clearly how this graph can be used to determine (*i*) Planck's constant and (*ii*) work function of the material. ***[CBSE Delhi 2017, (F) 2012]***



Ans. (*a*) All photons of light of a particular frequency 'ν' have same energy and momentum whatever the intensity of radiation may be.

(*b*) Photons are electrically neutral and are not affected by presence of electric and magnetic fields, (*i*) From this graph, the Planck constant can be calculated by the slope of the current

$$h = \frac{\Delta(KE)}{\Delta\nu}$$

(*ii*) Work function is the minimum energy required to eject the photo-electron from the metal surface.

$\phi = h\nu_0$, where ν_0 = Threshold frequency

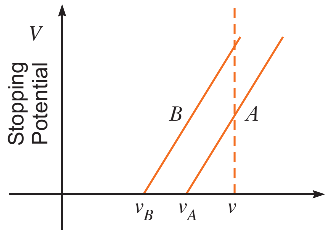
Q. 7. Sketch the graphs showing variation of stopping potential with frequency of incident radiations for two photosensitive materials *A* and *B* having threshold frequencies $\nu_A > \nu_B$.

(*i*) In which case is the stopping potential more and why?

(*ii*) Does the slope of the graph depend on the nature of the material used? Explain.

[*CBSE Central 2016*]

Ans. (*i*) From the graph for the same value of 'ν', stopping potential is more for material 'B'.



From Einstein's photoelectric equation

$eV_0 = h\nu - h\nu_0$

$$V_0 = \frac{h}{e}\nu - \frac{h}{e}\nu_0 = \frac{h}{e}(\nu - \nu_0)$$

$\therefore$ V_0 is higher for lower value of ν_0

(*ii*) No, as slope is given by $\frac{h}{e}$ which is a universal constant.

Q. 8. A proton and a deuteron are accelerated through the same accelerating potential. Which one of the two has

(*i*) greater value of de-Broglie wavelength associated with it, and

(*ii*) less momentum?

Give reasons to justify your answer. [*CBSE Delhi 2014*]

Ans. (*i*) de Broglie wavelength, $\lambda = \frac{h}{\sqrt{2mqV}}$

Here *V* is same for proton and deutron.

As mass of proton < mass of deutron and $q_p = q_d$

Therefore, $\lambda_p > \lambda_d$ for same accelerating potential.

(*ii*) We know that momentum $= \frac{h}{\lambda}$

Therefore, $\lambda_p > \lambda_d$

So, momentum of proton will be less than that of deutron.

Q. 9. A beam of monochromatic radiation is incident on a photosensitive surface. Answer the following questions giving reasons:

(*i*) Do the emitted photoelectrons have the same kinetic energy?

(*ii*) Does the kinetic energy of the emitted electrons depend on the intensity of incident radiation?

(*iii*) On what factors does the number of emitted photoelectrons depend? [*CBSE (F) 2015*]

Ans. In photoelectric effect, an electron absorbs a quantum of energy $h\nu$ of radiation, which exceeds the work function, an electron is emitted with maximum kinetic energy,

$K_{max} = h\nu - W$

(*i*) No, all electrons are bound with different forces in different layers of the metal. So, more tightly bound electron will emerge with less kinetic energy. Hence, all electrons do not have same kinetic energy.

(*ii*) No, because an electron cannot emit out if quantum energy $h\nu$ is less than the work function of the metal. The *K.E.* depends on energy of each photon.

(*iii*) Number of emitted photoelectrons depends on the intensity of the radiations provided the quantum energy $h\nu$ is greater than the work function of the metal.

Q. 10. Why are de Broglie waves associated with a moving football not visible?

The wavelength 'λ' of a photon and the de Broglie wavelength of an electron have the same value. Show that the energy of photon is $\frac{2\lambda mc}{h}$ times the kinetic energy of electron, where *m*, *c*, *h* have their usual meanings. [*CBSE (F) 2016*]

Ans. Due to large mass of a football the de Broglie wavelength associated with a moving football is much smaller than its dimensions, so its wave nature is not visible.

de Broglie wavelength of electron $\lambda = \frac{h}{mv} \Rightarrow v = \frac{h}{m\lambda}$ ....(*i*)

energy of photon $E = \frac{hc}{\lambda}$ (because λ is same) ...(*ii*)

Ratio of energy of photon and kinetic energy of electrons

$$\frac{E}{E_k} = \frac{hc/\lambda}{\frac{1}{2}mv^2} = \frac{2hc}{\lambda mv^2}$$

Substituting value of v from (*i*), we get

$$\frac{E}{E_k} = \frac{2hc}{\lambda m(h/m\lambda)^2} = \frac{2\lambda mc}{h}$$

$\therefore$ Energy of photon $= \frac{2\lambda mc}{h} \times$ kinetic energy of electron

Q. 11. An α-particle and a proton are accelerated from rest by the same potential. Find the ratio of their de- Broglie wavelengths. [*CBSE Delhi 2017, (AI) 2010*]

Ans. de-Broglie wavelength $\lambda = \frac{h}{\sqrt{2mE}} = \frac{h}{\sqrt{2mqV}}$

For -particle, $\lambda_\alpha = \frac{h}{\sqrt{2m_\alpha q_\alpha V}}$

For proton, $\lambda_p = \frac{h}{\sqrt{2m_p q_p V}}$

$\therefore$ $\frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{m_p q_p}{m_\alpha q_\alpha}}$

But $\frac{m_\alpha}{m_p} = 4, \frac{q_\alpha}{q_p} = 2$

$\therefore$ $\frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{1}{4}\cdot\frac{1}{2}} = \frac{1}{\sqrt{8}} = \mathbf{\frac{1}{2\sqrt{2}}}$.

Q. 12. A proton and an α-particle have the same de-Broglie wavelength. Determine the ratio of (*i*) their accelerating potentials (*ii*) their speeds. [*CBSE Delhi 2015; 2019 (55/4/1)*]

Ans. de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mqV}}$

where, m = mass of charge particle, q = charge of particle, V = potential difference

(*i*) $\lambda^2 = \frac{h^2}{2mqV} \Rightarrow V = \frac{h^2}{2mq\lambda^2}$

$\therefore$ $\frac{V_p}{V_\alpha} = \frac{2m_\alpha q_\alpha}{2m_p q_p} = \frac{2 \times 4m2q}{2mq} = \frac{8}{1}$

$\therefore$ $V_p : V_\alpha = \mathbf{8 : 1}$

(*ii*) $$\lambda = \frac{h}{mv}, \lambda_p = \frac{h}{m_p v_p}, \lambda_\alpha = \frac{h}{m_\alpha v_\alpha}$$

$$\lambda_p = \lambda_\alpha \Rightarrow \frac{h}{m_p v_p} = \frac{h}{m_\alpha v_\alpha}$$

$$\frac{v_p}{v_\alpha} = \frac{m_\alpha}{m_p} = \frac{4}{1} = \mathbf{4:1}$$

Q. 13. An electron and a proton, each have de Broglie wavelength of 1.00 nm.

(*a*) Find the ratio of their momenta.

(*b*) Compare the kinetic energy of the proton with that of the electron. [*CBSE (F) 2013*]

Ans. (*a*) $\lambda_e = \frac{h}{p_e}$ and $\lambda_p = \frac{h}{p_p}, \lambda_e = \lambda_p = 1.00\,\text{nm}$

So, $$\frac{\lambda_e}{\lambda_p} = \frac{p_p}{p_e} = \frac{1}{1} \Rightarrow \frac{p_p}{p_e} = \frac{1}{1} = \mathbf{1:1}$$

(*b*) From relation $K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$

$$K_e = \frac{p_e^2}{2m_e} \text{ and } K_p = \frac{p_p^2}{2m_p}$$

$$\frac{K_p}{K_e} = \frac{p_p^2}{2m_p} \times \frac{2m_e}{p_e^2} = \frac{m_e}{m_p}$$

Since $m_e <<< m_p$. So $K_p <<< K_e$.

$$\frac{K_p}{K_e} = \frac{9.1 \times 10^{-31}}{1.67 \times 10^{-27}} = \mathbf{5.4 \times 10^{-4}}$$

Q. 14. Write briefly the underlying principle used in Davison-Germer experiment to verify wave nature of electrons experimentally. What is the de-Broglie wavelength of an electron with kinetic energy (*KE*) 120 eV? [*CBSE South 2016*]

Ans. **Principle:** Diffraction effects are observed for beams of electrons scattered by the crystals.

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE_k}} = \frac{h}{\sqrt{2meV}}$$

$$= \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times 120}}$$

$$\lambda = \mathbf{0.112\ nm}$$

Q. 15. (*a*) Define the term 'intensity of radiation' in terms of photon picture of light.

(*b*) Two monochromatic beams, one red and the other blue, have the same intensity. In which case (*i*) the number of photons per unit area per second is larger, (*ii*) the maximum kinetic energy of the photoelectrons is more? Justify your answer. [*CBSE Patna 2015*]

Ans. (*a*) The number of photons incident normally per unit area per unit time is determined the intensity of radiations.

(*b*) (*i*) Red light, because the energy of red light is less than that of blue light

$$(h\nu)_R < (h\nu)_B$$

(*ii*) Blue light, because the energy of blue light is greater than that of red light

$$(h\nu)_B > (h\nu)_R$$

Q 16. Determine the value of the de Broglie wavelength associated with the electron orbiting in the ground state of hydrogen atom (Given $E_n = -(13.6/n^2)$ eV and Bohr radius $r_0 = 0.53$ Å). How will the de Broglie wavelength change when it is in the first excited state? [*CBSE Bhubaneshwar 2015*]

Ans. In ground state, the kinetic energy of the electron is

$$K = -E = \frac{+13.6 \text{ eV}}{1^2} = 13.6 \times 1.6 \times 10^{-19} \text{ J} = 2.18 \times 10^{-18} \text{ J}$$

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

$$\lambda_1 = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 2.18 \times 10^{-18}}}$$

$$= 0.33 \times 10^{-9} \text{ m} = 0.33 \text{ nm}$$

Kinetic energy in the first excited state ($n=2$)

$$K = -E = +\frac{13.6}{2^2} \text{ eV} = +3.4 \text{ eV} = 3.4 \times 1.6 \times 10^{-19} \text{ J} = 0.54 \times 10^{-18} \text{ J}$$

de Broglie wavelength, $\lambda_2 = \frac{h}{\sqrt{2mK}}$

$$= \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 0.544 \times 10^{-18}}}$$

$$= 2 \times 0.33 \text{ nm} = \mathbf{0.66 \text{ nm}}$$

i.e., de Broglie wavelength will increase (or double).

Q 17. Define the term 'intensity of radiation' in photon picture of light.

Ultraviolet light of wavelength 2270 Å from 100 W mercury source irradiates a photo cell made of a given metal. If the stopping potential is –1.3 V, estimate the work function of the metal. How would the photocell respond to a high intensity (~ 10^5 Wm^{-2}) red light of wavelength 6300 Å produced by a laser? [*CBSE Bhubaneshwar 2015*]

Ans. The intensity of light of certain frequency (or wavelength) is defined as the number if photons passing through unit area in unit time.

For a given wavelength, (λ) of light

$$\frac{hc}{\lambda} = W + K$$

$$= W + eV_s \qquad \text{(where } V_s \text{ is stopping potential)}$$

$$\frac{6.63 \times 10^{-34} \times 3 \times 10^8}{2270 \times 10^{-10}} = W + 1.6 \times 10^{-19} \times (-1.3 \text{ eV})$$

$$\therefore \qquad W = \left(\frac{6.63 \times 10^{-34} \times 3 \times 10^8}{2270 \times 10^{-10} \times 1.6 \times 10^{-19}} - 1.3\right) \text{eV}$$

$$W = 4.2 \text{ eV}$$

The wavelength of red light 6300 Å >> 2270 Å. So, the energy of red light must be

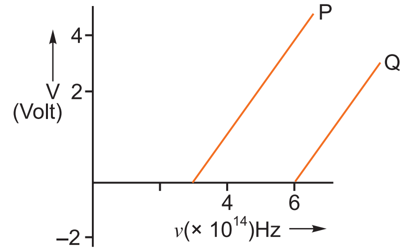
$$E = h\nu = \frac{hc}{e\lambda} \text{ in eV}$$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{1.6 \times 10^{-19} \times 6300 \times 10^{-10}}$$

$$= \frac{6.63 \times 3}{1.6 \times 63} \times 10 = \frac{198.9}{1.6 \times 63} \text{ eV} = \mathbf{1.973 \text{ eV}}$$

The energy of red light is very less than its work function, even intensity is very high. Hence no emission of electron is possible.

Q. 18. In the study of a photoelectric effect the graph between the stopping potential *V* and frequency ν of the incident radiation on two different metals *P* and *Q* is shown below:



(*i*) Which one of the two metals has higher threshold frequency?

(*ii*) Determine the work function of the metal which has greater value.

(*iii*) Find the maximum kinetic energy of electron emitted by light of frequency 8×10^{14} Hz for this metal. [*CBSE Delhi 2017*]

Ans. (*i*) Threshold frequency of *P* is 3×10^{14} Hz.

Threshold frequency of *Q* is 6×10^{14} Hz.

Clearly *Q* has higher threshold frequency.

(*ii*) Work function of metal *Q*, $\phi_0 = h\nu_0$

$$= (6.6 \times 10^{-34}) \times 6 \times 10^{14} \text{ J}$$

$$= \frac{39.6 \times 10^{-20}}{1.6 \times 10^{-19}} \text{eV} = \mathbf{2.5 \ eV}$$

(*iii*) Maximum kinetic energy, $K_{max} = h\nu - h\nu_0$

$$= h(\nu - \nu_0)$$

$$= 6.6 \times 10^{-34} (8 \times 10^{14} - 6 \times 10^{14})$$

$$= 6.6 \times 10^{-34} \times 2 \times 10^{14} \text{ J}$$

$$= \frac{6.6 \times 10^{-34} \times 2 \times 10^{14}}{1.6 \times 10^{-19}} \text{eV}$$

$$\therefore \quad K_{max} = \mathbf{0.83 \ eV}$$

Q. 19. Two monochromatic beams *A* and *B* of equal intensity *I*, hit a screen. The number of photons hitting the screen by beam *A* is twice that by beam *B*. Then what inference can you make about their frequencies? [*NCERT Exemplar*]

Ans. Let no. of photons falling per second of beam $A = n_A$

No. of photons falling per second of beam $B = n_B$

Energy of beam $A = h\nu_A$

Energy of beam $B = h\nu_B$

According to question, $I = n_A h\nu_A = n_B h\nu_B$

$$\frac{n_A}{n_B} = \frac{\nu_B}{\nu_A} \text{ or, } \frac{2n_B}{n_B} = \frac{\nu_B}{\nu_A} \Rightarrow \nu_B = 2\nu_A$$

The frequency of beam *B* is twice that of *A*.

Q. 20. A monochromatic light source of power 5 mW emits 8×10^{15} photons per second. This light ejects photo electrons from a metal surface. The stopping potential for this set up is 2 eV. Calculate the work function of the metal. [*CBSE Sample Paper 2016*]

Ans. $P = 5 \times 10^{-3}$ W, $N = 8 \times 10^{15}$ photons per second

Energy of each photon,

$$E = \frac{P}{N} = \frac{5 \times 10^{-3}}{8 \times 10^{15}} = 6.25 \times 10^{-19} \text{J} = \frac{6.25 \times 10^{-19}}{1.6 \times 10^{-19}} \text{eV}$$

$E = 3.9$ eV

Work function, $W_0 = E - V_0$

$= (3.9 - 2)$ eV$=$ **1.9 eV**

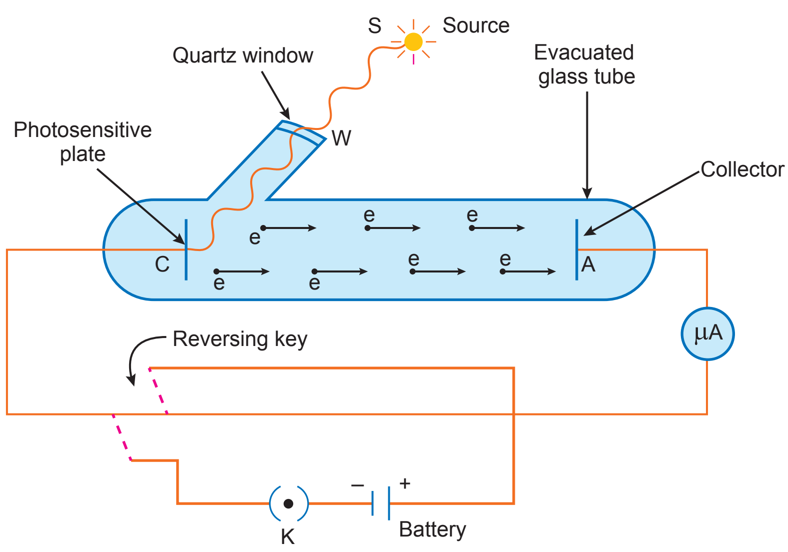
Long Answer Questions [5 marks]

Q. 1. Describe an experimental arrangement to study photoelectric effect. Explain the effect of (*i*) intensity of light on photoelectric current, (*ii*) potential on photoelectric current and (*iii*) frequency of incident radiation on stopping potential.

Ans. **Experimental study of Photoelectric Effect:** The apparatus consist of an evacuated glass or quartz tube which encloses a photosensitive plate *C* (called emitter) and a metal plate *A* (called collector).

A transparent window *W* is sealed on the glass tube which can be covered with a filter for a light of particular radiation. This will allow the light of particular wavelength to pass through it.

The plate *A* can be given a desired positive or negative potential with respect to plate *C*, using the arrangement as shown in figure.



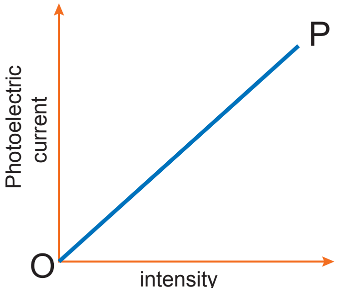
Working: When a monochromatic radiations of suitable frequency obtained from source *S* fall on the photosensitive plate *C*, the photoelectrons are emitted from *C*, which gets accelerated towards the plate *A* (collector) if it is kept at positive potential.

These electrons flow in the outer circuit resulting in the photoelectric current. Due to it, the microammeter shows a deflection. The reading of microammeter measures the photoelectric current.

This experimental arrangement can be used to study the variation of photoelectric current with the following quantities.

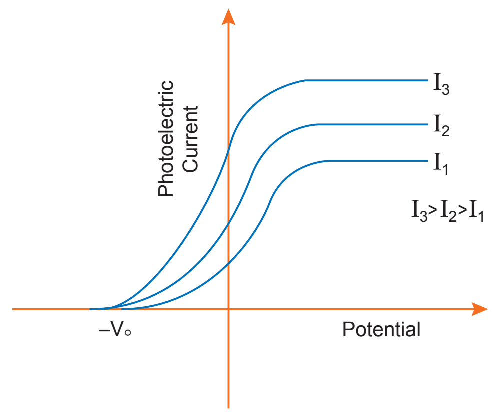
(*i*) **Effect of intensity of the incident radiation:** By varying the intensity of the incident radiations, keeping the frequency constant, it is found that the photoelectric current varies linearly with the intensity of the incident radiation.

Also, the number of photoelectrons emitted per second is directly proportional to the intensity of the incident radiations.



(ii) **Effect of potential of plate *A* w.r.t place *C*:** It is found that the photoelectric current increases gradually with the increase in positive potential of plate *A*.

At one stage for a certain positive potential of plate *A*, the photoelectric current becomes maximum or saturates. After this if we increase the positive potential of plate *A*, there will be no increase in the photoelectric current.



This maximum value of current is called saturation current: The saturation current corresponds to the state when all the photoelectrons emitted from *C* reach the plate *A*.

Now apply a negative potential on plate *A* w.r.t. plate *C*. We will note that the photoelectric current decreases, because the photoelectrons emitted from *C* are repelled and only energetic photoelectrons are reaching the plate *A*.

By increasing the negative potential of plate *A*, the photoelectric current decreases rapidly and becomes zero at a certain value of negative potential V_0 on plate *A*.

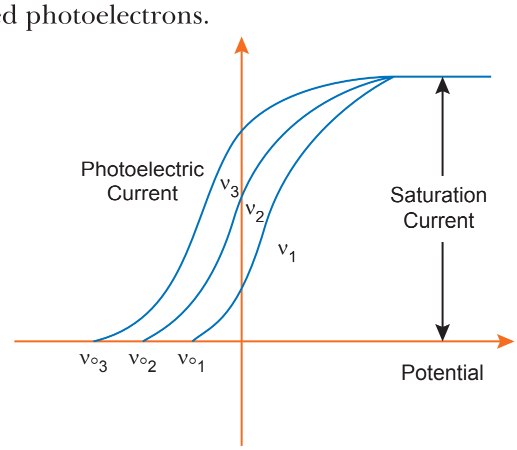
This maximum negative potential V_0, given to the plate *A* w.r.t. plate *C* at which the photoelectric current becomes zero is called stopping potential or cut off potential.

$$K_{max} = eV_0 = \frac{1}{2} m V_{max}^2$$

where e = charge on electron, m = mass of electrons

V_{max} = maximum velocity of emitted photoelectrons.

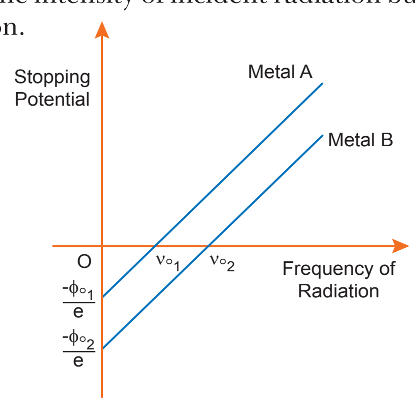
The value of stopping potential is independent of the intensity of the incident radiation. It means, the maximum kinetic energy of emitted photoelectrons depends on the radiation source and nature of material of plate *C* but is independent of the intensity of incident radiation.



(iii) **Effect of frequency of the incident radiation:** When we take the radiations of different frequencies but of same intensity, then the value of stopping potential is different for radiation of different frequency.

The value of stopping potential is more negative for radiation of higher incident frequency. The value of saturation current depends on the intensity of incident radiation but is independent of the frequency of the incident radiation.

(iv) **Effect of frequency on stopping potential:** For a given photosensitive material, the stopping potential varies linearly with the frequency of the incident radiation.



For every photosensitive material, there is a certain minimum cut off frequency ν_0 (threshold frequency) for which the stopping potential is zero.

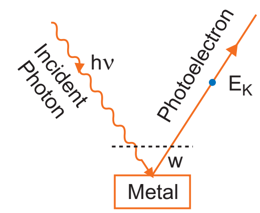
The intercept on the potential axis $= -\frac{\phi_0}{e} = -\frac{h\nu_0}{e}$.

Hence, work function $\phi_0 = e \times$ magnitude of intercept on the potential axis

Q. 2. Derive Einstein's photoelectric equation $\frac{1}{2}mv^2 = h\nu - h\nu_0$.

Ans. Einstein's Explanation of Photoelectric Effect: Einstein's Photoelectric Equation

Einstein explained photoelectric effect on the basis of quantum theory. The main points are



1. Light is propagated in the form of bundles of energy. Each bundle of energy is called a **quantum** or **photon** and has energy $h\nu$ where h = Planck's constant and ν = frequency of light.
2. The photoelectric effect is due to collision of a photon of incident light and a bound electron of the metallic cathode.
3. When a photon of incident light falls on the metallic surface, it is completely absorbed. Before being absorbed it penetrates through a distance of nearly 10^{-8} m (or 100 Å). The absorbed photon transfers its whole energy to a single electron. The energy of photon goes in two parts: a part of energy is used in releasing the electron from the metal surface (*i.e.*, in overcoming work function) and the remaining part appears in the form of kinetic energy of the same electron.

If ν be the frequency of incident light, the energy of photon = $h\nu$. If W be the work function of metal and E_K the maximum kinetic energy of photoelectron, then according to Einstein's explanation.

$$h\nu = W + E_K$$

or $$E_K = h\nu - W \quad ...(i)$$

This is called **Einstein's photoelectric equation.**

If ν_0 be the threshold frequency, then if frequency of incident light is less then ν_0 no electron will be emitted and if the frequency of incident light be ν_0 then $E_K = 0$; so from equation (*i*)

$$0 = h\nu_0 - W \quad \text{or} \quad W = h\nu_0$$

If λ_0 be the threshold wavelength, then $\nu_0 = \frac{c}{\lambda_0}$,

where c is the speed of light in vacuum

$\therefore$ Work function $$W = h\nu_0 = \frac{hc}{\lambda_0} \quad ...(ii)$$

Substituting this value in equation (*i*), we get

$$E_K = h\nu - h\nu_0 \quad \Rightarrow \quad \frac{1}{2}mv^2 = h\nu - h\nu_0 \quad ...(iii)$$

This is another form of Einstein's photoelectric equation.

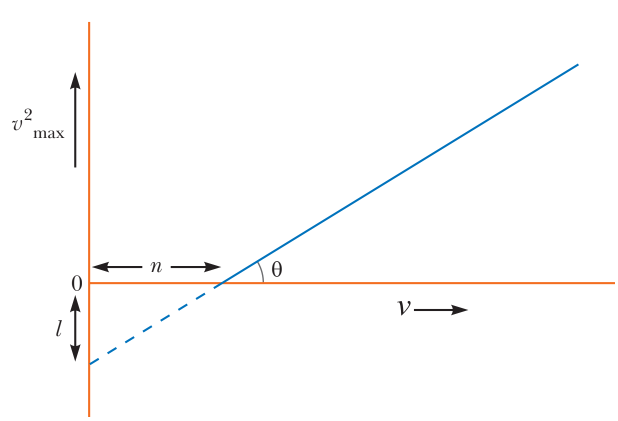
Q. 3. (*a*) Give a brief description of the basic elementary process involved in the photoelectric emission in Einstein's picture.

(*b*) When a photosensitive material is irradiated with the light of frequency ν, the maximum speed of electrons is given by v_{max}. A plot of v^2_{max} is found to vary with frequency ν as shown in the figure.

Use Einstein's photoelectric equation to find the expressions for

(*i*) Planck's constant and

(*ii*) work function of the given photosensitive material, in terms of the parameters *l*, *n* and mass *m* of the electron.



Ans. (*a*) Refer to Q. 2 above.

(*b*) (*i*) v_1^2 and v_2^2 are the velocities of the emitted electrons for radiations of frequencies $\nu_1 > \nu$ and $\nu_2 > \nu$ respectively. So,

$$h\nu_1 = h\nu + \frac{1}{2}mv_1^2 \quad \ldots(i)$$

and $$h\nu_2 = h\nu + \frac{1}{2}mv_2^2 \quad \ldots(ii)$$

From equation (*i*) and (*ii*), we get

$$h(\nu_2 - \nu_1) = \frac{1}{2}m(v_2^2 - v_1^2)$$

$$\therefore \quad h = \frac{\frac{1}{2}m(v_2^2 - v_1^2)}{(\nu_2 - \nu_1)}$$

Slope of v_{max}^2 vs frequency graph is

$$\tan\theta = \frac{v_2^2 - v_1^2}{(\nu_2 - \nu_1)}$$

$$\therefore \quad h = \frac{1}{2}m \cdot \tan\theta$$

From graph $\tan\theta = \frac{l}{n}$

So, $$h = \frac{1}{2}m\left(\frac{l}{n}\right) \quad \ldots(iii)$$

(*ii*) From graph, the work function of the material is

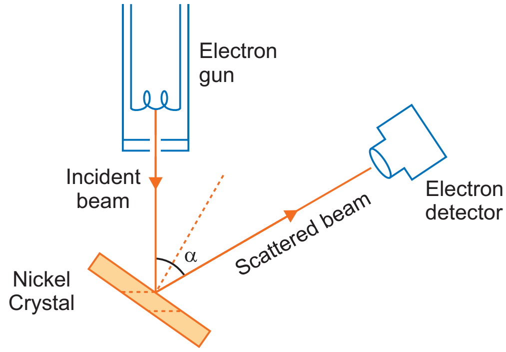
$$W = hn \quad \ldots(iv)$$

From equations (*iii*) and (*iv*), we get

$$W = \frac{1}{2}m\left(\frac{l}{n}\right) \times n = \frac{1}{2}ml$$

Q. 4. Describe Davisson and Germer's experiment to demonstrate the wave nature of electrons. Draw a labelled diagram of apparatus used. **[*CBSE (F) 2014*]**

Ans. **Davisson and Germer Experiment:** In 1927 Davisson and Germer performed a diffraction experiment with electron beam in analogy with *X*-ray diffraction to observe the wave nature of matter.



Apparatus: It consists of three parts:

(*i*) **Electron Gun:** It gives a fine beam of electrons. de Broglie used electron beam of energy 54 eV. de Broglie wavelength associated with this beam

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

Here m = mass of electron = 9.1×10^{-31} kg

E_K = Kinetic energy of electron = 54 eV

$= 54\times1.6\times10^{-19}$ joule $= 86.4\times10^{-19}$ joule

$$\therefore \quad \lambda = \frac{6.6\times10^{-34}}{\sqrt{2\times9.1\times10^{-31}\times86.4\times10^{-19}}}$$

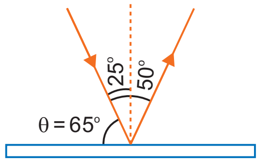
$= 1.66\times10^{-10}$ m = **1.66 Å**

(*ii*) **Nickel Crystal:** The electron beam was directed on nickel crystal against its (*iii*) face. The smallest separation between nickel atoms is 0.914 Å. Nickel crystal behaves as diffraction grating.

(*iii*) **Electron Detector:** It measures the intensity of electron beam diffracted from nickel crystal. It may be an ionisation chamber fitted with a sensitive galvanometer. The energy of electron beam, the angle of incidence of beam on nickel crystal and the position of detector can all be varied.

Method: The crystal is rotated in small steps to change the angle (α say) between incidence and scattered directions and the corresponding intensity (I) of scattered beam is measured. The variation of the intensity (I) of the scattered electrons with the angle of scattering α is obtained for different accelerating voltages.

The experiment was performed by varying the accelerating voltage from 44 V to 68 V. It was noticed that a strong peak appeared in the intensity (I) of the scattered electron for an accelerating voltage of 54 V at a scattering angle $\alpha = 50°$



$\therefore$ From Bragg's law

$$2d \sin \theta = n\lambda$$

Here $n = 1$, $d = 0.914$ Å, $\theta = 65°$

$$\therefore \qquad \lambda = \frac{2d \sin \theta}{n}$$

$$= \frac{2 \times (0.914 \text{ Å}) \sin 65°}{1}$$

$$= 2 \times 0.914 \times 0.9063 \text{ Å} = 1.65 \text{ Å}$$

The measured wavelength is in close agreement with the estimated de Broglie wavelength. Thus the wave nature of electron is verified. Later on G.P. Thomson demonstrated the wave nature of fast electrons. Due to their work Davission and G.P. Thomson were awarded Nobel prize in 1937.

Later on experiments showed that ***not only electrons but all material particles in motion (e.g., neutrons, α-particles, protons etc.) show wave nature.***

Self-Assessment Test

Time allowed: 1 hour **Max. marks: 30**

1. Choose and write the correct option in the following questions. **(3 × 1 = 3)**

(*i*) Photoelectric emission occurs only when the incident light has more than a certain minimum

(*a*) power (*b*) wavelength

(*c*) intensity (*d*) frequency

(*ii*) The threshold frequency for a photosensitive metal is 3.3×10^{14} Hz. If light of frequency 8.2×10^{14} Hz is incident on this metal, the cut-off voltage for the photoelectron emission is nearly

(*a*) 1 V (*b*) 2 V

(*c*) 3 V (*d*) 5 V

(*iii*) When the light of frequency $2\nu_0$ (where ν_0 is threshold frequency), is incident on a metal plate, the maximum velocity of electrons emitted is v_1. When the frequency of the incident radiation is increased to $5\nu_0$, the maximum velocity of electrons emitted from the same plate is v_2. The ratio of v_1 to v_2 is

(*a*) 1 : 2 (*b*) 1 : 4

(*c*) 4 : 1 (*d*) 2 : 1

2. Fill in the blanks. **(2 × 1 = 2)**

(*i*) The maximum kinetic energy of emitted photoelectrons is independent of ______________ of incident radiation.

(*ii*) The expression for de Broglie wavelength of an electron moving under a potential difference of V volts is ______________.

3. Plot a graph of the de-Broglie wavelength associated with a proton versus its momentum. **1**

4. Draw graphs showing variation of photoelectric current with applied voltage for two incident radiations of equal frequency and different intensities. Mark the graph for the radiation of higher intensity. **1**

5. Show on a graph variation of the de Broglie wavelength (λ) associated with the electron versus $1/\sqrt{V}$, where V is the accelerating potential for the electron. **1**

6. A deuteron and an alpha particle are accelerated with the same accelerating potential. Which one of the two has

(*a*) greater value of de Broglie wavelength, associated with it? and

(*b*) less kinetic energy? Explain. **2**

7. The work function of caesium is 2.14 eV. Find (*i*) the threshold frequency for caesium and (*ii*) wavelength of incident light if the photocurrent is brought to zero by a stopping potential of 0.60 V. **2**

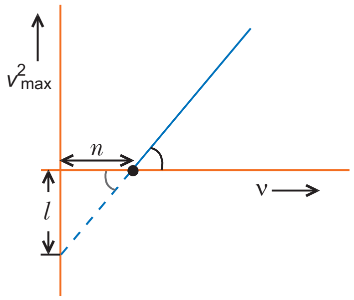
8. Light of wavelength 2500 Å falls on a metal surface of work function 3.5 V. What is the kinetic energy (in eV) of (*i*) the fastest and (*ii*) the slowest electronic emitted from the surface?

If the same light falls on another surface of work function 5.5 eV, what will be the energy of emitted electrons? **2**

9. Plot a graph showing variation of de Broglie wavelength (λ) associated with a charged particle of mass m, versus $1/\sqrt{V}$, where V is the potential difference through which the particle is accelerated. How does this graph give us the information regarding the magnitude of the charge of the particle? **2**

10. Deduce de Broglie wavelength of electrons accelerated by a potential of V volt. Draw a schematic diagram of a localized wave describing the wave nature of moving electron. **3**

11. When a given photosensitive material is irradiated with light of frequency ν, the maximum speed of the emitted photoelectrons equals v_{max}. The graph shown in the figure gives a plot of v^2_{max} varying with frequency ν.



Obtain an expression for

(*a*) Planck's constant, and

(*b*) The work function of the given photosensitive material in terms of the parameters 'l', 'n' and the mass 'm' of the electron.

(*c*) How is threshold frequency determined from the plot? **3**

12. Light of wavelength 2000 Å falls on a metal surface of work functions 4.2 eV. What is the kinetic energy (in eV) of the fastest electrons emitted from the surface?

(*i*) What will be the change in the energy of the emitted electrons if the intensity of light with same wavelength is doubled?

(*ii*) If the same light falls on another surface of work functions 6.5 eV, what will be the energy of emitted electrons? **3**

13. Draw graphs showing the variation of photoelectric current with anode potential of a photocell for (*i*) same frequency but different intensities $I_1 > I_2 > I_3$ of incident radiation. (*ii*) same intensity but different frequency $\upsilon_1 > \upsilon_2 > \upsilon_3$ of incident radiation. Explain why the saturation current is independent of the anode potential for incident radiation of different frequencies but same intensity. **5**

Answers

1. (*i*) (*d*) (*ii*) (*b*) (*iii*) (*a*)

2. (*i*) intensity (*ii*) $\lambda = \frac{12.27}{\sqrt{V}}$ Å

7. (*i*) 5. 187 × 10^{14} Hz, (*ii*) 4536 Å