

CHAPTER 11



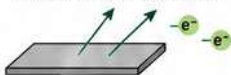
Dual Nature of Radiation and Matter



1. ELECTRON EMISSION

Emission of electron from a metal surface.

- 1 Thermionic emission (when metal is heated)
- 2 Field emission (very strong electric field)
- 3 Photoelectric emission (light of suitable frequency)



2. WORK FUNCTION (ϕ_0)

Minimum energy required to escape from metal surface.

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

Work function of:

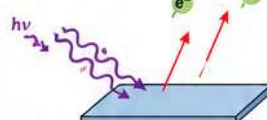
- Platinum = 5.65 eV (highest)
- Caesium = 2.14 eV (lowest)



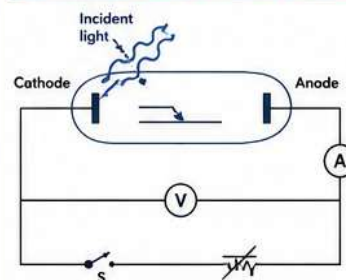
3. PHOTOELECTRIC EFFECT

Emission of electrons from metal surface when light of suitable frequency illuminates it.

Discovered by Heinrich Hertz



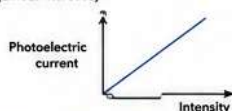
4. LENARD'S EXPERIMENTAL SETUP



5. EFFECTS ON PHOTOELECTRIC CURRENT

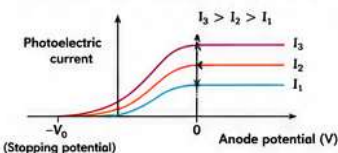
(i) Effect of Intensity (ν, V constant)

Photoelectric current $\propto$ Intensity (Linear increase)



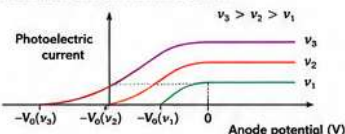
(ii) Effect of Potential (ν constant)

- Increasing positive potential $\rightarrow$ current increases until saturation.
- Negative potential $\rightarrow$ current decreases.
- At stopping potential (V_0), current becomes zero.



(iii) Effect of Frequency (Intensity constant)

- Greater frequency $\rightarrow$ greater stopping potential $\rightarrow$ greater $K_{\max}$
- Saturation current remains same.



6. LAWS OF PHOTOELECTRIC EFFECT

- 1 Photoelectric current $\propto$ intensity of radiation (for fixed frequency).
- 2 Saturation current $\propto$ intensity; stopping potential is independent of intensity.
- 3 No emission occurs below threshold frequency (ν_0).
- 4 $K_{\max} \propto$ frequency of incident radiation (ν); independent of intensity.
- 5 Photoelectric emission is instantaneous (delay $\propto 10^{-9}$ s).

7. FAILURE OF CLASSICAL THEORY

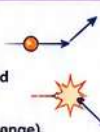
Wave theory predicts electron absorbs energy continuously.

Contradictions:

- a. $K_{\max}$ should depend on intensity (Observed: depends on frequency)
- b. Any frequency should cause emission (Observed: only above threshold freq.)
- c. Should be delayed process (Observed: instantaneous)

10. PARTICLE NATURE OF LIGHT

- Light interacts with matter as photons.
- Photon energy: $h\nu$
- Photon momentum: $\frac{h\nu}{c}$
- Photons have no charge $\rightarrow$ not deflected by E or B fields.
- Photon collisions conserve energy & momentum (number of photons may change).
- Compton scattering confirmed particle nature of light.



8. EINSTEIN'S PHOTOELECTRIC EQUATION

$$\text{Photon energy} = h\nu = K_{\max} + \phi_0$$

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

$$\text{where, } \nu_0 = \text{threshold frequency} = \frac{\phi_0}{h}$$

Explanation of Laws

- Intensity $\uparrow \rightarrow$ photon number $\uparrow \rightarrow$ current $\uparrow$
- If $\nu < \nu_0 \rightarrow K_{\max}$ negative (impossible) $\rightarrow$ no emission
- Photon-electron interaction is instantaneous $\rightarrow$ no time lag

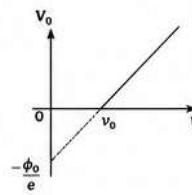
9. GRAPH (ν vs STOPPING POTENTIAL)

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

Straight line

$$\text{Slope} = \frac{h}{e}$$

$$y\text{-intercept} = -\frac{\phi_0}{e}$$



11. DUAL NATURE OF RADIATION

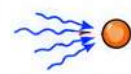
Wave Nature

- Interference
- Diffraction
- Polarisation



Particle Nature

- Photoelectric effect
- Compton scattering



$\Rightarrow$ Light shows wave-particle duality

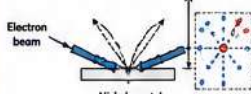
12. DUAL NATURE OF MATTER

Louis de Broglie (1924) proposed particles have wave nature.

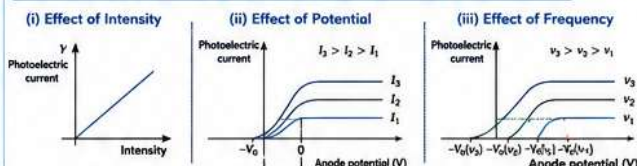
de-Broglie Equation

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

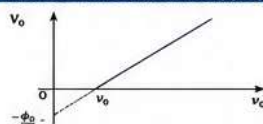
Davison-Germer experiment confirmed electron wave nature.



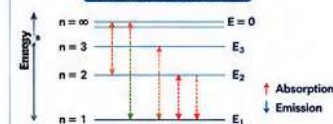
13. PHOTOELECTRIC EFFECT - ALL GRAPHS



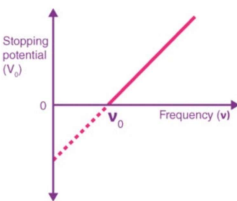
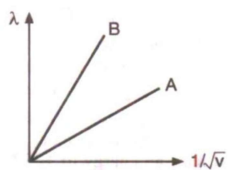
14. PHOTOELECTRIC EQUATION GRAPH (V_0 vs ν)



15. ENERGY DIAGRAM



MULTIPLE CHOICE QUESTIONS

1. A graph is plotted between the stopping potential (on y-axis) and the frequency of incident radiation (on x-axis) for a metal. The product of the slope of the straight line obtained and the magnitude of charge on an electron is equal to:
 (a) h (b) h/c (c) $h/2c$ (d) $2h/c$
- 
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
 3. The work-function of a substance is 4.0 eV. The longest wavelength of light that can cause photoelectron emission from this substance is approximately: -
 (a) 540 nm (b) 400 nm (c) 310 nm (d) 220 nm
 4. Photoelectric effect takes place in element A. Its work function is 2.5 eV and threshold wavelength is λ . An other element B is having work function of 5 eV. Then find out the maximum wavelength that can produce photoelectric effect in B: -
 (a) $\lambda/2$ (b) 2λ (c) λ (d) 3λ
 5. The de-Broglie wavelength of a neutron in thermal equilibrium with heavy water at a temperature T (Kelvin) and mass m, is
 (a) $\frac{h}{\sqrt{mkt}}$ (b) $\frac{h}{\sqrt{3mkt}}$ (c) $\frac{2h}{\sqrt{3mkt}}$ (d) $\frac{2h}{\sqrt{mkt}}$
 6. The photoelectric threshold wavelength of silver is 3250×10^{-10} m. The velocity of the electron ejected from a silver surface by ultraviolet light of wavelength 2536×10^{-10} m is:
 (Given: $h = 4.14 \times 10^{-15}$ eV s and $c = 3 \times 10^8$ m s $^{-1}$)
 (a) $\approx 6 \times 10^5$ m s $^{-1}$ (b) $\approx 0.6 \times 10^4$ m s $^{-1}$ (c) $\approx 61 \times 10^3$ m s $^{-1}$ (d) $\approx 0.3 \times 10^6$ m s $^{-1}$
 7. The two lines A and B shown in figure are the graphs of the de Broglie wavelength λ as a function of $1/\sqrt{V}$ (V is the accelerating potential) for two particles having the same charge. Which of the two represents the particle of heavier mass ?
 (a) A (b) B
 (c) Both A and B (d) Insufficient Data
- 
8. 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) 4 : 1 (b) 1 : 4 (c) 1 : 2 (d) 2 : 1
 9. Photons with energy 5 eV are incident on a cathode C in a photoelectric cell. The maximum energy of emitted photoelectrons is 2 eV. When photons of energy 6 eV are incident on C, no photoelectrons will reach the anode A, if the stopping potential of A relative to C is
 (a) +3 V (b) +4 V (c) -1 V (d) -3 V
 10. An electron of mass m and a photon have same energy E. the ratio of de-Broglie wavelengths associated with them is:
 (a) $\frac{1}{c} \left[\frac{E}{2m} \right]^{\frac{1}{2}}$ (b) $\left[\frac{E}{2m} \right]^{\frac{1}{2}}$ (c) $c[2mE]^{\frac{1}{2}}$ (d) $\frac{1}{c} \left[\frac{2m}{E} \right]^{\frac{1}{2}}$

11. When the mass of an electron becomes equal to thrice its rest mass, its speed is
 (a) $\frac{2\sqrt{2}}{3}c$ (b) $\frac{2}{3}c$ (c) $\frac{1}{3}c$ (d) $\frac{1}{4}c$
12. Which of the following cannot be observed by an increase in the intensity of light alone?
 (a) Increase in photocurrent (b) Increase in stopping potential
 (c) Increase in number of emitted electrons (d) Increase in rate of emission
13. In an experiment, intensity of light is increased but photoelectric current remains constant after sometime. This is due to:
 (a) saturation current has been reached
 (b) frequency of light is below threshold
 (c) work function is larger than incident photon energy
 (d) electrons are absorbed back
14. The photoelectric current becomes zero when:
 (a) The intensity of light is zero (b) Frequency is below the threshold
 (c) Work function is very high (d) Any of the above
15. In a photoelectric experiment with light of intensity I , the current is I_0 . When light is filtered to allow only 50% photons through, the current becomes:
 (a) $2 I_0$ (b) $\frac{I_0}{2}$ (c) $\sqrt{2} I_0$ (d) Remains same
16. Consider a photoelectric tube where magnitude of negative anode potential is gradually increased. The photoelectric current decreases to zero because:
 (a) Kinetic energy of electrons is reduced (b) All photons are absorbed
 (c) Potential suppresses even fastest electrons (d) Frequency becomes less than threshold
17. In an experiment, when frequency is increased, the stopping potential increases linearly. This verifies:
 (a) Planck's quantization (b) de Broglie relation
 (c) Einstein's photoelectric equation (d) Wave-particle duality
18. Which observation supports the quantum nature of light?
 (a) Instantaneous emission (b) $KE \propto \text{frequency}$
 (c) Threshold frequency exists (d) All of the above
19. In photoelectric emission, a radiation whose frequency is 2 times threshold frequency of a certain metal is incident on the metal. Then the maximum possible velocity of the emitted electron will be:
 (a) $\sqrt{\frac{h\nu_0}{m}}$ (b) $\sqrt{\frac{2h\nu_0}{m}}$ (c) $2\sqrt{\frac{h\nu_0}{m}}$ (d) $\sqrt{\frac{6h\nu_0}{m}}$
20. For two particles with equal momenta, which of the following is true regarding their de Broglie wavelengths?
 (a) The heavier particle has smaller wavelength (b) Both have same wavelength
 (c) The faster particle has smaller wavelength (d) Depends on nature of the particles

Answers

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

Assertion- Reason Type Questions

- (A) Both (A) & (R) are true and the (R) is the correct explanation of the (A)
(B) Both (A) & (R) are true but the (R) is not the correct explanation of the (A)
(C) (A) is true but (R) is false
(D) Both (A) and (R) are false

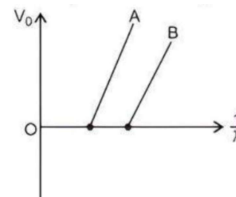
1. **Assertion:** At a fixed frequency above the threshold, doubling the intensity of light doubles the stopping potential.
Reason: Stopping potential is proportional to the energy of the photoelectrons, which increases with intensity.
2. **Assertion:** Even when monochromatic light falls on a metal surface, the emitted photoelectrons have varying kinetic energies.
Reason: Electrons originating from within the metal lose part of their energy due to collisions with other atoms before escaping the surface.
3. **Assertion:** A time delay is observed before photoelectrons are emitted from a metallic surface under light exposure.
Reason: According to Einstein's theory, electrons take time to absorb sufficient energy from the incoming wavefront.
4. **Assertion:** A heavier particle moving slowly can have a longer de Broglie wavelength than a lighter particle.
Reason: The de Broglie wavelength is independent of the particle's mass and velocity.
5. **Assertion:** An infinite time delay is observed when light of frequency less than the threshold is incident on a metal surface.
Reason: According to Einstein's theory, electrons need to accumulate energy over time from multiple photons to be emitted.
6. **Assertion (A):** A beam of electrons with energy of 150 eV is incident on a crystal, and a diffraction pattern is observed. If the energy is increased to 600 eV, the fringe spacing in the diffraction pattern will decrease.
Reason (R): The de Broglie wavelength of a particle is inversely proportional to the square root of its kinetic energy.
7. A photon and an electron both have energy 50 eV.
Assertion (A): Both have different wavelengths.
Reason (R): Wavelength depends on energy and not on mass.
8. **Assertion (A):** The relative velocity of two photons travelling in opposite directions is c .
Reason (R): The rest mass of a photon is infinite.
9. **Assertion (A):** An electron microscope is based on de Broglie's hypothesis of matter waves.
Reason (R): Higher the accelerating potential, smaller is the de Broglie wavelength of the electron.
10. **Assertion (A):** Photoelectric effect demonstrates the wave nature of light.
Reason (R): The number of photoelectrons is proportional to the frequency of light.

Answers

1. D, 2. A, 3. D, 4. C, 5. C, 6. A, 7. C, 8. D, 9. A, 10. D

Short Answer Questions (2 marks each)

- 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.
- (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 ($I_1 > I_2$).
- 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 information regarding the magnitude of charge of the particle?
- An α -particle and a proton are accelerated from rest by the same potential. Find the ratio of their de-Broglie wavelengths.
- An electron and alpha particle have the same de-Broglie wavelength associated with them. How are their kinetic energies related to each other?
- Figure shows the stopping potential (V_0) for the photoelectron versus $1/\lambda$ 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?
- If light of wavelength 412.5 nm is incident on each of the metals given below, which one will show photoelectric emission and why?
- An electron is accelerated through a potential difference of 100 volts. What is the de-Broglie wavelength associated with it? To which part of the electromagnetic spectrum does this value of wavelength correspond?
- If an electron has a wavelength, does it also have a colour?
- A parallel beam of monochromatic light of wavelength 663 nm is incident on a totally reflecting plane mirror. The angle of incidence is 60° and the number of photons striking the mirror per second is 1.0×10^{19} . Calculate the force exerted by the light beam on the mirror.



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

Answers

Ans – 1 -(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 increase.

(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 decrease.

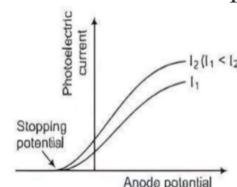
Justification: According to de-Broglie wavelength $\lambda = \frac{h}{p}$, if the velocity of the electron decreases. The momentum of the electron also decreases. Resulting in an increase in the de-

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.

Ans – (2)- 1(a) Threshold frequency: The minimum value of frequency of incident radiation that can cause photoemission from a given photo sensitive surface is called threshold frequency.

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

(ii) Graph of photocurrent versus anode potential.



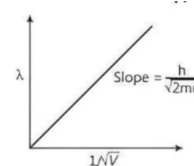
3. The de-Broglie wavelength is $\lambda_1 = \frac{h}{p} = \frac{h}{\sqrt{2mK}} = \frac{h}{\sqrt{2mqV}} \Rightarrow \lambda \propto \frac{1}{\sqrt{V}}$

So, the graph between λ & $\frac{1}{\sqrt{V}}$

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

4. The ratio of the de Broglie wavelength of an α particle (λ_α) to that of a proton (λ_p) accelerated from rest by the same potential is

$$\frac{\lambda_\alpha}{\lambda_p} = \frac{h/\sqrt{2m_\alpha q_\alpha V}}{h/\sqrt{2m_p q_p V}} = \sqrt{\frac{m_p q_p}{m_\alpha q_\alpha}} \Rightarrow \frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{m_p \cdot e}{4m_p \cdot 2e}} = \sqrt{\frac{1}{8}} = \frac{1}{2\sqrt{2}}$$



5. $E_K = \frac{p^2}{2m}$ where, E_K = Kinetic Energy, p = momentum and m = mass

de-Broglie wavelength, $\lambda = \frac{h}{p}$, where, h = Planck's constant Therefore, $\lambda = \frac{h}{\sqrt{2mE_K}}$

Both the particles have the same de-Broglie wavelength. (Given) $\therefore \frac{h}{\sqrt{2m_e E_{Ke}}} = \frac{h}{\sqrt{2m_\alpha E_{K\alpha}}}$

or, $\frac{m_e}{m_\alpha} = \frac{E_{K\alpha}}{E_{Ke}}$ As, $m_\alpha > m_e \therefore E_{Ke} > E_{K\alpha}$

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

Since we know that Slope of the graph = $\frac{hc}{e}$, where, h = Planck's constant, c = velocity of light in vacuum and e = charge of electron

(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.

7. Given, $\lambda = 412.5 \text{ nm} = 412.5 \times 10^{-9} \text{ m}$

$$E = hc/\lambda = (6.62 \times 10^{-34} \times 3 \times 10^8) / (412.5 \times 10^{-9} \times 1.6 \times 10^{-19}) \text{ eV} = 3.01 \text{ eV}$$

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

$$8. \lambda = \frac{12.27}{\sqrt{V}} = \frac{12.27}{\sqrt{100}} = 1.227 \text{ Å}. \text{ This wavelength corresponds to X-rays.}$$

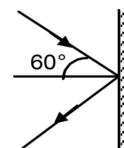
9. Colour is a characteristic of electromagnetic waves. Electrons behave as a de- Broglie wave because of their velocity. A de-Broglie wave is not an electromagnetic wave and is one dimensional. Hence, no colour is shown by an electron.

10. $\lambda = 663 \times 10^{-9} \text{ m}$, $\theta = 60^\circ$, $n = 1 \times 10^{19}$, $\lambda = \frac{h}{p} \Rightarrow p = \frac{h}{\lambda} = 10^{-27}$

Force exerted on the wall = $n(mv \cos \theta - (-mv \cos \theta))$

$= 2n mv \cos \theta = 2n p \cos \theta$

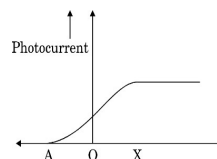
$= 2 \times 1 \times 10^{19} \times 10^{-27} \times \frac{1}{2} = 1 \times 10^{-8} \text{ N}$.



Short Answer type Questions (3 Marks each)

1. The following graph shows the variation of photocurrent for a photosensitive metal:

- Identify the variable X on the horizontal axis.
- What does the point A on the horizontal axis represent?
- 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.

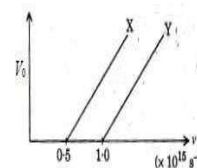


- Draw this graph for three different values of intensities of incident radiation I_1 , I_2 , and I_3 ($I_1 > I_2 > I_3$) having same frequency.

2. In a plot of photoelectric current versus anode potential, how does?

- The saturation current vary with anode potential for incident radiations of different frequencies but same intensity?
- The stopping potential vary for incident radiations of different intensities but same frequency?
- Photoelectric current vary for different intensities but same frequency of incident radiations? Justify your answer in each case.

3. The following graph shows the variation of stopping potential V_0 with the frequency ν of the incident radiation for two photosensitive metals X & Y:



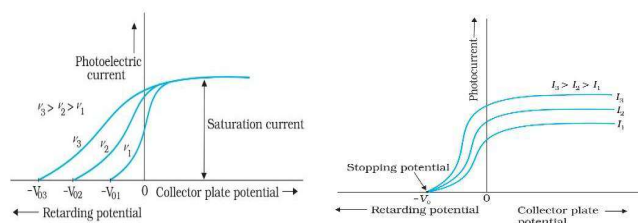
- Which of the metals has larger threshold wavelength? Give reason.
 - Explain, giving reason, which metal gives out electrons, having larger kinetic energy, for the same wavelength of the incident radiation.
 - If the distance between the light source and metal X is halved, how will the kinetic energy of electrons emitted from it change? Give reason.
4. Two neutral particles are kept 1m apart. Suppose by some mechanism some charge is transferred from one particle to the other and the electric potential energy lost is completely converted into a photon. Calculate the longest and the next smaller wavelength of the photon possible.
5. Why do different metals emit electrons only when exposed to light of certain minimum frequencies? The threshold frequency of a metal is f_0 . When the light of frequency $2f_0$ is incident on the metal plate, the maximum velocity of electrons emitted is v_1 . When the frequency of the incident radiation is increased to $5f_0$ the maximum velocity of electrons emitted is v_2 . Find the ratio of v_1 to v_2 .
6. An electron and a photon each have a wavelength 1.00 nm. Find:
- Their momenta,
 - The energy of the photon and,
 - The kinetic energy of electron
7. Explain by giving reasons for the following:
- Photoelectric current in a photocell increases with the increase in the intensity of the incident radiation.
 - 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.

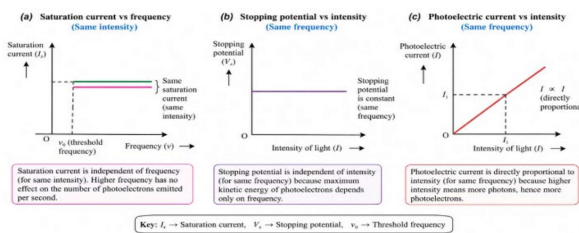
- c) Maximum kinetic energy of the photoelectrons is independent of the intensity of incident radiation.
8. A photoelectric cell has two plates 2 cm apart with no external battery connected. Light of wavelength 310 nm is incident on a metal surface of work function 2.3 eV. An electric field of 2×10^2 N/C exists between the plates, directed such that it opposes the motion of emitted electrons. (a) Calculate the maximum kinetic energy of emitted photoelectrons. (b) Calculate the work done by the electric field against the electrons. (c) Will any photoelectrons reach the collector plate? Justify.
9. An electron is accelerated through a potential of 100 V and directed toward a thin metal foil with atomic spacing 0.2 nm.
- (a) Calculate the de Broglie wavelength of the electron.
- (b) Will diffraction be observed?
- (c) What happens to the wavelength if the voltage increases to 400 V?
10. 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 400V.

ANSWERS

- 1.
- a. X is collector plate potential.
- b. A is stopping potential.
- c. Graph for different frequencies.
- Graph for three different Intensities



2. i. Saturation current does not change.
 ii. Stopping potential does not change.
 iii. Photoelectric current increases with increase in intensity.
3. 'X' as it has smaller threshold frequency.



a) $KE_{max} = h\nu - \phi_0$

Since $\phi_y > \phi_x \Rightarrow K_y < K_x$ therefore 'X' gives out electrons with larger KE.

b) No change as KE of photoelectron does not depend on the intensity of incident radiations.

4. $r = 1m$

Potential Energy = $\frac{kq^2}{r} = \frac{kq^2}{1}$, Energy of photon = $\frac{hc}{\lambda} = \frac{kq^2}{1} \Rightarrow \lambda = \frac{hc}{kq^2}$

For max λ , 'q' should be min, i.e $q = e = 1.6 \times 10^{-19}$ C

Substituting we get, $\lambda_{max} = 863 \text{ m}$

For next smaller wavelength, $q = 2e$ and $\lambda = \frac{863}{4} = 215.74 \text{ m}$.

5. There is minimum energy required to free an electron from its surface binding called work function.

Einstein's photoelectric equation is $h\nu = h\nu_0 + \frac{1}{2}mv^2$

In first case $\nu = 2f_0$, $\nu_0 = f_0$, $\nu = \nu_1$, hence $h(2f_0) = hf_0 + \frac{1}{2}mv_1^2 \Rightarrow \frac{1}{2}mv_1^2 = hf_0$

Similarly in second case we get, $\frac{1}{2}mv_2^2 = 4hf_0$, Dividing both we get, $\frac{v_1}{v_2} = \sqrt{\frac{hf_0}{4hf_0}} = \frac{1}{2}$

6. $\lambda_e = \lambda_{\text{photon}} = 1.00\text{nm} = 10^{-9}\text{m}$.

a) For electron or photon, momentum $p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{10^{-9}} = 6.63 \times 10^{-25} \text{ kg m/s}$

b) Energy $= \frac{hc}{\lambda} = 19.89 \times 10^{-17} \text{ J} (\approx 124 \text{ eV})$

c) Kinetic energy of electron $= \frac{p^2}{2m} = 2.42 \times 10^{-19} \text{ J} = 1.51 \text{ eV}$

7. a) 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.

b) We have, $eV_s = h(\nu - \nu_0)$, $V_s = \frac{h}{e}\nu + (-\frac{h}{e})\nu_0$

$\therefore$ Graph of V_s with ν is a straight line and slope (h/e) is a constant.

c) According to Einstein's photoelectric equation ($KE_{\text{ma}} = h\nu - \phi_0$), KE is independent of intensity.

8. a) $KE_{\text{ma}} = h\nu - \phi_0 = \frac{hc}{e\lambda} - \phi_0 = \frac{6.4 \times 10^{-19}}{1.6 \times 10^{-1}} - 2.3 = 1.7 \text{ eV}$

b) $W = eEd = 1.6 \times 10^{-19} \times 2 \times 10^2 \times 0.02 = 4 \text{ eV}$

c) $KE_{\text{ma}} < W$, No, photoelectrons will not reach the collector plate. The electric field does more work than the electrons' available kinetic energy, so they are stopped before reaching the collector.

9. a) $\lambda = \frac{12.27}{\sqrt{V}} = \frac{12.27}{\sqrt{100}} = 1.227 \text{ \AA}$

b) Yes, diffraction will be observed if the wavelength is comparable to the atomic spacing of the target material.

Calculated wavelength: 0.123 nm

Atomic spacing: 0.2 nm

Since $\lambda \sim d$, diffraction will occur.

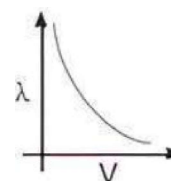
d) When voltage is increased to four times, the wavelength is reduced to half and hence fringe width decreases.

10. (i) Graph showing de-Broglie wavelength & associated with as a function of V

(ii) Given, Potential difference $V = 400\text{V}$

$\therefore$ Energy $= q \cdot V = 1.6 \times 10^{-19} \times 400 = 640 \times 10^{-19} \text{ J} = 6.40 \times 10^{-17} \text{ Joule}$.

de-Broglie wavelength $\lambda = 12.27/\sqrt{V} = 12.27/\sqrt{400} = 12.27/20 = 0.6135 \text{ \AA} = 6.135 \times 10^{-11} \text{ m}$



CASE STUDY BASED QUESTIONS (4 MARKS)

Case Study: Smart Door Lock with Fingerprint Scanner

1. In modern homes and offices, smart biometric door locks that use fingerprint scanning have become popular. These devices work based on the photoelectric effect, a concept that demonstrates the dual nature of radiation. When you place your finger on the scanner, a beam of light, usually from a laser or LED source, illuminates your fingerprint. The light consists of photons (particles of light) that strike the surface of the finger. The ridges and valleys of the fingerprint reflect this light differently. Some parts absorb the photons, while others reflect them back to a sensor.
- 
- i. Why can't the wave theory of light alone explain the working of fingerprint scanners based on the photoelectric effect?
- (A) The wave theory fails to explain reflection of light.
(B) The wave theory does not account for the threshold frequency required to emit electrons.
(C) The wave theory suggests light can't interact with electrons.
(D) The wave theory explains the continuous emission of light, not its speed.
- ii. What would happen if the intensity of light increased but its frequency remains below the threshold frequency in a fingerprint scanner?
- (A) More electrons would be emitted with higher energy.
(B) The fingerprint image would become clearer.
(C) Electrons would emit with the same energy as before.
(D) The emission of electrons would not occur.
- iii. How does the concept of de Broglie wavelength support the miniaturization and efficiency of the fingerprint scanner's electronic components?
- (A) By allowing light to be diffracted and focused more accurately.
(B) By explaining how heat is dissipated in semiconductors.
(C) By enabling high-resolution imaging using wave properties of electrons.
(D) By reducing the speed of electron movement in circuits.
- iv. Which technological limitation would most directly challenge the use of wave nature of electrons in fingerprint sensor development?
- (A) Requirement for extremely small de Broglie wavelengths for high resolution
(B) Slow scanning speed
(C) Difficulty in focusing particle beams
(D) Interference from ambient light

OR

Suppose a new fingerprint scanner is designed using blue light instead of red light. What would be the most likely outcome regarding the photoelectric effect?

- (A) The emitted electrons would have lower kinetic energy.
(B) The emission of electrons would decrease due to lower intensity.
(C) The emitted electrons would have higher kinetic energy due to higher photon frequency.
(D) The resolution of the scanner would decrease.

Case Study: Automatic Sliding Doors

2. Automatic sliding doors are now a common feature at the entrances of supermarkets and malls. These doors open when a person approaches. One common mechanism used in such systems is an infrared motion sensor, which detects changes in infrared radiation emitted or reflected by a human body. These sensors rely on the particle nature of light (photons) to detect motion. The human body emits infrared radiation, and when this radiation is incident on a photodiode or sensor, it gets absorbed, causing electron excitation and the generation of a signal.



- i. Why is infrared radiation suitable for motion detection in automatic doors, considering the concept of dual nature of light?
 - (A) Because it consists of photons that can be detected by a photoelectric sensor
 - (B) Because it is not absorbed by human skin
 - (C) Because it reflects better than visible light
 - (D) Because it has the highest frequency among radiations
- ii. How does the photoelectric effect contribute to the function of motion sensors in automatic doors?
 - (A) It enables light waves to diffract around the human body
 - (B) It measures temperature differences
 - (C) It causes infrared photons to trigger electron emission in the sensor
 - (D) It allows the human body to reflect visible light better
- iii. If the frequency of infrared radiation emitted by the human body were lower than the threshold frequency of the sensor's material, what would happen?
 - (A) The sensor would detect motion faster
 - (B) The door would open before the person arrived
 - (C) No electrons would be emitted, so the door wouldn't open
 - (D) More current would be generated
- iv. Which property of electrons is exploited when using electron beam microscopes to design sensor components for automatic doors?

(A) Their energy levels (B) Their mass (C) Their wave-like nature (D) Their charge only

OR

A new sensor is developed with a material having a higher work function. What change must be made to ensure continued efficient operation using the same infrared radiation?

- A. Reduce the ambient temperature B. Increase the intensity of radiation
C. Decrease the distance from the sensor. D. Increase the frequency of incident photons

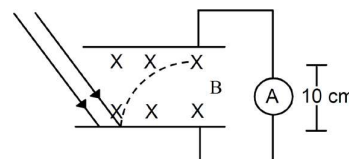
ANSWERS

- | | | | |
|---------|-------|--------|------------|
| 1. i) B | ii) D | iii) C | iv) A or C |
| 2. i) A | ii) C | iii) C | iv) C or D |

LONG ANSWER TYPE QUESTIONS (5 Marks)

1. a) Light of a particular wavelength does not eject electrons from the surface of a given metal. Should the wavelength of the light be increased or decreased in order make ejection of electrons possible? Justify.

- b) In an experiment on photoelectric effect, the emitter and the collector plates are placed at a separation of 10 cm and are connected through an ammeter without any cell. A magnetic field B exists parallel to the plates. The work function of the emitter is 2.39 eV and the light incident on it has wavelengths between 400 nm and 600 nm. Find the minimum value of B for which the current registered by the ammeter is zero. Neglect any effect of space charge.



2. a) A particle of mass M at rest decays into two particles of masses m_1 and m_2 having non-zero velocities. What is the ratio of de Broglie wavelengths of the two particles?
 b) Determine the value of the de Broglie wavelength associated with the electron orbiting in the ground state of hydrogen atom. How will the de Broglie wavelength change when it is in the first excited state?
3. a) 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?
- b) A satellite in space is fitted with a photoelectric sensor to detect solar flares. The sensor uses a metal surface with a work function of 2.2 eV & is exposed to solar radiation of wavelength 330 nm. The emitted electrons are collected in a spherical metal shell of radius 10 cm that surrounds the sensor plate. Due to limited power on the satellite, no external electric field is used to collect the electrons. Instead, the sensor relies on the natural motion of photoelectrons. As electrons accumulate on the shell, they develop a negative potential that begins to repel further photoelectrons. Calculate the maximum charge that can accumulate on the spherical shell before photoemission stops.

ANSWERS

1. a) The wavelength should be decreased because photon energy is inversely proportional to wavelength ($E=hc/\lambda$). Decreasing the wavelength increases the energy of incident photons, making it possible to overcome the metal's work function and eject electrons.
 b) $\phi_0 = 2.39\text{ eV}$ $\lambda_1 = 400\text{ nm}$, $\lambda_2 = 600\text{ nm}$
 for B to be minimum, energy should be maximum $\therefore \lambda$ should be minimum (i.e. λ_1)

$$K = \frac{hc}{\lambda} - \phi_0 = 3.105 - 2.39 = 0.715\text{ eV} = 1.144 \times 10^{-19}\text{ J}$$

The presence of magnetic field will bend the beam and there will be no current if the electron does not reach the other plate.

$$r = \frac{mv}{qB} = \frac{\sqrt{2mK}}{qB} \Rightarrow B = \frac{\sqrt{2mK}}{qr} = \frac{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.144 \times 10^{-19}}}{1.6 \times 10^{-19} \times 0.1} = 2.85 \times 10^{-5}\text{ T}$$

2. a) According to the law of conservation of momentum, the momentum of a system remains conserved.

$$Mv = m_1v_1 + m_2v_2 \Rightarrow 0 = m_1v_1 + m_2v_2 \Rightarrow m_1v_1 = -m_2v_2$$

$$\text{So, we can write, } p_1 = p_2 \Rightarrow \frac{hc}{\lambda_1} = \frac{hc}{\lambda_2} \Rightarrow \frac{\lambda_1}{\lambda_2} = 1$$

b) In ground state, the kinetic energy of the electron is, $K = 13.6 \text{ eV} = 2.18 \times 10^{-18} \text{ J}$

$$\lambda_0 = \frac{h}{\sqrt{2mK}} = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 2.18 \times 10^{-18}}} = 3.32 \times 10^{-10} \text{ m}$$

In the first excited state, $K = \frac{13.6}{2^2} = \frac{13.6}{4}$ so we get $\lambda_1 = 2 \times \lambda_0 = 6.64 \times 10^{-10} \text{ m}$

3. a) (i) No, the emitted photoelectrons do not have the same kinetic energy because some electrons lose part of their energy overcoming the surface barrier inside the material.
(ii) No, the kinetic energy of the emitted electrons depends only on the frequency of the incident radiation, not on its intensity.
(iii) The number of emitted photoelectrons depends on the intensity of the incident radiation and the area exposed.

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

$$\phi = 2.2 \text{ eV} = 2.2 \times 1.6 \times 10^{-19} = 3.52 \times 10^{-19}$$

$$KE_{\max} = E - \phi = 6.03 \times 10^{-19} - 3.52 \times 10^{-19} = 2.51 \times 10^{-19} \text{ J}$$

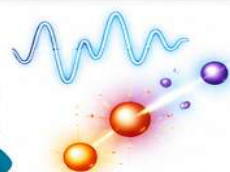
$$\text{Stopping potential, } V_0 = \frac{KE_{\max}}{e} = \frac{2.51 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.57 \text{ V}$$

$$V = \frac{kq}{r} \Rightarrow q = \frac{Vr}{k} = \frac{1.57 \times 0.1}{9 \times 10^9} = 1.75 \times 10^{-11} \text{ C}$$



DUAL NATURE OF RADIATION AND MATTER

CBSE Class XII Physics | NCERT Quick Revision Infographic



1. PHOTOELECTRIC EFFECT

Incident light ($h\nu$)

Metal surface

When light of suitable frequency falls on a metal surface, electrons are emitted from the surface. These emitted electrons are called photoelectrons.

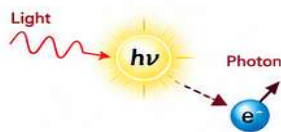
KEY FORMULAE

- $K_{\max} = h\nu - \phi_0$
- $eV_0 = h\nu - \phi_0$
- $\nu_0 = \frac{\phi_0}{h}$
- $\lambda_0 = \frac{hc}{\phi_0}$
- $K_{\max} = \frac{1}{2} m\nu^2$

ϕ_0 = Work function (eV)
 V_0 = Stopping potential (V)
 ν_0 = Threshold frequency
 λ_0 = Threshold wavelength

2. EINSTEIN PHOTON THEORY

Light consists of tiny packets of energy called photons.



- One photon of energy $h\nu$ interacts with one electron.
- Entire energy is transferred.
- If $h\nu > \phi_0$, electron is emitted with kinetic energy $K_{\max}$.

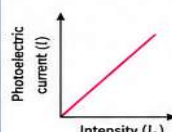
PHOTON & RADIATION

- $E = h\nu$ (Energy of photon)
- $E = \frac{hc}{\lambda}$
- $p = \frac{h\nu}{c}$ (Momentum)
- $p = \frac{h}{\lambda}$

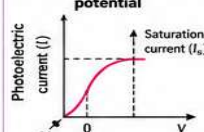
$h = 6.626 \times 10^{-34}$ J s (Planck's constant)
 $c = 3 \times 10^8$ m s⁻¹ (Speed of light)

3. EXPERIMENTAL GRAPHS

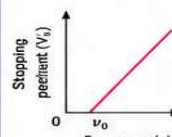
1. Photoelectric current vs Intensity



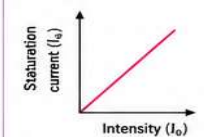
2. Photoelectric current vs Collector potential



3. Stopping potential vs Frequency



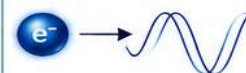
4. Saturation current vs Intensity



- I_s (Saturation current) increases with intensity.
- V_0 (Stopping potential) increases with frequency.
- Photoelectric current becomes zero at $V = -V_0$.

4. de BROGLIE MATTER WAVES

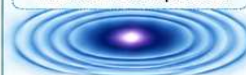
Particles like electrons show wave nature. Proposed by Louis de Broglie.



de BROGLIE RELATION

- $\lambda = \frac{h}{p}$ (Wavelength)
- $\lambda = \frac{h}{mv}$ (For non-relativistic particles)
- λ = de Broglie wavelength
 p = Momentum of particle
 m = Mass of particle
 v = Velocity of particle

★ Matter exhibits dual nature: Particles at one scale and waves at microscopic scale.



OBSERVATIONS IN PHOTOELECTRIC EFFECT

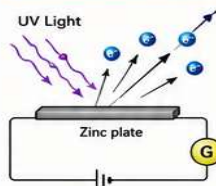
A. HERTZ' OBSERVATIONS (1887)



During electromagnetic wave experiments, Hertz observed that sparks across the detector were strengthened when the metal plate was illuminated by ultraviolet light.

Conclusion: Ultraviolet light enhances the electric discharge. (First observation of photoelectric effect)

B. HALLWACHS & LENARD OBSERVATIONS (1888 – 1902)



- Electrons are emitted from the zinc plate.
- For a given metal, there is a minimum frequency (Threshold frequency ν_0) below which no electrons are emitted, no matter how intense the light.
- Emission is instantaneous ($\sim 10^{-9}$ s).
- Depends on nature of material and frequency, not on intensity.

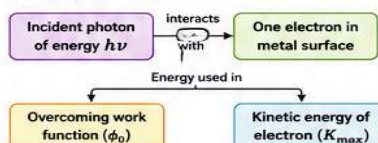
Conclusion: Existence of threshold frequency and instantaneous emission.

C. EXPERIMENTAL OBSERVATIONS (GENERAL)

- Photoelectric current is directly proportional to intensity of incident light (for $\nu > \nu_0$).
- Maximum kinetic energy ($K_{\max}$) depends on frequency of light, not on intensity.
- Stopping potential is independent of intensity but depends on frequency.
- There exists a threshold frequency (ν_0) for each metal below which no photoelectrons are emitted.
- Photoelectric emission is instantaneous ($\sim 10^{-9}$ s or less).
- Current rises with collector potential and becomes constant (saturation current).

EINSTEIN'S PHOTOELECTRIC EQUATION

According to Einstein,



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

(Einstein's Photoelectric Equation)

- If $h\nu < \phi_0 \rightarrow$ No emission
- If $h\nu = \phi_0 \rightarrow K_{\max} = 0$ (threshold condition)
- If $h\nu > \phi_0 \rightarrow K_{\max} > 0$

PARTICLE NATURE OF LIGHT (PHOTON)

- Light behaves as particles called photons.
- A photon has zero rest mass and travels at speed c in vacuum.
- Energy of photon: $E = h\nu$
- Momentum of photon: $p = \frac{h\nu}{c} = \frac{h}{\lambda}$
- Intensity of light depends on number of photons (more photons $\rightarrow$ more intensity).

WAVE-PARTICLE DUALITY



$E \propto \nu$ (Photon energy)
 $I \propto$ Number of photons
 $\nu > \nu_0$ for emission

MATTER WAVES

- Louis de Broglie proposed that every moving particle is associated with a wavelength.
- These waves are called matter waves.
- These waves are different from electromagnetic waves and are important at microscopic scale.

de Broglie Relation

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

where, $h = 6.626 \times 10^{-34}$ J s
 p = momentum, m = mass, v = velocity

Key Points about Matter Waves

- ★ As momentum increases, λ decreases.
- ★ As mass increases, λ decreases.
- ★ Matter waves are significant for electrons, protons, neutrons at microscopic scale.



IMPORTANT POINTS

- Light has dual nature – wave nature (interference, diffraction) and particle nature (photoelectric effect).
- Photoelectric effect can be explained only by particle nature of light (photon theory).
- Matter also shows wave nature (de Broglie hypothesis).
- Dual nature is a fundamental concept of quantum physics.

“Light is both a wave and a particle. Matter is also both a particle and a wave.”

