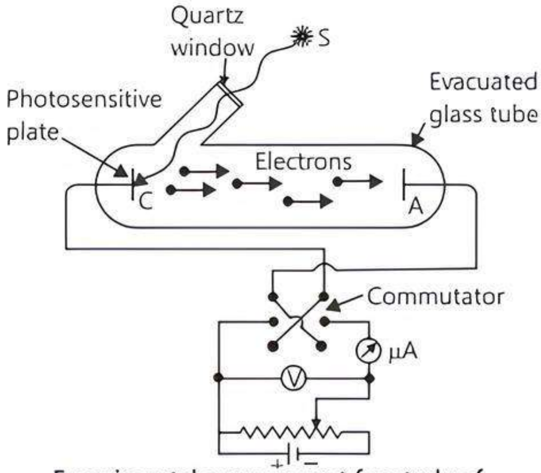
11 Dual Nature of Radiation and Matter

Fastrack Revision

- **Electron Emission:** The process of emission of electrons from the metal surface when a certain amount of energy is absorbed by the metal, is called electron emission.
  A certain minimum amount of energy is required to be given to an electron to pull it out from the surface of the metal, termed as work function.
- **Work Function:** The minimum amount of energy required by an electron to just escape from the metal surface is known as work function of the metal.
  It is denoted by W or ϕ_0.
  Work function $W = \phi_0 = h\nu_0$
  It is measured in eV (electron volt)
  $$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$
  $\phi_0 = 5.65$ eV is highest for platinum, while $\phi_0 = 2.14$ eV is lowest for Caesium.
  The work function energy can be supplied to the free electrons by any of the following physical processes:
- **Observation of Photoelectric Effect**
  - **Thermionic Emission:** Electrons are emitted from the metal surface with the help of sufficient thermal energy.
  - **Field or Cold Cathode Emission:** Electrons are emitted from a metal surface by subjecting it to a very high electric field.
  - **Photoelectric Emission:** Electrons are emitted from a metal surface with the help of suitable electromagnetic radiations.
- **Photoelectric Effect:** The phenomenon of emission of electrons from the surface of substances (mainly metals), when exposed to electromagnetic radiations of suitable frequency, is called photoelectric effect and the emitted electrons are called photoelectrons.
  - **Hertz's Observations:** In experimental investigation on the production of electromagnetic waves by means of a spark discharge, Hertz (1857-1894) observed that high voltage sparks across the detector loop were enhanced when the emitter plate was illuminated by ultraviolet light from an arc lamp.
  - **Lenard's Observations:** Lenard (1862-1947) observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube enclosing two electrodes (metal plates), current flows in the circuit. As soon as the ultraviolet radiations were stopped, the current flow also stopped.
- **Experimental Study of Photoelectric Effect:** The figure given below shows a schematic view of the arrangement used for the experimental study of the photoelectric effect.



Experimental arrangement for study of photoelectric effect.

This experimental arrangement is used to study the variation of photocurrent with intensity of radiation, frequency of incident radiation, potential difference between the plates A and C and the nature of the materials of plate C.

- **Effect of Intensity of Light on Photocurrent:** The number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation.
- **Effect of Potential on Photoelectric Current:** For a fixed frequency and intensity of incident light, the photoelectric current increases with increase in the potential applied to collector plate.
- **Saturation Current:** The maximum value of the photoelectric current is called saturation current.
- **Cut-off or Stopping Potential:** The value of the retarding potential at which the photoelectric current becomes zero is called cut-off or stopping potential for the given frequency of the incident radiation.
  Photoelectric current is zero when the stopping potential is sufficient to repel even the most energetic photoelectrons, with the maximum kinetic energy (K_{max}), so that
  $$K_{max} = eV_0$$
- **Effect of Frequency of Incident Radiation on Stopping Potential:** The stopping potential varies linearly with the frequency of incident radiation for a given photosensitive material and exists a certain minimum cut-off frequency for which the stopping potential is zero.
- **Threshold Frequency:** The minimum value of the frequency of incident radiation below which the photoelectric emission stops altogether is called threshold frequency.

- **Laws of Photoelectric Effect**
  - For a given metal and a radiation of fixed frequency, the number of photoelectrons emitted is proportional to the intensity of incident radiation.
  - For every metal, there is a certain minimum frequency below which no photoelectrons are emitted, however high is the intensity of incident radiation. This frequency is called threshold frequency.
  - For the radiation of frequency higher than the threshold frequency, the maximum kinetic energy of the photoelectrons is directly proportional to the frequency of incident radiation and is independent of the intensity of incident radiation.
  - The photoelectric emission is an instantaneous process.
- **Einstein's Theory of Photoelectric Effect:**
  - Einstein explained photoelectric effect with the help of Planck's quantum theory.
  - When a radiation of frequency ν is incident on a metal surface, it is absorbed in the form of discrete packets of energy called quanta or photons.
  - A part of energy $h\nu$ of the photon is used in removing the electrons from the metal surface and remaining energy is used in giving kinetic energy to the photoelectron.
  - Einstein's photoelectric equation is,

$$K_{max} = h\nu - \phi_0$$

    where, ϕ_0 is the work function of the metal.

    If ν_0 is the threshold frequency, then

$$K_{max} = h(\nu - \nu_0)$$

  - All the experimental observations can be explained on the basis of Einstein's photoelectric equation.
- **Photocell:** It is an arrangement which converts light energy into electric energy. It works on the principle of photoelectric effect. It is used in cinematography for the reproduction of sound.
- **Particle Nature of Light:** Photoelectric effect gave evidence that light consists of packets of energy. These packets of energy are called light quantum that are associated with particles named as photons. Thus photons confirm the particle nature of light.

  Energy of photon, $E = h\nu = \dfrac{hc}{\lambda}$

  and momentum, $p = \dfrac{h\nu}{c} = \dfrac{h}{\lambda}$

  Photons are electrically neutral and are not deflected by electric and magnetic fields.
- **Dual Nature of Radiation:** Light has dual nature. It manifests itself as a wave in diffraction, interference, polarisation, etc., while it shows particle nature in photoelectric effect, compton scattering, etc.
- **Dual Nature of Matter**
  - As there is complete equivalence between matter (mass) and radiation (energy) and the principle of symmetry is always obeyed, de-Broglie suggested that moving particles like protons, neutrons, electrons, etc., should be associated with waves known as de-Broglie waves and their wavelength (λ) is called de-Broglie wavelength.
  - The de-Broglie proposed that the wavelength λ associated with a particle of momentum p is given as,

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

  where, h is Planck's constant, m is the mass of particle and v its velocity.

  The above relation is called de-Broglie relation.
- **de-Broglie Wavelength of an Electron:** The wavelength associated with an electron beam accelerated through a potential,

$$\lambda = \frac{h}{\sqrt{2meV}} = \frac{12.27}{\sqrt{V}} \text{Å}$$

  where, V is the magnitude of accelerating potential.

  de-Broglie wavelength associated with the photon given by momentum p is,

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

Practice Exercise

Multiple Choice Questions

Q 1. The minimum energy required for the electron emission from the metal surface can be supplied to the free electrons by which of the following physical process?

a. Thermionic emission
b. Field emission
c. Photoelectric emission
d. All of these

Q 2. A metal surface ejects electrons when hit by green light but none when hit by yellow light. The electrons will be ejected when the surface is hit by:

a. blue light
b. heat rays
c. infrared light
d. red light

Q 3. The practical application of the phenomenon of photoelectric effect and the concept of 'matter waves' is in:

a. photocells
b. automatic doors at shops and malls
c. automatic light switches
d. All of the above

Q 4. In an experiment on photoelectric effect, the intensity of incident radiation is increased, keeping the frequency ν the same. The number of photoelectrons emitted will: *(CBSE 2023)*

a. increase
b. decrease
c. remain same
d. depend on frequency

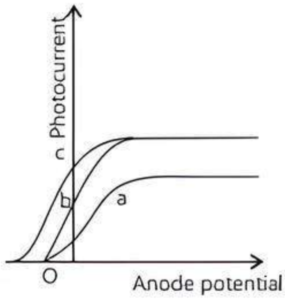
Q 5. In photoelectric effect, the photocurrent:

a. depends both on intensity and frequency of the incident light.
b. does not depend on the frequency of incident light but depends on the intensity of the incident light.
c. decreases with increase in frequency of incident light.
d. increases with increase in frequency of incident light.

Q 6. The maximum value of photoelectric current is called:

a. base current
b. saturation current
c. collector current
d. emitter current

Q 7. The figure shows the variation of photocurrent with anode potential for a photo-sensitive surface for three different radiations. Let I_a, I_b and I_c be the intensities and ν_a, ν_b and ν_c be the frequencies for the curves *a*, *b* and *c* respectively. Then:



a. $\nu_a = \nu_b$ and $I_a \neq I_b$
b. $\nu_a = \nu_c$ and $I_a = I_c$
c. $\nu_a = \nu_b$ and $I_a = I_b$
d. $\nu_a = \nu_c$ and $I_b = I_c$

Q 8. Light of wavelength 0.6 nm from a sodium lamp falls on a photocell and causes the emission of photoelectrons for which the stopping potential is 0.5 V. With light of wavelength 0.4 mm from a sodium lamp, the stopping potential is 1.5 V. With this data, the value of h/e is:

a. 4×10^{-59} Vs
b. 0.25×10^{15} Vs
c. 4×10^{-15} Vs
d. 4×10^{-8} Vs

Q 9. A metallic plate exposed to white light emits electrons. For which of the following colours of light, the stopping potential will be maximum? *(CBSE SQP 2023-24)*

a. Blue
b. Yellow
c. Red
d. Violet

Q 10. The threshold frequency of a certain metal is 3.3×10^{14} Hz. If light of frequency 8.2×10^{14} Hz (Given, $h = 6.63 \times 10^{-34}$ Js) is incident on the metal, then the cut-off voltage for photoelectric emission is:

a. 2V b. 4V c. 6V d. 8V

Q 11. *A* and *B* are two metals with threshold frequencies 1.8×10^{14} Hz and 2.2×10^{14} Hz. Two identical photons of energy 0.825 eV each are incident on them. Then photoelectrons are emitted in (Take $h = 6.6 \times 10^{-34}$ J s):

a. B alone
b. A alone
c. Neither A nor B
d. Both A and B

Q 12. Photons of energies 1 eV and 2 eV are successively incident on a metallic surface of work function 0.5 eV. The ratio of kinetic energy of most energetic photoelectrons in the two cases will be: *(CBSE 2020)*

a. 1 : 2 b. 1 : 1 c. 1 : 3 d. 1 : 4

Q 13. The monochromatic beams *A* and *B* of equal intensities *I*, hit a screen. The number of photons hit on the screen by beam *A* is twice that by beam *B*. The ratio of their frequencies will be:

a. 1 : 2 b. 2 : 1 c. 1 : 1 d. 1 : 3

Q 14. Which of the following has maximum stopping potential when metal is illuminated by visible light?

a. Blue
b. Yellow
c. Violet
d. Red

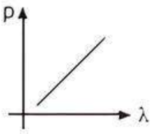
Q 15. When radiation of given frequency is incident upon different metals, the maximum kinetic energy of electrons emitted:

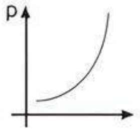
a. decrease with increase of work function
b. increase with increase of work function
c. remains same with the increase of work function
d. does not depend upon work function

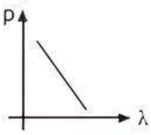
Q 16. *E*, *c* and ν represent the energy, velocity and frequency of a photon. Which of the following represents it wavelength? *(CBSE 2023)*

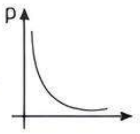
a. $\frac{h\nu}{c^2}$ b. $h\nu$ c. $\frac{hc}{E}$ d. $\frac{h\nu}{c}$

Q 17. Which of the following graphs correctly represents the variation of a particle momentum with its associated de-Broglie wavelength?: *(CBSE 2023)*

a.


b.


c.


d.


Q 18. A proton, a neutron, an electron and an alpha particle have same kinetic energy, then their de-Broglie wavelengths compare as:

a. $\lambda_e = \lambda_p = \lambda_n = \lambda_\alpha$
b. $\lambda_e > \lambda_p = \lambda_n > \lambda_\alpha$
c. $\lambda_\alpha < \lambda_p = \lambda_n < \lambda_e$
d. $\lambda_p = \lambda_n$ and $\lambda_e = \lambda_\alpha$

Q 19. If E_1, E_2, E_3, E_4 are the respective kinetic energies of electron, deuteron, proton and neutron having same de-Broglie wavelength. Select the correct order in which those values would increase:

a. E_1, E_3, E_4, E_2
b. E_2, E_4, E_1, E_3
c. E_2, E_4, E_3, E_1
d. E_3, E_1, E_2, E_4

Q 20. Light of frequency 6.4×10^{14} Hz is incident on a metal of work function 2.14 eV. The maximum kinetic energy of the emitted electrons is about: *(CBSE 2023)*

a. 0.25 eV b. 0.51 eV c. 1.02 eV d. 0.10 eV

Q 21. Consider the four gases hydrogen, oxygen, nitrogen and helium at the same temperature. Arrange them in the increasing order of the de-Broglie wavelengths of their molecules.

a. Hydrogen, helium, nitrogen, oxygen
b. Oxygen, nitrogen, hydrogen, helium
c. Oxygen, nitrogen, helium, hydrogen
d. Nitrogen, oxygen, helium, hydrogen

Q 22. The work function for a metal surface is 4.14 eV. The threshold wavelength for this metal surface is: *(CBSE SQP 2022-23)*

a. 4125 Å b. 2062.5 Å c. 3000 Å d. 6000 Å

Assertion & Reason Type Questions

Directions (Q.Nos. 23-32): *In the following questions, a statement of Assertion (A) is followed by a statement of Reason (R). Mark the correct choice as:*

a. Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
b. Both Assertion (A) and Reason (R) are true but Reason (R) is not the correct explanation of Assertion (A).
c. Assertion (A) is true but Reason (R) is false.
d. Both Assertion (A) and Reason (R) are false.

Q 23. **Assertion (A): For the radiation of a frequency greater than the threshold frequency, photoelectric current is proportional to the intensity of the radiation.**

Reason (R): Greater the number of energy quanta available, greater is the number of electrons absorbing the energy quanta and greater is number of electrons coming out of the metal.

(CBSE SQP 2023-24)

Q 24. **Assertion (A): Photoelectric effect demonstrates the wave nature of light.**

Reason (R): The number of photoelectrons is proportional to the frequency of light.

Q 25. **Assertion (A): The The photoelectrons produced by a monochromatic light beam incident on a metal surface have a spread in their kinetic energies.**

Reason (R) : The energy of electrons emitted from inside the metal surface, is lost in collision with the other atoms in the metal. *(CBSE SQP 2022-23)*

Q 26. **Assertion (A): Photosensitivity of a metal is high if its work function is small.**

Reason (R): Work function = $h\nu_0$ where ν_0 is the threshold frequency.

Q 27. **Assertion (A): Light is produced in gases in the process of electric discharge through them at high pressure.**

Reason (R): At high pressure electrons collide with gaseous atoms and reach at excited state.

Q 28. **Assertion (A): Kinetic energy of photoelectrons emitted by a photosensitive surface depends upon the intensity of incident photon.**

Reason (R): The ejection of electrons from metallic surface is possible with frequency of incident photon below the threshold frequency.

Q 29. **Assertion (A): The specific charge of positive rays is not constant.**

Reason (R): The mass of ions varies with speed.

Q 30. **Assertion (A): When the speed of an electron increases its specific charge decreases.**

Reason (R): Specific charge is the ratio of the charge to mass.

Q 31. **Assertion (A): Mass of moving photon varies inversely as the wavelength.**

Reason (R): Energy of the particle = Mass × (speed of light)^2.

Q 32. **Assertion (A): The de-Broglie wavelength of a molecule varies inversely as the square root of temperature.**

Reason (R): The root mean square velocity of the molecule depends on the temperature.

Fill in the Blanks Type Questions

Q 33. **The minimum energy required by a free electron to just escape from the metal surface is called as ....**

Q 34. **The minimum frequency required to eject an electron from the surface of a metal surface is called .... frequency.**

Q 35. **The velocity of photon in different media is ....**

Q 36. **The maximum kinetic energy of emitted photoelectrons depends on the .... of incident radiation and the nature of material.**

Q 37. **The maximum kinetic energy of emitted photoelectrons is independent of .... of incident radiation.**

Q 38. **Photon is not a material particle but it is a packet of ....**

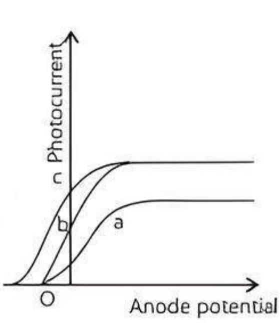
Q 39. **The expression for de-Broglie wavelength of an electron moving under a potential difference of V volts is ....**

Answers

1. (d) All of these
2. (a) blue light

   The photoelectric emission is possible if the wavelength of the incident light is less than that of yellow light.
3. (d) All of the above
4. (a) increase
5. (b) does not depend on the frequency of incident light but depends on the intensity of the incident light.
6. (b) saturation current
7. (a) $\nu_a = \nu_b$ and $I_a \neq I_b$

   From the graph, we note that the saturation current is same for curves *b* and *c* but different for curve *a*. Therefore, intensities of *b* and *c* will be equal but different from that of *a* i.e., $I_a \neq I_b$ but $I_b = I_c$. As stopping potential is same for curves *a* and *b*, hence $\nu_a = \nu_b$.



8. (c) 4×10^{-15} Vs

Here, $eV = \frac{hc}{\lambda} - W$

$$\therefore\ 0.5e = \frac{hc}{6 \times 10^{-7}} - W \Rightarrow 0.5 = \frac{h}{e}\left(\frac{c}{6 \times 10^{-7}}\right) - \frac{W}{e} \quad ...(1)$$

$$\text{Similarly, } 1.5 = \frac{h}{e}\left(\frac{c}{4 \times 10^{-7}}\right) - \frac{W}{e} \quad ...(2)$$

From eqs. (1) and (2),

$$1 = \frac{h}{e}\frac{c}{10^{-7}}\left[\frac{1}{4} - \frac{1}{6}\right] \Rightarrow \frac{h}{e} = \frac{12 \times 10^{-7}}{3 \times 10^{9}} = 4 \times 10^{-15}\ \text{Vs}$$

9. (d) Violet

10. (a) 2V

Given threshold frequency, $\nu_0 = 3.3 \times 10^{14}$ Hz

Frequency of incident light, $\nu = 8.2 \times 10^{14}$ Hz

As $eV_0 = h(\nu - \nu_0)$ or $V_0 = \frac{h(\nu - \nu_0)}{e}$

$$V_0 = \frac{6.63 \times 10^{-34}\ (8.2 \times 10^{14} - 3.3 \times 10^{14})}{1.6 \times 10^{-19}} = 2\ \text{V}$$

11. (b) A alone

Work function for metal A, $\phi_{0A} = \frac{h\nu_0}{e}$ eV

$$= \frac{(6.6 \times 10^{-34}) \times (1.8 \times 10^{14})}{1.6 \times 10^{-19}}\ \text{eV} = 0.74\ \text{eV}$$

and work function for metal B,

$$\phi_{0B} = \frac{(6.6 \times 10^{-34}) \times (2.2 \times 10^{14})}{1.6 \times 10^{-19}}\ \text{eV} = 0.91\ \text{eV}$$

Since the incident energy 0.825 eV is greater than 0.74 eV and less than 0.91 eV, so photoelectrons are emitted from metal A only.

12. (c) 1 : 3

Ratio of kinetic energy,

$$\frac{KE_1}{KE_2} = \frac{h\nu_1 - \phi_0}{h\nu_2 - \phi_0}$$

$$= \frac{1 - 0.5}{2 - 0.5} = \frac{0.5}{1.5} = \frac{1}{3} = 1:3$$

13. (a) 1 : 2

Let n_A, n_B are number of photons falling per second of beam A and B respectively.

$\therefore$ Energy of falling photon of beam $A = h\nu_A$

Energy of falling photon of beam $B = h\nu_B$

According to the question,

intensity of A = intensity of B

$$n_A h\nu_A = n_B h\nu_B$$

$$\frac{\nu_A}{\nu_B} = \frac{n_B}{n_A} = \frac{n_B}{2n_B} = \frac{1}{2}$$

Hence, $\nu_A : \nu_B = 1 : 2$

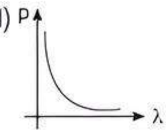
14. (c) Violet

$KE_{max} = h\nu - \phi_0 \Rightarrow KE_{max}$ is maximum for violet.

15. (a) decrease with increase of work function because $KE_{max} = h\nu - \phi_0$.

16. (d) $\frac{h\nu}{c}$

17. (d)



The linear momentum of a photon is inversely proportional to the de-Broglie wavelength. So the graph of p and λ shall be a rectangular hyperbola.

18. (c) $\lambda_e > \lambda_p = \lambda_n > \lambda_\alpha$

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

For the given value of K, $\lambda \propto \frac{1}{\sqrt{m}}$

$$\therefore\ \lambda_p : \lambda_n : \lambda_e : \lambda_\alpha = \frac{1}{\sqrt{m_p}} : \frac{1}{\sqrt{m_n}} : \frac{1}{\sqrt{m_e}} : \frac{1}{\sqrt{m_\alpha}}$$

Since $m_p = m_n$, hence $\lambda_p = \lambda_n$

As $m_\alpha > m_p$, therefore $\lambda_\alpha < \lambda_p$

As $m_e < m_n$, therefore $\lambda_n < \lambda_e$

Hence $\lambda_\alpha < \lambda_p = \lambda_n < \lambda_e$

19. (c) E_2, E_4, E_3, E_1

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

$$\therefore\ m \propto \frac{1}{K}$$

Since $m_e < m_p < m_n < m_D$

Thus, $KE_1 > KE_3 > KE_4 > KE_2$

$\therefore\ E_1 < E_3 < E_4 < E_2$

$\therefore$ Increasing order $= E_2$; E_4, E_3, E_1

20. (b) 0.51 eV

Given that,

Work function, $\phi_0 = 2.14$ eV

Frequency of light $\nu = 6.4 \times 10^{14}$ Hz

Maximum KE is given by the photoelectric effect.

$$K = h\nu - \phi_0$$

$$K = \left(\frac{6.626 \times 10^{-34} \times 6.4 \times 10^{14}}{1.6 \times 10^{-19}}\right) - 2.14$$

$$= 0.51\ \text{eV.}$$

21. (c) Oxygen, nitrogen, helium, hydrogen

de-Broglie wavelength of a gas molecule, $\lambda = \frac{h}{\sqrt{3mk_BT}}$

where, T = Absolute temperature,

k_B = Boltzmann's constant

and m = Mass of gas molecule

For the same temperature $\lambda \propto \frac{1}{\sqrt{m}}$

As $m_{O_2} > m_{N_2} > m_{He} > m_{H_2}$

$\therefore\ \lambda_{O_2} < \lambda_{N_2} < \lambda_{He} < \lambda_{H_2}$

22. (c) 3000Å

Work function for a metal surface, $W = \frac{hc}{\lambda_0}$

where, λ_0 = threshold wavelength for a metal surface.

Given: $W = 4.14$ eV

$= 4.14 \times 1.6 \times 10^{-19}$ Joule

$\therefore \quad \lambda_0 = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{4.14 \times 1.6 \times 10^{-19}}$

[$\because h = 6.6 \times 10^{-34}$ Joule-hertz^{-1} and $c = 3 \times 10^8$ m/s]

$= 3000$ Å

23. (a) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).

24. (d) Photoelectric effect demonstrates the particle nature of light. Number of emitted photoelectrons depends upon the intensity of light.

25. (a) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).

26. (b) Less work function means less energy is required for ejecting out the electrons.

27. (d) Light is produced in gases in the process of electric discharge at low pressure. When accelerated electrons collide with atoms of the gas, atoms get excited. The excited atoms return to their normal state and in this process light radiations are emitted.

28. (d) According to Einstein equation $KE = h\nu - h\nu_0$; *i.e.*, KE depends upon the frequency. Photoelectron emitted only if incident frequency is more than threshold frequency.

29. (b) The specific charge (e/m) of the positive rays is not universal constant because these rays may consist of ions of different elements.

30. (b) Charge does not change with speed but mass varies with the speed as per relation $m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$.

Hence, specific charge e/m $\left(\frac{\text{electron}}{\text{mass}}\right)$ decreases with increase in speed.

31. (b) Mass of moving photon,

$$m = \frac{h\nu}{c^2} = \frac{h}{c\lambda}$$

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

According to Einstein's mass-energy equivalence, $E = mc^2$

32. (a) de-Broglie wavelength associated with gas molecules varies as $\lambda \propto \frac{1}{\sqrt{T}}$.

33. work function 34. threshold 35. different

36. frequency 37. intensity 38. energy

39. $\lambda = \frac{12.27}{\sqrt{V}}$ Å

Case Study Based Questions

Case Study 1

The discovery of the phenomenon of photoelectric effect has been one of the most important discoveries in modern science. The experimental observations associated with this phenomenon made us realise that our, 'till then', widely accepted picture of the nature of light. The electromagnetic (wave) theory of light—was quite inadequate to understand this phenomenon. A 'new picture' of light was needed and it was provided by Einstein through his 'photon theory' of light. This theory, regarded light as a stream of particles. Attempts to understand photoelectric effect thus led us to realise that light, which was being regarded as 'waves', could also behave like 'particles'. This led to the idea of 'wave-particle duality' *vis-à-vis* the nature of light. Attempts to understand this 'duality' and related phenomenon, led to far reaching and very important developments, in the basic theories of Physics.

Read the given passage carefully and give the answer of the following questions:

Q 1. Which of the following phenomenon explain the wave nature of light?

a. Interference b. Diffraction

c. Polarisation d. All of these

Q 2. Wave-particle duality is shown by:

a. light only b. matter only

c. Both a. and b. d. None of these

Q 3. The experiment to explain the wave nature of light *i.e.*, electromagnetic wave theory is given by:

a. Hertz b. Einstein

c. Lenard d. Huygens'

Q 4. The concept of photoelectric effect given by Einstein explains that the light is a:

a. photon b. wave

c. particle d. Both b. and c.

Answers

1. (d) All of these 2. (c) Both a. and b.

3. (a) Hertz 4. (c) particle

Case Study 2

Lenard observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube, enclosing two electrodes (metal plates), current started flowing in the circuit connecting the plates. As soon as the ultraviolet radiations were stopped, the current flow also stopped. These observations proved that it was ultraviolet radiation, falling on the emitter plate, that ejected some charged particles from the emitter and the positive plate attracted them.

Read the given passage carefully and give the answer of the following questions:

Q 1. Why do we not observe the phenomenon of photoelectric effect with non-metals?

a. For non-metals the work function is high
b. Work function is low
c. Work function can not be calculated
d. For non-metals, threshold frequency is low

Q 2. What is the effect of intensity on photoelectric current?

a. It increases
b. It decreases
c. There is no change
d. It varies with the square of intensity

Q 3. Name one factor on which the stopping potential depends.

a. Work function
b. Frequency
c. Current
d. Energy of photon

Q 4. How does the maximum KE of the electrons emitted vary with the work function of metal?

a. It doesn't depend on work function
b. It decreases as the work function increases
c. It increases as the work function increases
d. Its value is doubled with the work function

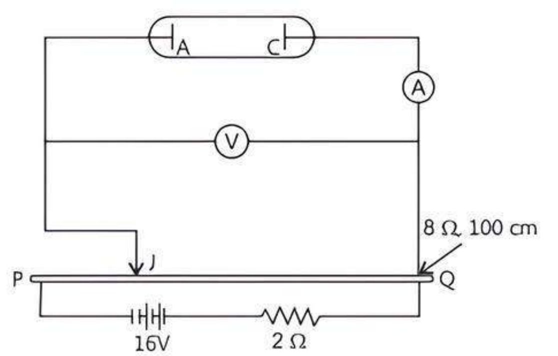
Answers

1. (a) For non-metals the work function is high
2. (a) It increases
3. (b) Frequency
4. (b) It decreases as the work function increases

Case Study 3

An experimental setup of verification of photoelectric effect is shown in figure. The voltage across the electrodes is measured with the help of an ideal voltmeter and which can be varied by moving jockey J on the potentiometer wire. The battery used in potentiometer circuit is of 16V and its internal resistance is 2 Ω.

The resistance of 100 cm long potentiometer wire is 8 Ω.



The photocurrent is measured with the help of an ideal ammeter. Two places of potassium oxide of area 50 cm^2 at separation 0.5 mm are used in the vacuum tube. Photocurrent in the circuit is very small, so we can treat the potentiometer circuit as an independent circuit.

The wavelength for different colours of light are tabulated as:

Light	λ (in Å)
Violet	4000-4500
Blue	4500-5000
Green	5000-5500
Yellow	5500-6000
Orange	6000-6500
Red	6500-7000

Read the given passage carefully and give the answer of the following questions:

Q 1. When radiation falls on the cathode plate, a current of 2μA is recorded in the ammeter. Assuming that the vacuum tube setup follows Ohm's law, then what is the equivalent resistance of vacuum tube operating in the case when jockey is at end *P*?

Q 2. It is found that ammeter current remains unchanged (2 μA) even when the jockey is moved from the end *P* to the middle point of the potentiometer wire. Assuming that all the incident photons eject electrons and the power of the light incident is 4×10^{-6} W. Then what is the colour of the incident light?

Q 3. Which colour may not give photoelectric effect for this cathode?

Q 4. When other light falls on the anode plate, the ammeter reading is zero till jockey is moved from the end *P* to the middle point of the wire *PQ*. Therefore, the deflection is recorded in the ammeter. What is the maximum kinetic energy of the emitted electron?

Answers

1. Equivalent resistance, $R = \frac{V}{I} = \frac{16}{2 \times 10^{-6}}$

$$= 8 \times 10^6\ \Omega = 8\ \text{M}\Omega$$

2. Since $P = \frac{Ihc}{\lambda e}$

$$\therefore \quad \lambda = \frac{(2 \times 10^{-6})(6.6 \times 10^{-34})(3 \times 10^8)}{(4 \times 10^{-6})(1.6 \times 10^{-19})}$$

$$= \frac{9.9}{1.6} \times 10^{-7}\ \text{m} = \frac{9900}{1.6}\ \text{Å} = 6187\ \text{Å}$$

Which is in the range of orange light.

3. The range of wavelength for red light is beyond the wavelength of incident light.
4. Stopping potential, $V_s = 8$V

and $\quad KE_{max} = eV_s$

$\therefore \quad KE_{max} = 8$ eV

Case Study 4

According to Einstein, when a photon of light of frequency ν and wavelength λ is incident on a photosensitive metal surface of work function ϕ_0, where $\phi_0 < h\nu$ (here, h is Planck's constant), then the emission of photoelectrons takes place.

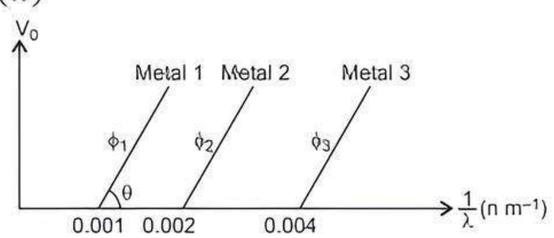
The maximum kinetic energy of the emitted photoelectrons is given by $K_{max} = h\nu - \phi_0$. If the frequency of the incident light is ν_0 called threshold frequency, the photoelectrons are emitted from metal without any kinetic energy. So, $h\nu_0 = \phi_0$.

Read the given passage carefully and give the answer of the following questions:

Q 1. A metal of work function 3.3 eV is illuminated by light of wavelength 300 nm. What is the maximum kinetic energy of photoelectrons emitted (taking $h = 6.6 \times 10^{-34}$ Js)?

Q 2. Show the variation of maximum kinetic energy (K_{max}) of the emitted photoelectrons with frequency (ν) of the incident radiations.

Q 3. The graph between the stopping potential (V_0) and $\left(\frac{1}{\lambda}\right)$ is shown in the figure.



ϕ_1, ϕ_2, ϕ_3 are work function. What will be the ratio in ϕ_1, ϕ_2 and ϕ_3?

Q 4. Show the graph to represent variation of particle momentum and the associated de-Broglie wavelength?

Answers

1. Maximum Kinetic Energy.

$$K_{max} = h\nu - \phi_0 = \frac{hc}{\lambda} - \phi_0$$

$$= \frac{(6.6 \times 10^{-34}) \times (3 \times 10^8)}{(300 \times 10^{-9})} - 3.3 \times 1.6 \times 10^{-19}$$

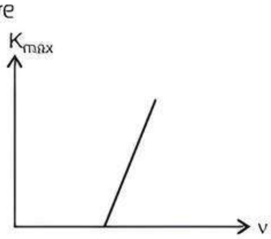
$$= 6.6 \times 10^{-19} - 3.3 \times 1.6 \times 10^{-19}$$
$$= 1.6 \times 10^{-19} (4.125 - 3.3)$$
$$= 1.6 \times 10^{-19} \times 0.825$$
$$= 0.825 \text{ eV}$$

2. We know, $K_{max} = h\nu - \phi_0$, when $\nu = \nu_0$, $K_{max} = 0$

$\therefore \quad 0 = h\nu_0 - \phi_0$ or $\phi_0 = h\nu_0$

If $\nu < \nu_0$, then K_{max} is negative *i.e.*, no photoelectric emission takes place.

The variation of maximum kinetic energy (K_{max}) of the emitted photoelectron with frequency (ν) is shown in figure.



3. From Einstein's photoelectric equation,

$$K_{max} = eV_0 = \frac{hc}{\lambda} - \phi$$

or
$$V_0 = \frac{hc}{e} \cdot \frac{1}{\lambda} - \frac{\phi}{e}$$

Graph of V_0 versus $\frac{1}{\lambda}$ is a straight line.

Slope of straight line, $\tan\theta = \frac{hc}{e}$

At $V_0 = 0$, we have

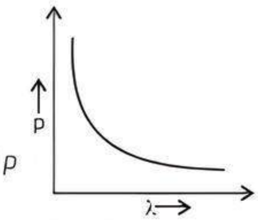
$$\phi_1 : \phi_2 : \phi_3 = \frac{hc}{\lambda_{01}} : \frac{hc}{\lambda_{02}} : \frac{hc}{\lambda_{03}}$$
$$= 0.001\, hc : 0.002\, hc : 0.004\, hc$$

$\therefore \quad \phi_1 : \phi_2 : \phi_3 = 1 : 2 : 4$

4. de-Broglie wavelength

$$\lambda = \frac{h}{p} \text{ i.e., } \lambda \propto \frac{1}{p}$$

So, the graph between λ and p is shown in figure:



Very Short Answer Type Questions

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

Ans. Photoelectric effect.

Q 2. What is photoelectric effect?

Ans. When an electromagnetic radiation (such as UV rays, X-rays, etc.) of suitable frequency is incident on a metal surface, electrons are emitted from the surface. This phenomenon is called photoelectric effect.

Q 3. Define the term work function of a photoelectric surface.

Ans. The minimum energy required by an electron to just eject out from the metallic surface is called work function of that surface.

Work function, $\quad W = h\nu_0 = \frac{hc}{\lambda_0}$

Q 4. Define the term "stopping potential" or "cut-off potential" in relation to photoelectric effect.

Ans. The minimum negative potential of anode at which photoelectric current becomes zero is called stopping potential.

Q 5. Define the term "threshold frequency", in the context of photoelectric emission. *(CBSE 2019)*

Ans. For a given material, there exists a certain minimum frequency of the incident radiation below which no emission of photoelectrons takes place. This frequency is known as threshold frequency of that material.

Knowledge BOOSTER

Threshold frequency and cut-off frequency are same.

Q 6. Define the term "intensity" in photon picture of electromagnetic radiation.

Ans. Intensity is the number of photons passing through an area in a given interval of time. Its SI unit is watt/metre^2.

Q 7. A photosensitive surface emits photoelectrons when red light falls on it. Will the surface emit photoelectrons when blue light is incident on it? Give reason. *(CBSE 2017)*

Ans. The photoelectrons can be emitted from a metal surface if the frequency of incident radiation is more than the threshold frequency.

Now, photosensitive surface emits photoelectrons on falling red light on it, that means, work function of the surface $W < h\nu_{red}$ or $W < \frac{hc}{\lambda_{red}}$.

When blue light is incident on the surface then energy imparted to electrons,

$$E = \frac{hc}{\lambda_{blue}}$$

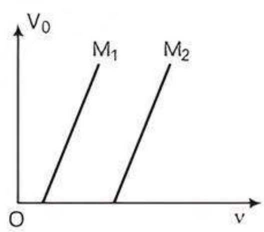
As $\lambda_{red} > \lambda_{blue}$

so $\frac{hc}{\lambda_{blue}} > \frac{hc}{\lambda_{red}}$

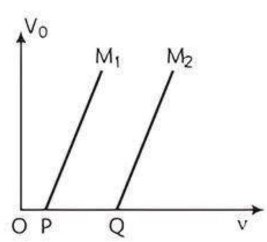
Therefore, $\frac{hc}{\lambda_{blue}} > W$

So, photoelectrons will be emitted when blue light is incident on the photosensitive surface.

Q 8. The variation of the stopping potential (V_0) with the frequency (ν) of the light incident on two different photosensitive surfaces M_1 and M_2 is shown in the figure. Identify the surface which has greater value of the work function. *(CBSE 2020)*



Ans.

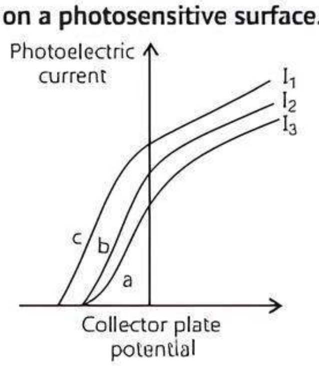


As $OP < OQ$

$\therefore$ $\nu_{M_1} < \nu_{M_2}$

So, the threshold frequency of metal M_2 is greater than metal M_1.

Q 9. The figure shows a plot of three curves a, b, c showing the variation of photocurrent *versus* 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 photosensitive surface.



Point out the two curves for which the incident radiations have same frequency but different intensities.

Ans. Stopping potential will be same for the same frequency. So curves '*a*' and '*b*' have same frequency but different intensities ($I_2 > I_3$).

Q 10. State one factor which determines the intensity of light in the photon picture of light?

Ans. The factor determining the intensity of light is number of electrons emitted per second.

Q 11. State one reason to explain why wave theory of light does not support photoelectric effect?

Ans. One reason why wave theory of light does not support photoelectric effect is that the kinetic energy of photoelectrons does not depend on the intensity of incident light.

Q 12. If the distance between the source of light and the cathode of a photocell is doubled, how does it affect the stopping potential applied to the photo cell?

Ans. Stopping potential remains unchanged, if the distance between the light source and cathode is doubled.

Q 13. What is the stopping potential applied to a photocell if the maximum kinetic energy of a photoelectron is 5eV?

Ans. Since $K_{max} = eV_0$

$\therefore$ Stopping potential, $V_0 = \frac{K_{max}}{e} = \frac{5eV}{e} = 5V$

Q 14. For a photosensitive surface, threshold wavelength is λ_0, does photoemission occur, if the wavelength (λ) of the incident radiation is

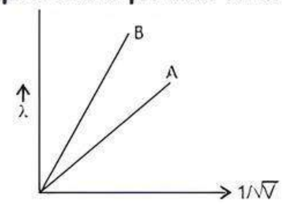
(i) more than λ_0,

(ii) less than λ_0. Justify your answer.

Ans. (i) No

(ii) Yes, as for photoelectric emission $\frac{hc}{\lambda} \geq \frac{hc}{\lambda_0}$, hence $\lambda \leq \lambda_0$.

Q 15. Two lines A and B in the plot given below show the variation of de-Broglie wavelength, λ *versus* $\frac{1}{\sqrt{V}}$, where V is the accelerating potential difference, for two particles carrying the same charge. Which one of two represents a particle of smaller mass?



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

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

The slope is given by

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

Slope of B > Slope of A

$$\frac{1}{\sqrt{m_B}} > \frac{1}{\sqrt{m_A}} \Rightarrow \sqrt{m_B} < \sqrt{m_A}$$

$\therefore$ $m_B < m_A$

Hence, B represents a particle of smaller mass.

Q 16. An electron and an alpha particle have the same de-Broglie wavelength associated with them. How are their kinetic energies related to each other?

Ans. We know,

de-Broglie wavelength $\lambda = \frac{h}{\sqrt{2mKE}}$

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

$$\therefore \frac{h}{\sqrt{2m_eKE_e}} = \frac{h}{\sqrt{2m_\alpha KE_\alpha}}$$

or $$\frac{m_e}{m_\alpha} = \frac{KE_\alpha}{KE_e}$$

where
- m_e = mass of electron,
- m_α = mass of α-particle,
- KE_e = Kinetic energy of electron,
- KE_α = Kinetic energy of α-particle

As $m_\alpha > m_e$

$\therefore$ $KE_e > KE_\alpha$

Short Answer Type-I Questions

Q 1. How will the de-Broglie wavelength associated with an electron be affected when the (i) velocity of the electron decreases? (ii) accelerating potential is increased? Justify your answer. *(CBSE 2023)*

Ans. (i) According to the de-Broglie wavelength formula, the wavelength is inversely proportional to the momentum of the electron. As momentum is the product of mass and velocity, when the velocity of the electron decreases, its momentum also decreases. Therefore, the de-Broglie wavelength of the electron will increases.

(ii) When the accelerating potential is increased, the velocity of the electron also increases. As a result, the momentum of the electron increases, and according to the de-Broglie wavelength formula, the wavelength decreases. Therefore, the de-Broglie wavelength of the electron will decreases.

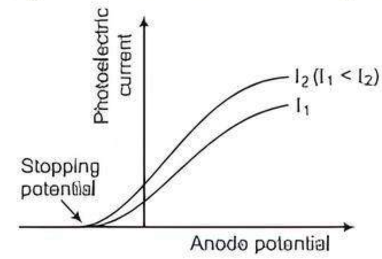
Justification: According to de-Broglie wavelength $\lambda = h/p$, if the velocity of the electron decreases, the momentum of the electron also decreases, resulting in an increase in the de-Broglie wavelength. Similarly, if the accelerating potential is increased, the velocity of the electron increases, leading to an increase in the momentum of the electron and a decrease in the de-Broglie wavelength.

Q 2. (i) Define the terms, (a) threshold frequency and (b) stopping potential in photoelectric effect.
(ii) Plot a graph of photocurrent *versus* anode potential for a radiation of frequency ν and intensities I_1 and I_2 ($I_1 < I_2$). *(CBSE 2019)*

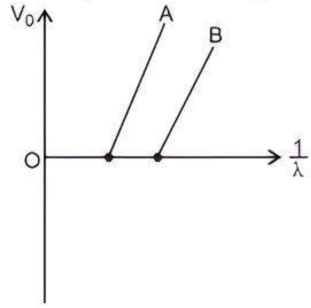
Ans. (i) **(a) Threshold frequency:** The minimum value of frequency of incident radiation (light) that can cause photoemission from a given photo sensitive surface is called threshold frequency.

(b) Stopping potential: The minimum negative i.e., retarding potential, given to the anode i.e., collector plate for which the photocurrent stops or becomes zero is called stopping potential.

(ii) Graph of photocurrent versus anode potential.



Q 3. Figure shows the stopping potential (V_0) for the photoelectron versus $\frac{1}{\lambda}$ graph, for two metals A and B, λ being the wavelength of incident light.



(i) How is the value of Planck's constant determined from the graph?

(ii) If the distance between the light source and the surface of metal A is increased, how will the stopping potential from electrons emitted from it be effected? *(CBSE 2020)*

Ans. (i) We can determine Planck's constant by calculating the slope of the graph.

Slope of the graph $= \frac{hc}{e}$

where, h = Planck's constant,

c = velocity of light in vacuum or free space

and e = charge of electron

The values of c and e are known which are 3×10^8 m/s and 1.6×10^{-19} C respectively.

Hence, h can be determined.

(ii) If distance between source of light and surface of metal A is increased, the intensity of incident light decreases, but stopping potential does not depend on the intensity of the incident light. So, the stopping potential will not be affected.

Q 4. How would the stopping potential for a given photosensitive surface change if (i) the frequency of the incident radiation were increased? (ii) the intensity of incident radiation were decreased? Justify your answer. *(CBSE 2023)*

Ans. (i) The stopping potential for a given photosensitive surface would increase if the frequency of the incident radiation is increased. This is because the stopping potential is directly proportional to the frequency of the incident radiation according to the photoelectric effect equation: $K_{max} = hf - \phi$.

(ii) The stopping potential for a given phtotosensitive surface would not be affected by the decrease in the intensity of the incident radiation. This is because the stopping potential depends only on the frequency of the incident radiation and not on its intensity.

Justification: The stopping potential for a given photosensitive surface depends on the kinetic energy of the emitted photoelectrons, which is determined by the frequency of the incident radiation and the work function of the metal. Therefore, increasing the frequency of the incident radiation would increase the stopping potential while decreasing the intensity of the incident radiation would not affect the stopping potential, as it depends only on the frequency of the radiation.

Q 5. In case of photoelectric effect experiment, explain the following facts, giving reasons.

(i) The wave theory of light could not explain the existence of the threshold frequency.

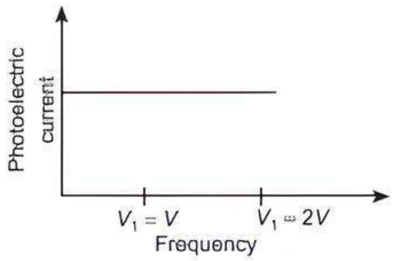
(ii) The photoelectric current increases with increase in the intensity of incident light. *(CBSE 2020)*

Ans. (i) The wave theory of light could not explain the existence of the threshold frequency because energy of the wave is dependent on the square of its amplitude. The classical wave theory predicts that if sufficiently intense light is incident, the electrons would absorb that energy to escape. There should not be any threshold frequency for the emission of electrons from metal's surface due to incident light.

(ii) According to wave theory, if intensity of light increases, the kinetic energy of an ejected electron will also increase. This is because the greater the intensity of light, the larger the energy of the light wave striking the metal surface, so electrons are ejected with greater kinetic energy. However, it cannot explain the increase of number of ejected electrons *i.e.*, the increase of photoelectric current, with the increase in intensity of incident light.

Q 6. Explain how does (i) photoelectric current and (ii) kinetic energy of the photoelectrons emitted in a photocell vary if the frequency of incident radiation is doubled, but keeping the intensity same? *(CBSE SQP 2022 Term 2)*

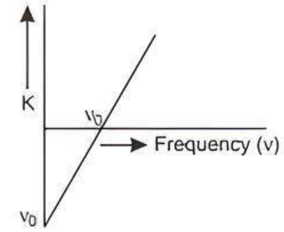
Ans. (i) Since, photoelectric current depends intensity of incident radiation and does not depend on the frequency of incident radiation. Therefore, when frequency of incident radiation is increased to double, then photoelectric current remains same. This is shown in the following graph:



(ii) Kinetic energy of emitted photoelectrons,

$$K = \frac{1}{2}mv^2_{max} = hv \Rightarrow K \propto v$$

Hence, on increasing the frequency of incident radiation to double, kinetic energy of emitted photoelectrons also will increase to double. This is shown below:



where, v_0 = threshold wavelength.

Q 7. Light of same wavelength is incident on three photosensitive surfaces *A*, *B* and *C*. The following observations are recorded:

(i) From surface *A*, photoelectrons are not emitted.

(ii) From surface *B*, photoelectrons are just emitted.

(iii) From surface *C*, photoelectrons with some kinetic energy are emitted.

Compare the threshold frequencies of the three surfaces and justify your answer. *(CBSE 2020)*

Ans. (i) From surface *A*, photoelectrons are not emitted. So, the value of threshold frequency is greater than the frequency of the incident radiation.

(ii) From surface *B*, photoelectrons are just emitted. So, the value of threshold frequency is equal to the frequency of the incident radiation.

(iii) From surface *C*, photoelectrons with some kinetic energy are emitted. So, the value of threshold frequency is less than the frequency of the incident radiation.

Justification: Threshold frequency is the minimum frequency of light which causes electron emission from a metal surface. No electron emission means that the frequency of the light is less than the threshold frequency and electron emission means that the frequency of the light is more than the threshold frequency.

Q 8. Explain, how the process of emission of photoelectrons is different from the process of emission of β-particles. *(CBSE 2020)*

Ans. Emission of photoelectrons is a phenomenon that is excited externally by incidence of photons on metal surface to provide necessary energy to eject electrons from metal.

Emission of β-particles is totally spontaneous in which no external excitation is involved. An unstable nucleus emits an electrons (β-particle) to become stable. Also, in photoelectron emission, radiation energy is absorbed by metal atoms while on β-particle emission, radiation energy is released.

Q 9. (i) Write two main observations of photoelectric effect experiment which could only be explained by Einstein's photoelectric equation.

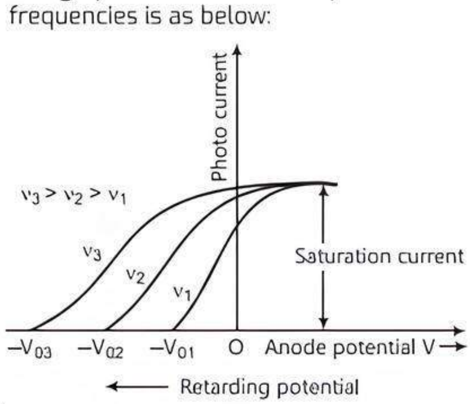
(ii) Draw a graph showing variation of photocurrent with the anode potential of a photocell. *(CBSE 2020)*

Ans. (i) The two observations of photoelectric effect experiment could be explained by Einstein's photoelectric equation are:

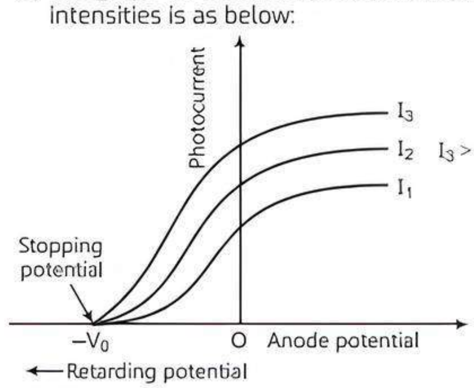
(a) Below threshold frequency, ν_0 corresponding to ϕ_0, no emission of photoelectrons take place.

(b) As energy of a photon depends on the frequency of light, so the maximum kinetic energy with which photoelectron is emitted depends only on the energy of photon or on the frequency of incident radiation.

(ii) (a) The graph for same intensity with different frequencies is as below:



(b) The graph for same frequency with different intensities is as below:



COMMON ERR(!)R

Students often draw only one graph.

Q 10. Why is wave theory of electromagnetic radiation not able to explain photoelectric effect? How does photon picture resolve this problem? *(CBSE 2019)*

Ans. When light is incident on a metal surface, it spread evenly all over the metal surface and it cannot explain the instantaneous emission of photoelectrons. According to wave nature of radiation, it is continuous and follow the principle of superposition hence it cannot explain the existence of threshold frequency. Wave nature cannot explain the fact that kinetic energy of the emitted electrons is independent of intensity of radiation and depends on frequency.

According to photon picture of radiation, photons are discrete packets of energy and energy depends on frequency ($E = h\nu$). Hence the emission of photoelectrons do not take place, till the frequency of incident light is above the value. As the energy depends on frequency so by increasing the frequency, kinetic energy of photoelectron increases.

Q 11. Explain with the help of Einstein's photoelectric, equation, any two observed features in photoelectric effect which cannot be explained by wave theory. *(CBSE 2019)*

Ans. There are two features in photoelectric effect which cannot be explained by wave theory but can be explained through Einstein's photoelectric equation.

Einstein's photoelectric equation is

$$K_{max} = h\nu - \phi_0 = \frac{1}{2}mv^2$$

(i) Threshold Frequency: For $K_{max} \geq 0$, $\nu \geq \nu_0$

Hence, the phenomenon of photoelectric effect takes place when incident frequency is greater or equal to a minimum frequency or threshold frequency ν_0 fixed for given metal.

(ii) Effect of Intensity of Incident Light: The number of photons incident per unit time per unit area increases with the increase of intensity of incident light. More number of photons facilitates ejection of more number of photoelectrons from metal surface leads to further increase of photocurrent till its saturation value is reached.

Q 12. If light of wavelength 412.5 nm is incident on each of the metals given below, which one 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. Given, $\lambda = 412.5\,\text{nm} = 412.5 \times 10^{-9}$ m

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

$$= \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{412.5 \times 10^{-9} \times 1.6 \times 10^{-19}}\,\text{eV} = 3.01\,\text{eV}.$$

Sol. (i) Maximum kinetic energy, $KE_{max} = h\nu - W$

$$= 1.6 \times 10^{-19}(2.48 - 2.14)\ J = 0.34\ eV$$

(ii) Since $eV_0 = KE_{max} = 0.34$ eV

$$\Rightarrow \quad V_0 = 0.34\ V$$

(iii) Since $\frac{1}{2}mv_{max}^2 = KE_{max}$

$$= 0.34\ eV = 0.34 \times 1.6 \times 10^{-19}\ J$$

$$\therefore \quad v_{max}^2 = \frac{0.34 \times 1.6 \times 10^{-19} \times 2}{9.1 \times 10^{-31}}$$

$$= 0.119 \times 10^{12}$$

$$\therefore \quad v_{max} = \sqrt{0.119 \times 10^{12}} = 0.3458 \times 10^6$$

$$\Rightarrow \quad v_{max} = 345.8 \times 10^3 m/s$$

COMMON ERR(!)R

Students often tend to forget to convert the incident radiation photon energy in eV.

Q 19. Light wavelength 2000 Å falls on a metal surface of work function 4.2 eV.

(i) What is the kinetic energy (in eV) of the (a) fastest and (b) slowest electrons emitted from the surface?

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

(iii) If the same light falls on another surface of work function 6.5 eV, what will be the energy of emitted electrons?

Sol. (i) (a) Kinetic energy of fastest electron,

$$KE_{max} = \frac{hc}{\lambda} - W$$

$$= \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{2000 \times 10^{-10}} - 4.2 \times 1.6 \times 10^{-19}$$

$$= 1.6 \times 10^{-19}\ (6.2 - 4.2)\ J = 2.0\ eV$$

(b) KE of slowest electron = 0 eV

(ii) No change in the energy of emitted electrons as it does not depend on intensity.

(iii) No emission as $E(6.2\ eV) < W\ (6.5\ eV)$

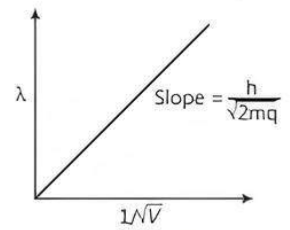
Q 20. Plot a graph showing variation of de-Broglie wavelength (λ) associated with a charged particle of mass m, versus $1/\sqrt{V}$, where V is the potential difference through which the particle is accelerated. How does this graph give us the information regarding the magnitude of the charge of the particle? *(CBSE 2019)*

Ans. The de-Broglie wavelength is given by

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

$$\Rightarrow \quad \lambda \propto \frac{1}{\sqrt{V}}$$

So, the graph between λ and $\frac{1}{\sqrt{V}}$ is as below:



Thus, it gives a straight line graph.

$$\lambda\sqrt{V} = \frac{h}{\sqrt{2mq}} = \text{slope of graph}$$

Knowing the mass of particle (m), and slope of graph, we can calculate charge (q) on a particle.

COMMON ERR(!)R

Students often draw graph of λ versus $\sqrt{V}$.

Short Answer Type-II Questions

Q 1. Explain giving reasons for the following:

(i) Photoelectric current in a photocell increases with the increase in the intensity of the incident radiation.

(ii) The stopping potential (V_0) varies linearly with the frequency (ν) of the incident radiation for a given photosensitive surface with the slope remaining the same for different surfaces.

(iii) Maximum kinetic energy of the photoelectrons is independent of the intensity of incident radiation. *(CBSE 2017)*

Ans. (i) The collision of a photon can cause emission of a photoelectron (above the threshold frequency). As intensity increases, number of photons increases. Hence, the current increases.

(ii) We have, $eV_0 = h(\nu - \nu_0)$

$$\therefore \quad V_0 = \frac{h}{e}(\nu) + \left(\frac{-h\nu_0}{e}\right)$$

Hence, graph of V_0 with ν is a straight line and slope ($= h/e$) is a constant.

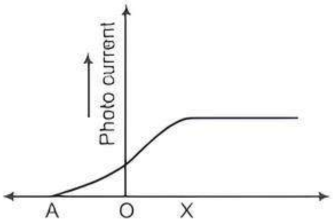
(iii) Maximum kinetic energy for different surfaces,

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

Hence, it depends on the frequency and not on the intensity of the incident radiation.

Q 2. The following graphs shows the variation of photocurrent for a photosensitive metal:

(i) Identify the variable X on the horizontal axis.



(ii) **What does the point A on the horizontal axis represent?**

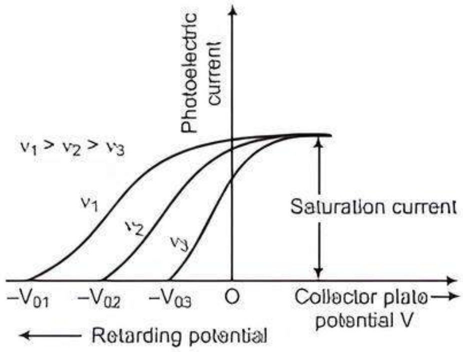
(iii) **Draw this graph for three different values of frequencies of incident radiation ν_1, ν_2 and ν_3 $(\nu_1 > \nu_2 > \nu_3)$ for same intensity.**

(iv) **Draw this graph for three different values of intensities of incident radiation I_1, I_2 and I_3 $(I_1 > I_2 > I_3)$ having same frequency.** *(CBSE 2017)*

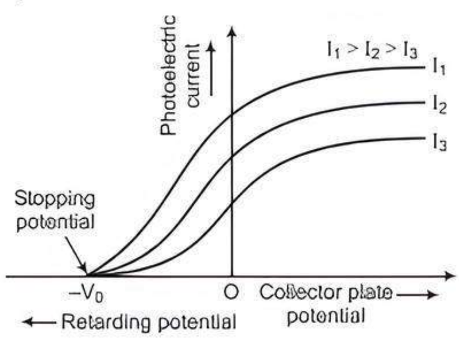
Ans. (i) The variable X on the horizontal axis is collector plate potential.

(ii) The point A on the horizontal axis represents stopping potential.

(iii) Graph for different frequencies:



(iv) Graph for three different intensities:



COMMON ERR(!)R

Several students do not know the correct relations.

Q 3. Sketch the graph 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 2016)*

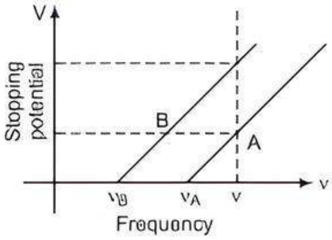
Ans. We know, $K_{max} = eV = h(\nu - \nu_0)$

or $$V = \frac{h}{e}\nu - \frac{h}{e}\nu_0$$

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

As. $V = \frac{h}{e}(\nu - \nu_0)$

$\therefore$ V is higher for lower value of ν_0. Here $\nu_B < \nu_A$, so $V_B > V_A$.



(ii) Slope of the graph is given by h/e which is constant for all the materials. Hence, slope of the graph does not depend on the nature of the material used.

Q 4. (i) How does one explain the emission of electrons from a photosensitive surface with the help of Einstein's photoelectric equation?

(ii) The work function of the following metals is given as Na = 2.75 eV, K = 2.3 eV, Mo = 4.17 eV and Ni = 5.15 eV. Which of these metals will not cause photoelectric emission for radiation of wavelength 3300Å form a laser source placed 1 m away from these metals? What happens if the laser source is brought nearer and placed 50 cm away? *(CBSE 2017)*

Ans. (i) From Einstein's photoelectric equation, we have,

$$K_{max} = h\nu - \phi_0$$

where, K_{max} is maximum kinetic energy of the photoelectrons, ϕ_0 is work function and $h\nu$ is energy of the incident photon.

As $K_{max} \geq 0$

So, $h\nu - \phi_0 \geq 0$

or $$\nu = \frac{\phi_0}{h}$$

Thus, photoemission occurs, when frequency is greater than threshold frequency, $\nu \geq \frac{\phi_0}{h}$.

(ii) Energy of the incident radiation of wavelength λ,

$$E = \frac{hc}{\lambda} = \frac{(6.63\times10^{-34})\times(3\times10^{8})}{3300\times10^{-10}\times1.6\times10^{-19}} = 3.76 \text{ eV}$$

This energy of the incident radiation is greater than the work function of Na and K but less than those of Mo and Ni, so photoelectric emission will occur only in Na and K metals and not in Mo and Ni.

If the laser is brought closer, the intensity of incident radiation increases. This does not affect the result regarding Mo and Ni metals, while photoelectric current from Na and K will increase in proportion to intensity.

TiP

Before comparing the work function with energy, the incident radiation photon energy should be converted in eV.

Q 5. (i) State two important features of Einstein's photoelectric equation.

(ii) Radiation of frequency 10^{15} Hz is incident on two photosensitive surfaces P and Q. There is no photoemission from surface P. Photoemission occurs from surface Q but photoelectrons have zero kinetic energy. Explain these observations and find the value of work function for surface Q. *(CBSE 2017)*

Ans. (i) Einstein's photoelectric equation is

$$eV_0 = K_{max} = h\nu - \phi_0$$

Important features of this equation are given below:

(a) Photoemission occurs when frequency of incident radiation is more than the threshold frequency, i.e., $\nu \geq \frac{\phi_0}{h}$.

(b) Energy of emitted photoelectron is proportional to energy of incident photon.

(ii) Energy of incident photon is less than work function of P but just equal to that of Q.

For Q, work function, $\phi_0 = \frac{h\nu}{e}$(eV)

$$= \frac{6.6\times10^{-34}\times10^{15}}{1.6\times10^{-19}} = 4.1 \text{ eV}$$

Q 6. State the main implications of observations obtained from various photoelectric experiments. Can these implications be explained by wave nature of light? Justify your answer. *(CBSE SQP 2020-21)*

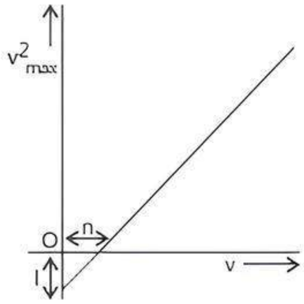
Ans. Main implications:

(i) Kinetic energy of emitted electrons depends upon frequency, but not on intensity of radiation.

(ii) There exist a frequency of radiation below which no photoemission takes place, how high intensity of radiation may be.

Wave nature of radiation fails to explain photoelectric effect.

Q 7. State Einstein's photoelectric equation explaining the symbols used.



Light of frequency ν is incident on a photosensitive surface. A graph of the square of the maximum speed of the electrons (v^2_{max}) *versus* ν is obtained as shown in the figure. Using Einstein's photoelectric equation, obtain expressions for work function of the given photosensitive material and Planck's constant.

Ans. Einstein's photoelectric equation is

$$h\nu = W_0 + \frac{1}{2}mv^2{}_{max}$$

where, ν = Frequency of incident light.

ν_0 = Threshold frequency of photosensitive material.

W_0 = Work function of photosensitive material

and $\frac{1}{2}mv^2{}_{max}$ = Maximum kinetic energy of the emitted photoelectrons.

We can write it as

$$h\nu = W_0 + eV_s$$

where, V_s = Stopping potential

From Einstein's photoelectric equation, we have

$$h\nu = W_0 + \frac{1}{2}mv^2{}_{max}$$

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

But $$\frac{1}{2}mv^2_{max} = eV_0$$

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

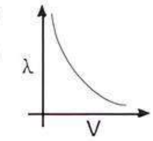
or $$V_0 = \frac{h(\nu - \nu_0)}{e}$$

or $$h = \frac{eV_0}{(\nu - \nu_0)}$$

Q 8. (i) A particle of mass m and charge q is accelerated through a potential difference V. Plot a graph of de-Broglie wavelength λ associated with it as a function of V.

(ii) Calculate the energy acquired by and de-Broglie wavelength associated with, an electron accelerated through a potential difference of 400 V. *(CBSE 2023)*

Ans. (i) Graph showing de-Broglie wavelength λ associated with as a function of V:



COMMON ERR(!)R

Students often draw graph of λ versus $\frac{1}{\sqrt{V}}$.

(ii) Given,

Potential difference $V = 400$V

∵ Energy $= q \cdot V$

∴ $E = 1.6 \times 10^{-19} \times 400$

$= 640 \times 10^{-19}$

$= 6.40 \times 10^{-17}$ Joule.

and de-Broglie wavelength $\lambda = \frac{12.27}{\sqrt{V}}$

$$= \frac{12.27}{\sqrt{400}} = \frac{12.27}{20}$$

$= 0.6135$ Å

$= 6.135 \times 10^{-11}$m

Q 9. Calculate the wavelength of de-Broglie waves associated with a proton having $\left(\frac{500}{1.673}\right)$ eV energy. How will the wavelength be affected for an alpha particle having the same energy? *(CBSE 2023)*

Sol. Given that,

Energy of proton $(K) = \frac{500}{1.673}$ eV $= 298.8$ eV
$= 298.8 \times 1.6 \times 10^{-19}$ J
$= 478.18 \times 10^{-19}$ J

$\because$ Mass on proton $(m) = 1.673 \times 10^{-27}$ kg

$\therefore$ Wavelength of de-Broglie waves

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

$$= \frac{6.62 \times 10^{-34}}{\sqrt{2 \times 1.673 \times 10^{-27} \times 478.18 \times 10^{-19}}}$$

$$= 1.65 \times 10^{-12} \text{ m}$$

For an alpha particle, the mass is four times the mass of proton. Thus, the momentum of the alpha particle for the same kinetic energy will be half that of the proton.

$\therefore$ The de-Broglie wavelength of an alpha particle

$$\lambda = \frac{h}{2 \times \sqrt{4 \times 2mk}}$$

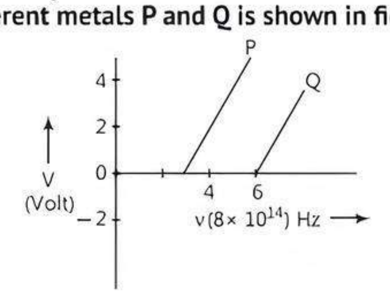
$$= \frac{6.62 \times 10^{-34}}{2 \times \sqrt{4 \times 2 \times 1.673 \times 10^{-27} \times 478.18 \times 10^{-19}}}$$

$$= 4.137 \times 10^{-13} \text{ m}$$

Thus, the de-Broglie wavelength of alpha particle is shorter than that of the proton.

Long Answer Type Questions

Q 1. (i) 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 in figure.



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

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

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

(ii) An electron microscope uses electrons accelerated by a voltage of 50 kV. Determine the de-Broglie wavelength associated with the electrons. Taking other factors, such as numerical aperture, etc., to be same, how does the resolving power of an electron microscope compare with that of an optical microscope which uses yellow light?

Ans. (i) (a) Einstein's photoelectric equation

$$h\nu = \phi + eV \quad \text{or} \quad V = \frac{h\nu}{e} - \frac{\phi}{e} \qquad \text{...(1)}$$

where, h is Planck's constant.

eq. (1) represents a straight line given by line P and Q. $\frac{\phi}{e}$ represents negative intercept on the Y-axis. Since, Q has greater negative intercept, it will have greater ϕ (work function) and hence higher threshold frequency.

(b) To know work function of Q, we put $V = 0$ in the eq. (1).

$$0 = \frac{h\nu}{e} - \frac{\phi}{e} \Rightarrow \phi = h\nu$$

$$\therefore \phi = 6.6 \times 10^{-34} \times 6 \times 10^{14} \text{ J}$$

($\because$ Planck's constant, $h = 6.6 \times 10^{-34}$ J-s)

$$= \frac{6.6 \times 6 \times 10^{-20}}{1.6 \times 10^{-19}} \text{ eV} = 2.5 \text{ eV}$$

(c) From the equation, $\nu\lambda = c$

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{8 \times 10^{14}} = \frac{30}{8} \times 10^{-7} \text{ m}$$

$$= \frac{30}{8} \times 10^3 \times 10^{-10} \text{ m} = \frac{30}{8} \times 10^3 \text{ Å} = 3750 \text{ Å}$$

$$\text{Energy, } E = \frac{12375}{\lambda(\text{Å})} = \frac{12375}{3750} \text{ eV} = 3.3 \text{ eV}$$

Maximum KE of emitted electron
$= 3.3 - 2.5 = 0.8$ eV.

(ii) Given, $V = 50$ kV $= 50 \times 10^3$ V

$\therefore$ de-Broglie wavelength,

$$\lambda = \frac{12.27}{\sqrt{V}} \text{Å} = \frac{12.27}{\sqrt{50 \times 10^3}} \text{Å} = 0.0550 \text{Å}$$

Resolving power of a microscope, $R = \frac{2\mu \sin\theta}{\lambda}$

From the formula, it is clear that if other factors remains same, then resolving power is inversely proportional to wavelength of the radiation used.

The wavelength of moving electron is very small as compared to that of yellow light, so it has greater resolving power than optical microscope.

Q 2. (i) Radiation of frequency 10^{15} Hz is incident on three photosensitive surfaces A, B and C. Following observations are recorded:

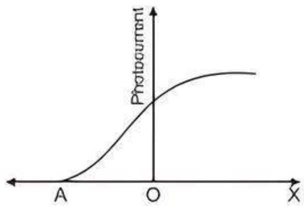
Surface A: no photoemission occurs

Surface B: photoemission occurs but the photo-electrons have zero kinetic energy.

Surface C: photoemission occurs and photo-electrons have some kinetic energy.

Using Einstein's photo-electric equation, explain the three observations. *(CBSE SQP 2022-23)*

(ii) The graph shows the variation of photocurrent for a photosensitive metal:



(a) **What does X and A on the horizontal axis represent?**

(b) **Draw this graph for three different values of frequencies of incident radiation ν_1, ν_2 and ν_3 ($\nu_3 > \nu_2 > \nu_1$) for the same intensity.**

(c) **Draw this graph for three different values of intensities of incident radiations I_1, I_2 and I_3 ($I_3 > I_2 > I_1$) having the same frequency.**

Ans. (i) From the observations made on the basis of Einstein's photoelectric equation, we can draw following conclusions:

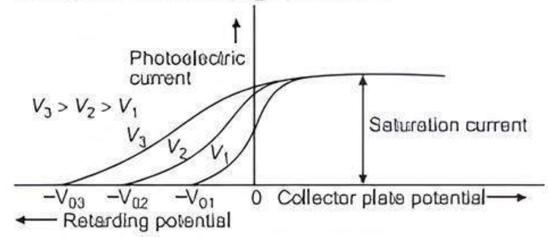
(a) For surface A, the threshold frequency is more than 10^{15} Hz, hence no photoemission is possible.

(b) For surface B, the threshold frequency is equal to the frequency of given radiation. Thus, photo-emission takes place but kinetic energy of photoelectrons is zero.

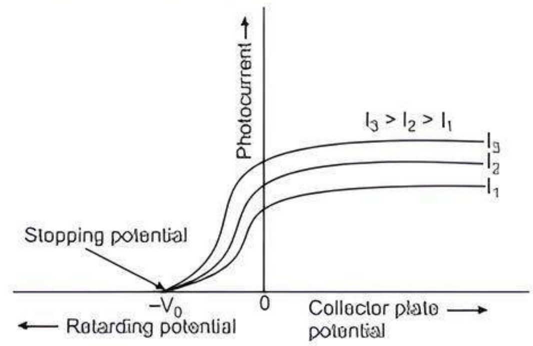
(c) For surface C, the threshold frequency is less than 10^{15} Hz. So, photoemission occurs and photoelectrons have some kinetic energy.

(ii) (a) A—cut-off or stopping potential
X—anode potential

(b) Variation of photoelectric current with collector plate potential for different frequencies of incident radiation are given below:



(c) Variation of photocurrent with collector plate potential for different intensity of incident radiation are given below:



Chapter Test

Multiple Choice Questions

Q 1. By which of the following physical processes can minimum energy required for the electron emission from the metal surface be supplied to the free electrons?

a. Field emission b. Thermionic emission
c. Photoelectric emission d. All of these

Q 2. Which of the following statements is true regarding the photoelectric experiment?

a. The stopping potential increases with the increase in the intensity of incident light
b. The photocurrent increases with the intensity of light
c. The photocurrent increases with the increase in frequency
d. All of the above

Assertion and Reason Type Questions

Directions (Q.Nos. 3-4): *In the questions given below, there are two statements marked as Assertion (A) and Reason (R). Read the statements and choose the correct option:*

a. Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
b. Both Assertion (A) and R are true but Reason (R) is not the correct explanation of Assertion (A).
c. Assertion (A) is true but Reason (R) is false.
d. Both Assertion (A) and Reason (R) are false.

Q 3. Assertion (A): On increasing the frequency of light, larger number of photoelectrons are emitted.
Reason (R): The number of electrons emitted is directly proportional to the intensity of incident light.

Q 4. Assertion (A): The de-Broglie wavelength of a neutron when its kinetic energy is K is l. Its wavelength is 2l when its kinetic energy is 4K.
Reason (R): The de-Broglie wavelength l is directly proportional to square root of the kinetic energy.

Fill in the blanks

Q 5. For a given frequency of the incident radiation, ... is independent of its intensity.

Q 6. Photons are electrically ....

Case Study Based Question

Q 7. When light of sufficiently high frequency is incident on a metallic surface, electrons are emitted from the metallic surface. This phenomenon is called photoelectric emission. Kinetic energy of the emitted photoelectrons depends on the wavelength of incident light and is independent of the intensity of light. Number of emitted photoelectrons depends on intensity.

$(h\nu - \phi)$ is the maximum kinetic energy of emitted photoelectrons (where ϕ is the work function of metallic surface). Reverse effect of photo- emission produces X-ray. X-ray is not deflected by electric and magnetic fields. Wavelength of a continuous X-ray depends on potential difference across the tube. Wavelength of characteristic X-ray depends on the atomic number.

Read the given passage carefully and give the answer of the following questions:

(i) Einstein's photoelectric equation is:

a. $E_{max} = h\nu - \phi$ b. $E = mc^2$

c. $E^2 = p^2c^2 + m_0^2c^4$ d. $E = \frac{1}{2}mv^2$

(ii) A monochromatic light is used in a photoelectric experiment. The stopping potential:

a. is related to the mean wavelength.
b. is related to the shortest wavelength.
c. is not related to the minimum kinetic energy of emitted photoelectrons.
d. intensity of incident light.

(iii) Light of wavelength λ which is less than threshold wavelength is incident on a photosensitive material. If incident wavelength is decreased so that emitted photoelectrons are moving with some velocity then stopping potential will:

a. increase
b. decrease
c. be zero
d. become exactly half

(iv) If frequency ($\nu > \nu_0$) of incident light becomes n times the initial frequency (ν), then KE of the emitted photoelectrons becomes (ν_0 threshold frequency):

a. n times of the initial kinetic energy.
b. more than n times of the initial kinetic energy.
c. less than n times of the initial kinetic energy.
d. kinetic energy of the emitted photoelectrons remains unchanged.

Very Short Answer Type Questions

Q 8. What is the de-Broglie wavelength of a ball of mass 0.12 kg moving with a speed of 20 ms^{-1}?

Q 9. If the distance between the source of light and the cathode of a photocell is doubled, how does it affect the stopping potential applied to the photo cell?

Short Answer Type-I Questions

Q 10. Monochromatic light of frequency 6.0×10^{14} Hz is produced by a laser. The power emitted is 2.0×10^{-3} W.

(i) What is the energy of a photon in the light beam?

(ii) How many photons per second, on an average, are emitted by the source?

Q 11. Define the term "cut-off frequency" in photoelectric emission. The threshold frequency of a metal is ν. When the light of frequency 2ν is incident on the metal plate, the maximum velocity of photo electrons is v_1. When the frequency of the incident radiation is increased to 5ν, the maximum velocity of photoelectrons is v_2. Find the ratio $v_1 : v_2$.

Q 12. The work function for the following metals is given: Na: 2.75 eV and Mo: 4.175 eV

(i) Which of these will not give photoelectron emission from a radiation of wavelength 3300 Å from a laser beam?

(ii) What happens if the source of laser beam is brought closer? *(CBSE 2016)*

Short Answer Type-II Questions

Q 13. 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 3300Å from a laser beam? What happens if the source of laser beam is brought closer?

Q 14. The work function of caesium is 2.14 eV. Find

(i) The threshold frequency for caesium and

(ii) The wavelength of the incident light if the photocurrent is brought to zero by a stopping potential of 0.60 V.

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?

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

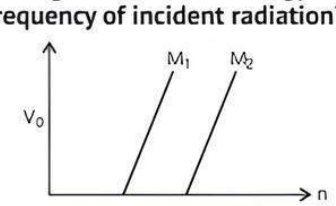
Long Answer Type Questions

Q 16. (i) Write three observed features of photoelectric effect which cannot be explained by wave theory of light.
Explain how Einstein's photoelectric equation is used to describe these features satisfactorily.

(ii) Figure shows a plot of stopping potential (V_0) with frequency (ν) of incident radiation for two photosensitive materials M_1 and M_2. Explain.

(a) Why the slope of both the lines is same?

(b) For which material emitted electrons have greater kinetic energy for the same frequency of incident radiation?



Q 17. (i) Why photoelectric effect can not be explained on the basis of wave nature of light? Give reasons.

(ii) Write the basic features of photon picture of electromagnetic radiation on which Einstein's photoelectric equation is based.