Dual Nature of Radiation & Matter

Class 12 Physics · Chapter 11 · CBSE

Handwritten Notes · Sequence: NCERT + S.L. Arora

How to use these notes: Topics follow the NCERT order (sections 11.1–11.8). Extra topics from S.L. Arora are added where they fit and marked [S.L. Arora]. Sections marked not in current CBSE syllabus are kept for JEE / NEET. Every derivation is written step by step. Boxed formulas are the ones to remember. **20 CBSE-pattern questions** are at the end.

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1. Introduction NCERT 11.1

→ Maxwell's equations and Hertz's experiments (1887) established light as an **electromagnetic wave** — it explains interference, diffraction and polarisation.

→ **Discharge-tube studies** (Crookes, J.J. Thomson 1897) showed cathode rays are streams of negatively charged particles — **electrons**, with $e/m \approx 1.76 \times 10^{11}$ C/kg.

→ Millikan's oil-drop experiment: charge on an electron $e = 1.602 \times 10^{-19}$ C; mass $m = 9.11 \times 10^{-31}$ kg.

Dual nature: light behaves as a **wave** (interference, diffraction) and as a **particle** (photoelectric effect). Matter, too, shows wave behaviour. This chapter studies both.

2. Electron Emission NCERT 11.2

→ Free electrons in a metal cannot normally leave the surface — they are held back by the attraction of the positive ions.

Work function (ϕ_0): the minimum energy needed by an electron to escape from the metal surface. It depends on the metal and the nature of its surface. Measured in electron-volt.

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

→ 1 eV is the energy gained by an electron accelerated through a potential difference of 1 V.

The minimum energy can be supplied in three ways:

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Type	Energy supplied by	Example
Thermionic emission	heating the metal	filament of a vacuum tube
Field emission	a very strong electric field ($\sim 10^8$ V/m)	spark plug
Photoelectric emission	light of suitable frequency	photocell

→ Platinum has the highest work function (≈ 5.65 eV); caesium one of the lowest (≈ 2.14 eV).

3. Photoelectric Effect NCERT 11.3

Photoelectric effect: the emission of electrons from a metal surface when light (radiation) of suitable frequency falls on it. The emitted electrons are called **photoelectrons**.

→ **Hertz (1887):** sparks across a gap jumped more easily when its electrodes were lit by ultraviolet light.

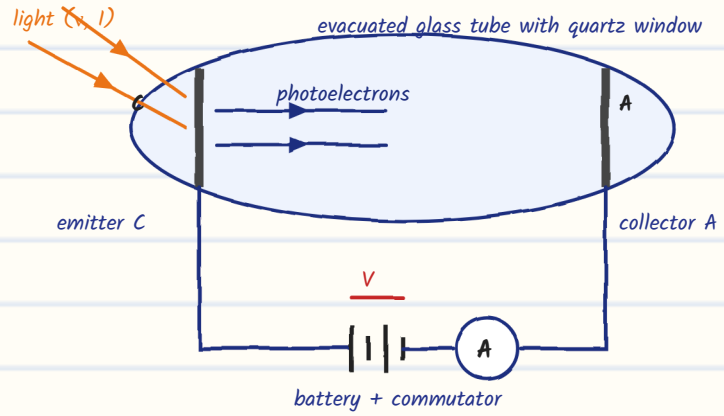
→ **Hallwachs and Lenard (1886–1902):** UV light on the emitter made current flow in an evacuated tube; no current flowed when light was stopped. A negatively charged zinc plate lost its charge in UV light; a neutral plate became positive.

→ For each metal there is a minimum frequency — the **threshold frequency ν_0** — below which no emission takes place, however intense the light.

→ Alkali metals (Li, Na, K, Cs, Rb) emit electrons even with visible light; zinc, cadmium and magnesium need ultraviolet light.

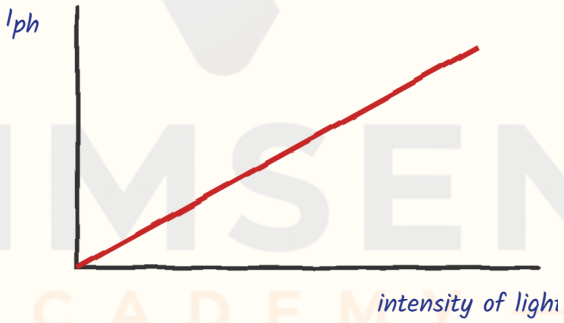
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4. Experimental Study of Photoelectric Effect NCERT 11.4



→ Light falls on emitter C; photoelectrons move to collector A. A potential V between C and A (can be made positive or negative) and microammeter A measure the photocurrent.

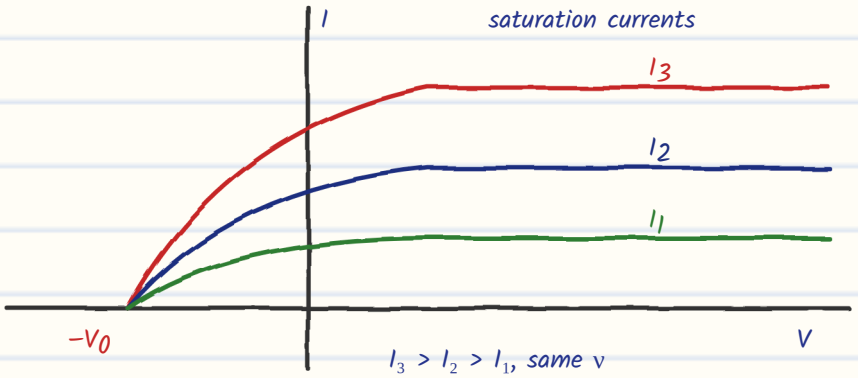
(a) Effect of intensity of light



→ At fixed ν and V, the photocurrent is **directly proportional to intensity** — number of photoelectrons emitted per second ∝ intensity.

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(b) Effect of potential — stopping potential



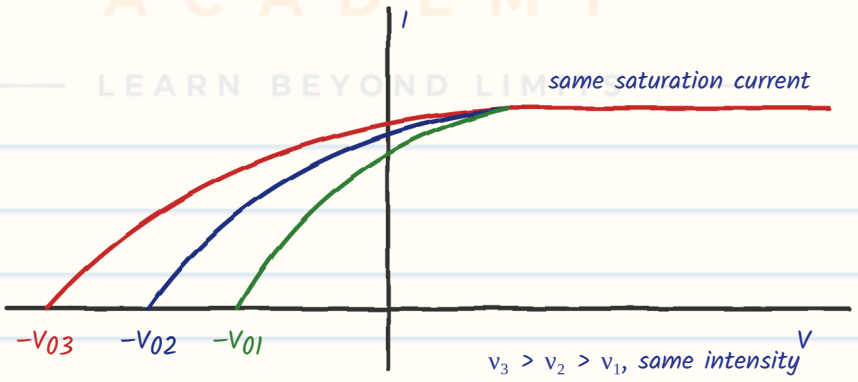
→ As the collector potential increases, current rises to a **saturation value** (all emitted electrons are collected).

→ With a negative (retarding) potential the current falls. At **stopping potential V_0** even the fastest electrons are stopped — current becomes zero.

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

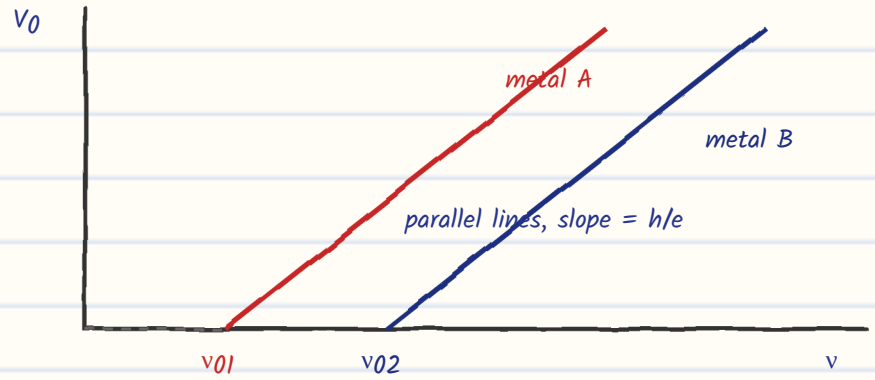
→ For a given frequency, V_0 is the **same for all intensities** — K_{max} does not depend on intensity.

(c) Effect of frequency



→ Higher frequency → larger stopping potential. Saturation current is the same (same intensity).

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→ V_0 varies **linearly** with ν. Below the threshold frequency ν_0, no emission occurs. Graphs for different metals are parallel straight lines.

Laws of photoelectric emission: (1) photocurrent ∝ intensity; (2) saturation current ∝ intensity, V_0 independent of intensity; (3) K_{max} increases linearly with ν, independent of intensity; (4) no emission below ν_0; (5) emission is **instantaneous** (~10^{-9} s).

5. Photoelectric Effect and Wave Theory NCERT 11.5

According to the wave picture, energy is spread continuously over the wavefront. This predicts:

Wave theory predicts	Experiment shows
K_{max} should increase with intensity	K_{max} is independent of intensity
Light of any frequency should cause emission if intense enough	No emission below ν_0
Electrons need time (hours) to absorb enough energy	Emission is instantaneous

→ So the wave theory **fails** to explain the photoelectric effect.

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6. Einstein's Photoelectric Equation NCERT 11.6

→ Einstein (1905): radiation consists of discrete energy packets called **quanta (photons)**, each of energy $E = h\nu$. One photon is absorbed by one electron, completely and instantly.

Derivation

⇒ Energy of one photon = $h\nu$. Part of it (ϕ_0) is used to free the electron; the rest appears as kinetic energy.

⇒ For the most loosely bound electron (no other losses): $h\nu = \phi_0 + K_{max}$

$$K_{max} = h\nu - \phi_0 \quad \text{(Einstein's photoelectric equation)}$$

⇒ At threshold, $K_{max} = 0 \Rightarrow \phi_0 = h\nu_0 = \frac{hc}{\lambda_0} \Rightarrow K_{max} = h(\nu - \nu_0)$

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

$$V_0 = \frac{h}{e}\nu - \frac{\phi_0}{e}$$

⇒ Compare with $y = mx + c$: graph of V_0 vs ν is a straight line with slope = h/e (same for all metals) and intercept on ν-axis = ν_0, on V_0-axis = $-\phi_0/e$.

→ Millikan verified this equation and found $h = 6.63 \times 10^{-34}$ J s from the slope.

How the equation explains each law

→ K_{max} depends only on ν and ϕ_0, not on intensity ✓. If $\nu < \nu_0$, $K_{max} < 0$ — impossible, so no emission ✓.

→ Greater intensity = more photons per second = more electrons emitted ⇒ larger current ✓. One photon is absorbed in one go ⇒ instantaneous emission ✓.

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$$\text{Useful: } E\,(\text{eV}) = \frac{1240}{\lambda\,(\text{nm})} \qquad hc = 1240 \text{ eV nm}$$

Sample problem: Caesium has work function 2.14 eV. Light of frequency 6×10^{14} Hz falls on it. Find K_{max} and V_0.

$h\nu = (6.63 \times 10^{-34} \times 6 \times 10^{14})/(1.6 \times 10^{-19}) = 2.49$ eV

$K_{max} = 2.49 - 2.14 = \mathbf{0.35\ eV}$; $V_0 = \mathbf{0.35\ V}$

Sample problem: Find the threshold wavelength of a metal of work function 2.0 eV.

$\lambda_0 = hc/\phi_0 = 1240/2.0$ nm $= \mathbf{620\ nm}$

7. Particle Nature of Light: The Photon NCERT 11.7

Energy and momentum of a photon — derivation

⇒ Energy: $E = h\nu = \frac{hc}{\lambda}$

⇒ Relativistic energy of a particle: $E^2 = p^2c^2 + m_0^2c^4$. A photon has zero rest mass ($m_0 = 0$) ⇒ $E = pc$

⇒ $p = \frac{E}{c} = \frac{h\nu}{c}$

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

Number of photons emitted per second [S.L. Arora]

⇒ A source of power P emits n photons per second, each of energy $h\nu$: $P = n\,h\nu$

$$n = \frac{P}{h\nu} = \frac{P\lambda}{hc}$$

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Properties of photons

- → All photons of light of frequency ν have the same energy $h\nu$ and momentum $h\nu/c$, whatever the intensity.
- → Increasing intensity increases the **number** of photons crossing unit area per second, not the energy of each photon.
- → Photons are electrically neutral — not deflected by electric or magnetic fields.
- → In photon–particle collisions (e.g. with electrons), total energy and momentum are conserved, but photons may be absorbed or created.
- → Rest mass of a photon is zero; it always travels at speed c in vacuum.

Sample problem: A 100 W sodium lamp radiates light of wavelength 589 nm uniformly. Find the energy of one photon and the number of photons emitted per second.

$E = hc/\lambda = (6.63 \times 10^{-34} \times 3 \times 10^{8})/(589 \times 10^{-9}) = \mathbf{3.38 \times 10^{-19}\ J}$

$n = P/E = 100/3.38 \times 10^{-19} = \mathbf{2.96 \times 10^{20}\ photons/s}$

8. Wave Nature of Matter — de Broglie Hypothesis

NCERT 11.8

de Broglie (1924): nature is symmetrical. If radiation has a dual nature, moving material particles should also show wave nature. The waves associated with moving particles are called **matter waves** or de Broglie waves.

de Broglie wavelength — derivation

- ⇒ For a photon, from Section 7: $p = \frac{h}{\lambda} \Rightarrow \lambda = \frac{h}{p}$
- ⇒ de Broglie proposed that the same relation holds for any material particle of mass m moving with speed v (momentum $p = mv$):

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

⇒ In terms of kinetic energy K: $K = \frac{p^2}{2m} \Rightarrow p = \sqrt{(2mK)}$

$$\lambda = \frac{h}{\sqrt{(2mK)}}$$

→ $\lambda \propto 1/p$: heavier or faster particles have smaller wavelengths. For everyday objects λ is so small that wave effects cannot be observed.

→ The de Broglie wavelength does **not** depend on the charge of the particle. A photon's $\lambda = h/p$ is the same relation, so the hypothesis is consistent with light.

Sample problem: Find the de Broglie wavelength of a ball of mass 0.12 kg moving at 20 m/s.

$\lambda = h/mv = 6.63 \times 10^{-34}/(0.12 \times 20) =$ **2.76×10^{-34} m** — far too small to detect.

9. λ of an Accelerated Charged Particle NCERT 11.8

⇒ A particle of charge q and mass m, starting from rest, is accelerated through a potential difference V. Energy gained: $K = qV$

⇒ From $\lambda = \frac{h}{\sqrt{(2mK)}}$:

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

For an electron

⇒ Put $h = 6.63 \times 10^{-34}$ J s, $m = 9.11 \times 10^{-31}$ kg, $q = e = 1.6 \times 10^{-19}$ C:

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⇒ $\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{(2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19} \times V)}}$

⇒ $= \frac{1.227 \times 10^{-9}}{\sqrt{V}}$ m

$$\lambda_e = \frac{1.227}{\sqrt{V}} \text{ nm} = \frac{12.27}{\sqrt{V}} \text{ Å}$$

→ For V = 100 V, λ = 0.1227 nm — comparable to the spacing of atoms in a crystal, so electrons are diffracted by crystals (basis of the electron microscope).

→ **Comparing particles** [S.L. Arora]: same V ⇒ $\lambda \propto 1/\sqrt{(mq)}$. For a proton and an α-particle: $\frac{\lambda_p}{\lambda_\alpha} = \sqrt{(\frac{4m \times 2e}{m \times e})} = \sqrt{8} = 2\sqrt{2}$.

Sample problem: An electron is accelerated through 100 V. Find its de Broglie wavelength.

λ = 1.227/√100 nm = **0.1227 nm**

10. Thermal Neutrons [S.L. Arora]

⇒ A particle in thermal equilibrium at temperature T has average kinetic energy $K = \frac{3}{2}kT$ (k = Boltzmann constant).

⇒ $\lambda = \frac{h}{\sqrt{(2mK)}} = \frac{h}{\sqrt{(2m \times 3kT/2)}}$

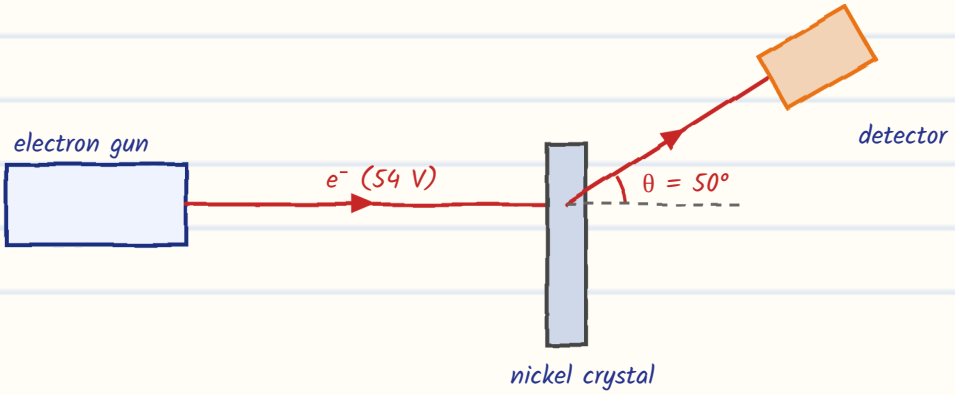
$$\lambda = \frac{h}{\sqrt{(3mkT)}}$$

→ For neutrons at room temperature (300 K) λ ≈ 0.146 nm — suitable for neutron diffraction from crystals.

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11. Davisson–Germer Experiment [S.L. Arora]

not in current CBSE syllabus



→ Electrons from a heated filament, accelerated through V, strike a nickel crystal. A detector measures the scattered electrons at different angles θ.

→ A sharp peak appears at V = 54 V and θ = 50° — this is **diffraction**, so electrons behave as waves.

⇒ From crystal data (Bragg's law, d = 0.091 nm, glancing angle 65°): $\lambda = 2d \sin 65° = 0.165$ nm

⇒ From de Broglie: $\lambda = 1.227/\sqrt{54}$ nm = 0.167 nm — excellent agreement, confirming the de Broglie hypothesis.

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12. Formula Sheet — Quick Revision

Electron-volt	$1\ eV = 1.602 \times 10^{-19}\ J$
Photon energy	$E = h\nu = hc/\lambda$; $E\ (eV) = 1240/\lambda\ (nm)$
Photon momentum	$p = h/\lambda = E/c$
Photons per second	$n = P/h\nu = P\lambda/hc$
Work function	$\phi_0 = h\nu_0 = hc/\lambda_0$
Einstein's equation	$K_{max} = h\nu - \phi_0 = h(\nu - \nu_0)$
Stopping potential	$eV_0 = K_{max}$; $V_0 = (h/e)\nu - \phi_0/e$
V_0–ν graph	slope h/e; ν-intercept ν_0; V-intercept $-\phi_0/e$
de Broglie	$\lambda = h/p = h/mv = h/\sqrt{(2mK)}$
Accelerated charge	$\lambda = h/\sqrt{(2mqV)}$
Electron	$\lambda = 1.227/\sqrt{V}\ nm$
Thermal particle	$\lambda = h/\sqrt{(3mkT)}$

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13. CBSE-pattern Questions

*20 questions of the kind asked in CBSE Class 12 board papers — MCQs, assertion–reason, short and long answers, numericals and a case study. Short answers / hints are given in **green**. Use hc = 1240 eV nm where needed.*

Section A — MCQ & Assertion–Reason (1 mark each)

Q1. Photoelectric emission from a metal surface occurs only when the frequency of incident light is [1]

(a) less than ν_0 (b) equal to or greater than ν_0 (c) any value if intensity is high (d) exactly ν_0

Ans: (b)

Q2. The stopping potential in a photoelectric experiment depends on [1]

(a) intensity of light (b) frequency of light (c) both (d) neither

Ans: (b) — $eV_0 = h\nu - \phi_0$.

Q3. The slope of the graph of stopping potential versus frequency gives [1]

(a) h (b) e/h (c) h/e (d) ϕ_0/e

Ans: (c)

Q4. A proton and an α-particle have the same kinetic energy. The ratio $\lambda_p : \lambda_\alpha$ of their de Broglie wavelengths is [1]

(a) 1 : 2 (b) 2 : 1 (c) 1 : 4 (d) 4 : 1

Ans: (b) — $\lambda = h/\sqrt{(2mK)} \Rightarrow \lambda \propto 1/\sqrt{m}$; $m_\alpha = 4m_p$.

Q5. The intensity of incident light is doubled, keeping frequency constant. The saturation photocurrent [1]

(a) is halved (b) remains the same (c) is doubled (d) becomes four times

Ans: (c) — number of photons per second doubles.

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Q6. An electron and a photon have the same de Broglie wavelength. The ratio of their momenta $p_e : p_{ph}$ is 1

(a) 1 : 1 (b) 1 : 2 (c) 2 : 1 (d) depends on mass

Ans: (a) — $p = h/\lambda$ for both.

Q7. The threshold wavelength for a metal of work function 3.1 eV is about 1

(a) 200 nm (b) 400 nm (c) 620 nm (d) 800 nm

Ans: (b) — $\lambda_0 = 1240/3.1 = 400$ nm.

Q8. **Assertion (A):** The photoelectric current increases with the intensity of incident light. **Reason (R):** The number of photons striking the surface per second increases with intensity. 1

(a) Both true, R explains A (b) Both true, R does not explain A

(c) A true, R false (d) A false, R true

Ans: (a)

Q9. **Assertion (A):** The maximum kinetic energy of photoelectrons increases with the intensity of light. **Reason (R):** K_{max} depends on the frequency of incident light. 1

(a) Both true, R explains A (b) Both true, R does not explain A

(c) A true, R false (d) A false, R true

Ans: (d) — K_{max} is independent of intensity.

Q10. **Assertion (A):** The wave nature of a moving cricket ball is not observed. **Reason (R):** Its de Broglie wavelength is extremely small. 1

(a) Both true, R explains A (b) Both true, R does not explain A

(c) A true, R false (d) A false, R true

Ans: (a)

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Section B — Short & Long Answer

Q11. Define (i) work function, (ii) threshold frequency and (iii) stopping potential. 2

Ans: see Topics 2–4.

Q12. Write Einstein's photoelectric equation. Use it to explain (i) the existence of threshold frequency, (ii) why K_{max} is independent of intensity. 3

Ans: see Topic 6 — $K_{max} = h\nu - \phi_0$.

Q13. Draw the graph of stopping potential versus frequency for two metals A and B ($\phi_A < \phi_B$). What does the slope represent? Why are the lines parallel? 2

Ans: see Topic 4(c) — slope h/e is the same for every metal.

Q14. State three features of the photoelectric effect that cannot be explained by the wave theory of light. 3

Ans: see Topic 5.

Q15. Derive an expression for the de Broglie wavelength of an electron accelerated from rest through a potential difference V. 2

Ans: see Topic 9 — $\lambda = h/\sqrt{(2meV)} = 1.227/\sqrt{V}$ nm.

Q16. Radiation of wavelength 330 nm falls on a metal of work function 2.5 eV. Find (i) the maximum kinetic energy of photoelectrons, (ii) the stopping potential. 2

Ans: $E = 1240/330 = 3.76$ eV; (i) $K_{max} = 3.76 - 2.5 =$ **1.26 eV**; (ii) $V_0 =$ **1.26 V**.

Q17. An electron and a proton have the same de Broglie wavelength. Which has greater kinetic energy, and by what factor? 2

Ans: same $\lambda \Rightarrow$ same p; $K = p^2/2m \Rightarrow K_e/K_p = m_p/m_e \approx$ **1836**, so the electron has greater kinetic energy.

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Q18. A 10 mW laser emits light of wavelength 632.8 nm. How many photons does it emit per second? 2

Ans: $E = hc/\lambda = 3.14 \times 10^{-19}$ J; $n = P/E = 10^{-2}/3.14 \times 10^{-19} =$ **3.2×10^{16} photons/s.**

Q19. Describe an experiment to study the photoelectric effect. Draw graphs showing the variation of photocurrent with collector potential for (i) different intensities at fixed frequency, (ii) different frequencies at fixed intensity. 5

Ans: see Topic 4 — set-up and graphs (b) and (c).

Q20. **Case study — Photocell.** A photocell converts light into electric current by the photoelectric effect. Light of wavelength 500 nm falls on a cathode of work function 2.0 eV. Answer: 4

(i) Find the energy of each photon in eV.

(ii) Find the maximum kinetic energy of the emitted electrons.

(iii) What happens to the photocurrent and the stopping potential if the intensity is doubled?

(iv) Find the momentum of each photon.

Ans: (i) $E = 1240/500 =$ **2.48 eV**. (ii) $K_{max} = 2.48 - 2.0 =$ **0.48 eV**. (iii) Current doubles; stopping potential stays the same. (iv) $p = h/\lambda = 6.63 \times 10^{-34}/5 \times 10^{-7} =$ **1.33×10^{-27} kg m/s.**

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