

CBSE Class 12 Physics Question Paper 2023 with Solution PDF-Set 55/3/3



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **35** questions. **All questions are compulsory.**
- (ii) This question paper is divided into **five** Sections – **A, B, C, D and E.**
- (iii) In **Section A** – Questions no. **1 to 18** are Multiple Choice (MCQ) type questions, carrying **1** mark each.
- (iv) In **Section B** – Questions no. **19 to 25** are Very Short Answer (VSA) type questions, carrying **2** marks each.
- (v) In **Section C** – Questions no. **26 to 30** are Short Answer (SA) type questions, carrying **3** marks each.
- (vi) In **Section D** – Questions no. **31 to 33** are Long Answer (LA) type questions carrying **5** marks each.
- (vii) In **Section E** – Questions no. **34 and 35** are case-based questions carrying **4** marks each.
- (viii) There is no overall choice. However, an internal choice has been provided in 2 questions in Section B, 2 questions in Section C, 3 questions in Section D and 2 questions in Section E.
- (ix) Use of calculators is **not** allowed.

Use the following values of physical constants, if required :

$$c = 3 \times 10^8 \text{ m/s}$$

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$$

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$$

$$\frac{1}{4\pi\epsilon_0} = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$$

$$\text{Mass of electron } (m_e) = 9.1 \times 10^{-31} \text{ kg}$$

$$\text{Mass of neutron} = 1.675 \times 10^{-27} \text{ kg}$$

$$\text{Mass of proton} = 1.673 \times 10^{-27} \text{ kg}$$

$$\text{Avogadro's number} = 6.023 \times 10^{23} \text{ per gram mole}$$

$$\text{Boltzmann constant} = 1.38 \times 10^{-23} \text{ JK}^{-1}$$

Section A (18 marks)

1. A battery of emf E and internal resistance r is connected to an external circuit. The potential drop within the battery is proportional to: [1 mark]

- (A) current in the circuit
- (B) total resistance of the circuit
- (C) emf of the battery
- (D) power dissipated in the circuit

Correct Answer: (A) current in the circuit

Solution:

Concept:

- Internal resistance r produces a potential drop $V_{\text{int}} = Ir$, where I is the current through the cell.
- For a discharging battery, its emf E , terminal voltage V and internal drop satisfy $E = V + Ir$.

Step 1: Apply Ohm's law inside the battery The battery's internal resistance carries the same current as the external series circuit. Applying Ohm's law to this resistance gives

$$V_{\text{int}} = Ir.$$

For the given battery, r is fixed, so the internal drop changes directly with current.

Step 2: Compare the proposed proportionalities With external resistance R , $I = E/(R+r)$; increasing total resistance reduces the internal drop, so (B) is incorrect. Emf alone does not determine this drop without specifying the load, so (C) is not the general relation sought. Dissipated power is quadratic in current, whereas the drop is linear, excluding (D).

Step 3: Conclusion The potential drop inside the battery is directly proportional to the current through it. Hence, the correct option is (A).

Quick Tip to Solve: For a battery's internal voltage loss, immediately write Ir ; use $E - Ir$ only for its terminal voltage.

2. The momentum of a photon of wavelength λ is : [1 mark]

- (A) $\frac{h\lambda}{c^2}$
- (B) $\frac{h\lambda}{c}$
- (C) $\frac{h}{\lambda}$
- (D) zero

Correct Answer: (C) $\frac{h}{\lambda}$

Solution:

Concept:

- A photon of frequency ν has energy $E = h\nu$, where h is Planck's constant.
- For a photon, $E = pc$ and $c = \nu\lambda$, where p is momentum, c is the speed of light and λ is wavelength.

Step 1: Express the energy in terms of wavelength Substituting $\nu = c/\lambda$ into Planck's relation gives

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

Although a photon has zero rest mass, it carries energy and therefore has nonzero momentum.

Step 2: Divide the photon energy by the speed of light Using the energy-momentum relation for radiation,

$$p = \frac{E}{c} = \frac{hc}{\lambda c} = \frac{h}{\lambda}.$$

Options (A) and (B) incorrectly make momentum increase with wavelength and have incorrect dimensions. Option (D) confuses zero rest mass with zero momentum.

Step 3: Conclusion The momentum is $p = h/\lambda$. Hence, the correct option is (C).

Quick Tip to Solve: Remember $p\lambda = h$: doubling a photon's wavelength halves its momentum.

3. Two thin long parallel wires A and B are separated by a distance r and carry current I each in the same direction. The force per unit length exerted by A on wire B is: [1 mark]

- (A) $\frac{\mu_0 I}{2r}$, attractive
(B) $\frac{\mu_0 I^2}{2\pi r}$, repulsive
(C) $\frac{\mu_0 I^2}{2\pi r}$, attractive
(D) $\frac{\mu_0 I}{2\pi r}$, repulsive

Correct Answer: (C) $\frac{\mu_0 I^2}{2\pi r}$, attractive

Solution:

Concept:

- A long straight wire carrying current I produces magnetic field $B = \mu_0 I / (2\pi r)$ at perpendicular distance r .
- A wire of length L , carrying current perpendicular to a magnetic field, experiences force $F = ILB$. Parallel currents in the same direction attract.

Step 1: Calculate the force per unit length At wire B, the field due to wire A is perpendicular to the current in B. Therefore,

$$\frac{F}{L} = I \left(\frac{\mu_0 I}{2\pi r} \right) = \frac{\mu_0 I^2}{2\pi r}.$$

The two factors of current arise from the source of the field and the wire experiencing the force.

Step 2: Determine the direction and compare options Applying the right-hand rule for the field and $\vec{F} = I\vec{L} \times \vec{B}$ gives a force on B towards A. Thus the force is attractive. Option (A) has the wrong

magnitude, including a missing current factor; option (B) has the right magnitude but incorrectly says repulsive. Option (D) has both a missing current factor and the wrong direction.

Step 3: Conclusion The force per unit length is $\mu_0 I^2 / (2\pi r)$, attractive. Hence, the correct option is (C).

Quick Tip to Solve: For parallel wires, first remember same-direction currents attract, then check the magnitude contains $I_1 I_2 / (2\pi r)$.

4. Two wires of equal length and radii r and $2r$ are connected in series. Their resistivities are 2ρ and ρ respectively. For the same current passing through the combination, the potential drop across their ends will be in the ratio of: [1 mark]

- (A) 2 : 1
- (B) 1 : 2
- (C) 4 : 1
- (D) 8 : 1

Correct Answer: (D) 8 : 1

Solution:

Concept:

- A uniform wire has resistance $R = \rho L / A$, where ρ is resistivity, L is length and $A = \pi r^2$ is cross-sectional area.
- Series wires carry equal current, so their potential drops satisfy $V_1 / V_2 = R_1 / R_2$ by Ohm's law.

Step 1: Write the two wire resistances Let their common length be L . Match each resistivity to its stated radius:

$$R_1 = \frac{2\rho L}{\pi r^2}, \quad R_2 = \frac{\rho L}{\pi (2r)^2} = \frac{\rho L}{4\pi r^2}.$$

The second wire's radius is twice as large, so its area is four times as large.

Step 2: Compare potential drops at equal current The common current cancels in the ratio:

$$\frac{V_1}{V_2} = \frac{R_1}{R_2} = \frac{2\rho L}{\pi r^2} \frac{4\pi r^2}{\rho L} = 8.$$

The factor of two in resistivity and factor of four from inverse area multiply. Options (A) and (C) omit one of these effects, while (B) reverses even the resistivity contribution.

Step 3: Conclusion The potential drops are in the ratio $V_1 : V_2 = 8 : 1$. Hence, the correct option is (D).

Quick Tip to Solve: For equal-length series wires, use $V_1 / V_2 = (\rho_1 / \rho_2)(r_2 / r_1)^2$; square the radius ratio.

5. A capacitor is charged by a battery. Between the plates, during process of charging:

[1 mark]

- (A) only displacement current exists.
- (B) only conduction current exists.
- (C) both displacement current and conduction current exist.
- (D) no current exists.

Correct Answer: (A) only displacement current exists.

Solution:

Concept:

- Conduction current requires transport of free charge through a material; an ideal capacitor has an insulating gap between its plates.
- A changing electric flux Φ_E produces displacement current $I_d = \epsilon_0 d\Phi_E/dt$, where ϵ_0 is the permittivity of free space.

Step 1: Identify the current in the plate gap During charging, conduction current flows in the connecting wires and deposits charge on the plates. Free charges do not travel across the insulating gap, so there is no conduction current between the plates. This excludes options (B) and (C).

Step 2: Account for the changing electric field As the plate charge Q increases, the electric field and electric flux in the gap increase. For ideal parallel plates, $\Phi_E = Q/\epsilon_0$, hence

$$I_d = \epsilon_0 \frac{d\Phi_E}{dt} = \frac{dQ}{dt}.$$

This is nonzero during charging and equals the conduction current in the wires, so (D) is incorrect.

Step 3: Conclusion Only displacement current exists between the plates during charging. Hence, the correct option is (A).

Quick Tip to Solve: Separate the locations: charging wires carry conduction current, while the insulating capacitor gap carries displacement current.

6. In the wave picture of light, the intensity I of light is related to the amplitude A of the wave as:

[1 mark]

- (A) $I \propto \sqrt{A}$
- (B) $I \propto A$
- (C) $I \propto A^2$
- (D) $I \propto \frac{1}{A^2}$

Correct Answer: (C) $I \propto A^2$

Solution:

Concept:

- Light intensity I is the time-averaged energy crossing unit area per unit time, perpendicular to propagation.
- In the same medium, wave energy density and intensity are proportional to the square of the wave amplitude A : $I = kA^2$, with constant k .

Step 1: Relate intensity to the oscillating field Light is an electromagnetic wave. Its instantaneous

energy density depends on the squares of its electric and magnetic fields. Averaging a sinusoidal field over a cycle preserves its amplitude-squared dependence; for electric-field amplitude E_0 in vacuum,

$$I = \frac{1}{2} \varepsilon_0 c E_0^2.$$

Step 2: Check the power of amplitude Thus doubling A multiplies intensity by four. Option (A) instead predicts a factor $\sqrt{2}$, and (B) predicts two. Option (D) would make a larger amplitude give a smaller intensity. None matches the energy carried by the wave.

Step 3: Conclusion The required relation is $I \propto A^2$. Hence, the correct option is (C).

Quick Tip to Solve: When amplitudes are compared, square their ratio to get the intensity ratio: $I_1/I_2 = (A_1/A_2)^2$.

7. For the forward biasing of a p-n junction diode, which of the following statements is not correct?

[1 mark]

- (A) The potential barrier decreases.
- (B) Minority carrier injection occurs.
- (C) Width of depletion layer increases.
- (D) Forward current is due to the diffusion of both holes and electrons.

Correct Answer: (C) Width of depletion layer increases.

Solution:

Concept:

- Forward bias connects the p-side to the positive terminal and the n-side to the negative terminal; its field opposes the junction's built-in field.
- Reducing the potential barrier narrows the depletion layer and promotes diffusion of majority carriers across the junction.

Step 1: Check the barrier and depletion-layer statements The applied forward voltage reduces the effective barrier, so statement (A) is correct. With the barrier weakened, the depletion-layer width decreases. Statement (C), which says the width increases, therefore contradicts forward-bias behaviour.

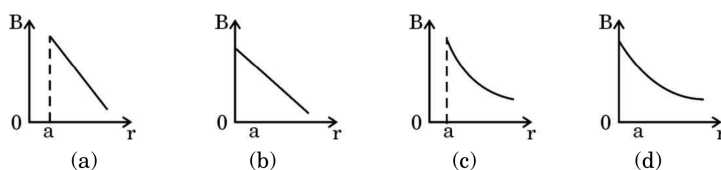
Step 2: Check the carrier-injection statements Electrons diffuse from the n-side into the p-side, where they become minority carriers; holes diffuse from the p-side into the n-side, where they become minority carriers. This is minority-carrier injection, so (B) is correct. Diffusion of both types contributes to forward current, confirming (D). The question asks for the incorrect statement.

Step 3: Conclusion The depletion layer narrows under forward bias; it does not widen. Hence, the correct option is (C).

Quick Tip to Solve: In forward bias, remember both barrier height and depletion width decrease; injected majority carriers become minority carriers on the opposite side.

8. Which of the following graphs correctly represents the variation of the magnitude of the magnetic field outside a straight infinite current carrying wire of radius ' a ', as a function of distance ' r ' from the centre of the wire?

[1 mark]



- (A) Graph (a)
 (B) Graph (b)
 (C) Graph (c)
 (D) Graph (d)

Correct Answer: (C) Graph (c)

Solution:

Concept:

- Ampere's circuital law gives $B(2\pi r) = \mu_0 I$ outside a long straight current-carrying wire, where I is the enclosed current.
- For a wire of radius a , the exterior field is $B = \mu_0 I / (2\pi r)$ for $r \geq a$; it decreases inversely with distance from the centre.

Step 1: Identify the exterior-field curve At the wire surface the magnetic field is finite:

$$B(a) = \frac{\mu_0 I}{2\pi a}.$$

As r increases beyond a , B decreases as $1/r$, with a progressively smaller slope magnitude, and approaches zero only at very large distance. A straight-line decrease, as in graphs (a) and (b), is incorrect.

Step 2: Check where the exterior region begins The graph requested concerns only the region outside the wire, so its curve must begin at $r = a$, not at the centre $r = 0$. Graph (c) explicitly begins at the dashed line $r = a$ and shows the inverse-distance decay. Graph (d) extends the drawn curve to the centre and does not represent the specified exterior domain correctly.

Step 3: Conclusion Graph (c) shows $B \propto 1/r$ in the exterior region $r \geq a$. Hence, the correct option is (C).

Quick Tip to Solve: For an outside-wire graph, check both the inverse-distance curve and its starting point $r = a$; shape alone is insufficient.

9. 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: [1 mark]

- (A) 0.25 eV
- (B) 0.51 eV
- (C) 1.02 eV
- (D) 0.10 eV

Correct Answer: (B) 0.51 eV

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where $h\nu$ is photon energy and ϕ is the metal's work function.
- Use the same energy unit in both terms: $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.

Step 1: Calculate the incident photon energy With $h = 6.63 \times 10^{-34} \text{ J s}$ and the printed frequency,

$$h\nu = \frac{6.63 \times 10^{-34} \times 6.4 \times 10^{14}}{1.6 \times 10^{-19}} \text{ eV} = 2.652 \text{ eV}.$$

This exceeds the work function, so photoelectrons are emitted.

Step 2: Subtract the work function The energy used to liberate an electron is not part of its kinetic energy:

$$K_{\max} = 2.652 - 2.14 = 0.512 \text{ eV}.$$

Values 0.25, 1.02 and 0.10 eV do not equal this energy difference; the maximum energy is not half or twice the calculated difference.

Step 3: Conclusion The maximum kinetic energy is about 0.51 eV. Hence, the correct option is (B).

Quick Tip to Solve: Convert the photon energy to eV before subtracting a work function quoted in eV.

10. A voltage signal is described by: $v = V_0$ for $0 \leq t \leq \frac{T}{2}$ and $v = 0$ for $\frac{T}{2} \leq t \leq T$ for a cycle. Its rms value is: [1 mark]

- (A) $\frac{V_0}{\sqrt{2}}$
- (B) V_0
- (C) $\frac{V_0}{2}$
- (D) $\sqrt{2} V_0$

Correct Answer: (A) $\frac{V_0}{\sqrt{2}}$

Solution:

Concept:

- The rms voltage is the square root of the mean of the squared instantaneous voltage over a complete period: $V_{\text{rms}} = \sqrt{T^{-1} \int_0^T v^2 dt}$.
- Here T is the period and the voltage is nonzero for only half of it. The rms value differs from the arithmetic mean.

Step 1: Average the squared voltage The first half-cycle contributes V_0^2 , while the second contributes zero:

$$\langle v^2 \rangle = \frac{1}{T} \left(V_0^2 \frac{T}{2} + 0 \frac{T}{2} \right) = \frac{V_0^2}{2}.$$

The value assigned at the single switching instant does not affect this time average.

Step 2: Take the square root For the positive amplitude V_0 , the square root gives $V_{\text{rms}} = V_0/\sqrt{2}$. The value $V_0/2$ is the mean voltage, not its rms value. A constant voltage would have rms V_0 , and $\sqrt{2}V_0$ cannot occur because rms cannot exceed the maximum magnitude of this signal.

Step 3: Conclusion The rms value is $\frac{V_0}{\sqrt{2}}$. Hence, the correct option is (A).

Quick Tip to Solve: For a pulse of amplitude V_0 present for a fraction d of a cycle, use $V_{\text{rms}} = V_0\sqrt{d}$.

11. At a certain temperature in an intrinsic semiconductor, the electrons and holes concentration is $1.5 \times 10^{16} \text{ m}^{-3}$. When it is doped with a trivalent dopant, hole concentration increases to $4.5 \times 10^{22} \text{ m}^{-3}$. In the doped semiconductor, the concentration of electrons (n_e) will be: [1 mark]

- (A) $3 \times 10^6 \text{ m}^{-3}$
- (B) $5 \times 10^7 \text{ m}^{-3}$
- (C) $5 \times 10^9 \text{ m}^{-3}$
- (D) $6.75 \times 10^{38} \text{ m}^{-3}$

Correct Answer: (C) $5 \times 10^9 \text{ m}^{-3}$

Solution:

Concept:

- At a fixed temperature in thermal equilibrium, the mass-action law is $n_e n_h = n_i^2$, where n_i is the intrinsic carrier concentration.
- A trivalent impurity is an acceptor: holes become majority carriers and electrons become minority carriers. The temperature-dependent product remains fixed.

Step 1: Identify the concentrations Before doping, each intrinsic carrier concentration is $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$. After doping, the hole concentration is $n_h = 4.5 \times 10^{22} \text{ m}^{-3}$. The electron concentration is obtained by division, not by multiplying these two concentrations.

Step 2: Apply the mass-action law

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5 \times 10^{16})^2}{4.5 \times 10^{22}} = 0.5 \times 10^{10} = 5 \times 10^9 \text{ m}^{-3}.$$

This is much smaller than the hole concentration, as expected for a p-type material. Options (A) and (B) have incorrect powers of ten, while (D) does not satisfy the required carrier product and even results from multiplying concentrations.

Step 3: Conclusion The electron concentration is $5 \times 10^9 \text{ m}^{-3}$. Hence, the correct option is (C).

Quick Tip to Solve: Square the intrinsic concentration first: its exponent becomes 32 before dividing by the doped hole concentration.

12. In a single-slit diffraction experiment, the width of the slit is halved. The width of the central maximum, in the diffraction pattern, will become: [1 mark]

- (A) half
- (B) twice
- (C) four times
- (D) one-fourth

Correct Answer: (B) twice

Solution:

Concept:

- For a single slit of width a , the first diffraction minima satisfy $a \sin \theta = \lambda$, where λ is the wavelength.
- In the usual small-angle arrangement, the central maximum has linear width $W = 2D\lambda/a$ on a screen at distance D . Thus W is inversely proportional to slit width.

Step 1: Compare the two slit widths Wavelength and screen distance are unchanged. If the new slit width is $a' = a/2$, then

$$\frac{W'}{W} = \frac{2D\lambda/a'}{2D\lambda/a} = \frac{a}{a/2} = 2.$$

A narrower slit spreads light through a larger diffraction angle.

Step 2: Eliminate the other changes Halving the maximum width would require doubling the slit width, so option (A) reverses the dependence. The width depends on $1/a$, not $1/a^2$, so it does not become four times. Nor does it become one-fourth, which would require the slit to be four times wider.

Step 3: Conclusion The width of the central maximum becomes twice its original value. Hence, the correct option is (B).

Quick Tip to Solve: Keep the product $aW = 2D\lambda$ constant when only the slit width is changed.

13. The ratio of maximum frequency and minimum frequency of light emitted in Balmer series of hydrogen spectrum, in Bohr's model, is: [1 mark]

- (A) $\frac{11}{9}$
- (B) $\frac{9}{5}$
- (C) $\frac{11}{7}$
- (D) $\frac{16}{7}$

Correct Answer: (B) $\frac{9}{5}$

Solution:

Concept:

- In the Balmer series all downward transitions terminate at $n_f = 2$. The emitted frequency is $\nu = cR(1/2^2 - 1/n^2)$, with initial level $n = 3, 4, \dots$
- The smallest energy gap is for $3 \rightarrow 2$; the maximum frequency is the series limit $n \rightarrow \infty$. Here R is the Rydberg constant and c is the speed of light.

Step 1: Identify the frequency limits The lowest-frequency Balmer line and the series-limit frequency are

$$\nu_{\min} = cR \left(\frac{1}{4} - \frac{1}{9} \right) = \frac{5cR}{36},$$

$$\nu_{\max} = cR \left(\frac{1}{4} - 0 \right) = \frac{cR}{4}.$$

Increasing the initial level increases the energy released in reaching level 2.

Step 2: Form the requested ratio

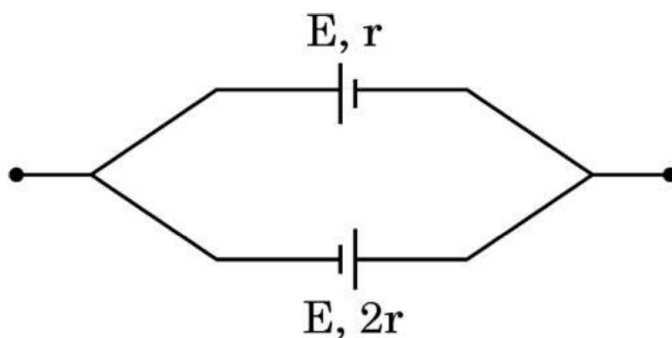
$$\frac{\nu_{\max}}{\nu_{\min}} = \frac{cR/4}{5cR/36} = \frac{9}{5}.$$

The constants cancel. The printed values 11/9, 11/7 and 16/7 do not follow from the Balmer limits; the last instead corresponds to a series ending at level 3.

Step 3: Conclusion The maximum-to-minimum frequency ratio is $\frac{9}{5}$. Hence, the correct option is (B).

Quick Tip to Solve: For any series ending at level m , compare $(m+1) \rightarrow m$ with the limit $\infty \rightarrow m$.

14. Two cells of emf E each and internal resistances r and $2r$ are connected in parallel as shown in the figure. The equivalent emf of the combination is: [1 mark]



- (A) zero
- (B) $\frac{E}{2}$
- (C) $\frac{E}{3}$
- (D) E

Correct Answer: (C) $\frac{E}{3}$

Solution:

Concept:

- The equivalent emf of a cell combination is its open-circuit terminal voltage. For parallel branches it is the conductance-weighted signed emf.
- A cell's longer plate is positive. In the printed figure the upper cell is positive towards the left, but the lower cell is positive towards the right, so their emfs oppose.

Step 1: Assign signs from the cell polarities Let $V = V_L - V_R$. Relative to this direction the upper branch has emf $+E$ and resistance r , while the lower has emf $-E$ and resistance $2r$. With no external

load, the branch currents sum to zero:

$$\frac{V - E}{r} + \frac{V + E}{2r} = 0.$$

A circulating current can exist internally even when the external circuit is open.

Step 2: Solve for the terminal voltage Multiplying by $2r$ gives $2(V - E) + (V + E) = 0$, so $3V - E = 0$. The unequal resistances prevent exact cancellation of the opposing cells. Thus zero and $E/2$ are not the result; E would apply to equal emfs connected with the same polarity, unlike this figure.

Step 3: Conclusion The equivalent emf is $E/3$, with the left terminal positive. Hence, the correct option is (C).

Quick Tip to Solve: Inspect the longer battery plates before using the parallel-cell formula; opposite polarities require opposite emf signs.

15. An inductor, a capacitor and a resistor are connected in series across an ac source of voltage. If the frequency of the source is decreased gradually, the reactance of: [1 mark]

- (A) both the inductor and the capacitor decreases.
- (B) inductor decreases and the capacitor increases.
- (C) both the inductor and the capacitor increases.
- (D) inductor increases and the capacitor decreases.

Correct Answer: (B) inductor decreases and the capacitor increases.

Solution:

Concept:

- An inductor of inductance L has reactance $X_L = 2\pi fL$, directly proportional to the source frequency f .
- A capacitor of capacitance C has reactance $X_C = 1/(2\pi fC)$, inversely proportional to frequency. Reactance is measured in ohms.

Step 1: Track the inductor reactance With L fixed, decreasing f decreases X_L . For example, if frequency becomes $f/2$, then inductive reactance becomes $X_L/2$. Options (C) and (D), which say that the inductor's reactance increases, therefore fail.

Step 2: Track the capacitor reactance With C fixed, decreasing the denominator $2\pi fC$ increases X_C . Halving frequency doubles capacitive reactance. Hence option (A), which makes both decrease, also fails. The resistor and the series connection affect the total impedance but do not alter these separate frequency dependences.

Step 3: Conclusion The inductor's reactance decreases and the capacitor's reactance increases. Hence, the correct option is (B).

Quick Tip to Solve: Recall the low-frequency limits: an ideal inductor approaches a short circuit and a capacitor approaches an open circuit.

16. Assertion (A): The nucleus 7_3X is more stable than the nucleus 4_3Y .

Reason (R): 7_3X contains more number of protons.

[1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
- (B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
- (C) Assertion (A) is true, but Reason (R) is false.
- (D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (C) Assertion (A) is true, but Reason (R) is false.

Solution:

Concept:

- In nuclear notation A_ZX , the atomic number Z counts protons and the mass number A counts all nucleons. Neutron number is $N = A - Z$.
- Stability of light nuclei requires a suitable neutron-to-proton balance. A strongly proton-rich nucleus is less stable than a nucleus with a suitable balance.

Step 1: Evaluate the assertion The nucleus 7_3X has three protons and $7 - 3 = 4$ neutrons, while 4_3Y has three protons and only $4 - 3 = 1$ neutron. Their neutron-to-proton ratios are $4/3$ and $1/3$, respectively. The former has the stable lithium-7 composition; the latter is strongly proton-rich. Thus the assertion is true.

Step 2: Evaluate the reason Both nuclei have the same lower number $Z = 3$, so both contain exactly three protons. The larger upper number of X signifies more neutrons here, not more protons. The reason is therefore false.

Step 3: Test the explanatory connection A false statement about proton count cannot explain the true stability comparison. Options (A) and (B) require a true reason, while option (D) also incorrectly declares the assertion false.

Step 4: Conclusion The assertion is true, but the reason is false. Hence, the correct option is (C).

Quick Tip to Solve: Read proton number from the subscript first; subtract it from the superscript to compare neutron numbers.

17. Assertion (A): The internal resistance of a cell is constant.

Reason (R): Ionic concentration of the electrolyte remains same during use of a cell.

[1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
- (B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
- (C) Assertion (A) is true, but Reason (R) is false.
- (D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (D) Assertion (A) is false and Reason (R) is also false.

Solution:

Concept:

- Internal resistance is the opposition to current inside a cell, mainly in its electrolyte; for fixed geometry, $r = \rho \ell / S$, where ρ is resistivity, ℓ is the ionic path length and S its effective area.
- Electrolyte conductivity depends on the concentration and mobility of its ions, which can change as the cell operates.

Step 1: Test the assertion The internal resistance is not an unchanging property of a real cell. It depends on the electrolyte, temperature and state of discharge. Therefore, Assertion (A) is false; treating internal resistance as constant in a simple circuit calculation is only an approximation.

Step 2: Test the reason During use, electrochemical reactions consume or produce ionic species and change the electrolyte composition. Thus ionic concentration need not remain the same. Reason (R), which claims that it remains unchanged, is false.

Step 3: Match the truth values Both statements are false, so R cannot be a true explanation of A. Options (A) and (B) incorrectly declare both statements true; option (C) incorrectly declares the assertion true.

Step 4: Conclusion The assertion and the reason are both false. Hence, the correct option is (D).

Quick Tip to Solve: Distinguish a circuit's assumed constant internal resistance from a real cell's changing electrolyte during discharge.

18. Assertion (A): When radius of a circular loop carrying a steady current is doubled, its magnetic moment becomes four times.

Reason (R): The magnetic moment of a circular loop carrying a steady current is proportional to the area of the loop. [1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
(B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
(C) Assertion (A) is true, but Reason (R) is false.
(D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).

Solution:

Concept:

- The magnetic dipole moment of a single current loop is $\mu = IS$, where I is the current and S is its area vector.
- For a circular loop of radius r , the area is $S = \pi r^2$, so its magnetic moment has magnitude $\mu = I\pi r^2$.

Step 1: Test the assertion Keep the steady current unchanged and replace r by $2r$. The new magnetic moment is

$$\mu' = I\pi(2r)^2 = 4I\pi r^2 = 4\mu.$$

Thus the moment becomes four times its original value, so the assertion is true.

Step 2: Test the reason Since $\mu = IS$, magnetic moment is directly proportional to the loop's area for the same current. Therefore the reason is true. The relevant quantity is area, not circumference.

Step 3: Check the explanatory link Doubling the radius quadruples the area, and the stated area proportionality therefore gives precisely the fourfold increase in moment. The reason explains the assertion, ruling out (B); (C) and (D) have incorrect truth values.

Step 4: Conclusion Both statements are true, and the reason correctly explains the assertion. Hence, the correct option is (A).

Quick Tip to Solve: At fixed current, scale magnetic moment with radius squared: a radius factor k gives a moment factor k^2 .

Section B (14 marks)

19. Explain the property of a p-n junction which makes it suitable for rectifying alternating voltages. Differentiate between a half-wave and a full-wave rectifier. [2 marks]

Solution:

Concept:

- A p-n junction conducts readily under forward bias and offers very high resistance under reverse bias; this asymmetric conduction provides rectification.
- Rectification converts an alternating input into a unidirectional, pulsating output. If the input

frequency is f , the output pulse frequency depends on how many half-cycles are used.

Step 1: Explain the rectifying property Forward bias reduces the junction's potential barrier and allows a substantial current. Reverse bias increases the barrier and permits only a very small leakage current below breakdown. An alternating voltage reverses the bias every half-cycle; the diode therefore effectively conducts in one direction and blocks the other.

Step 2: Compare the two rectifiers A **half-wave rectifier** uses only one half-cycle of the alternating input; current through the load is negligible during the other half-cycle. It gives one output pulse per input cycle, so its ripple frequency is f .

A **full-wave rectifier** uses both half-cycles. Its diodes direct the load current in the same direction during each half-cycle, giving two output pulses per input cycle and a ripple frequency of $2f$. Thus it uses the input more effectively and its output is easier to smooth with a filter.

Step 3: Conclusion The p-n junction's low forward resistance and high reverse resistance enable rectification. Half-wave rectification uses one half-cycle, whereas full-wave rectification uses both half-cycles with unchanged load-current direction.

Quick Tip to Solve: Count output pulses in one input cycle: one means half-wave with frequency f ; two means full-wave with frequency $2f$.

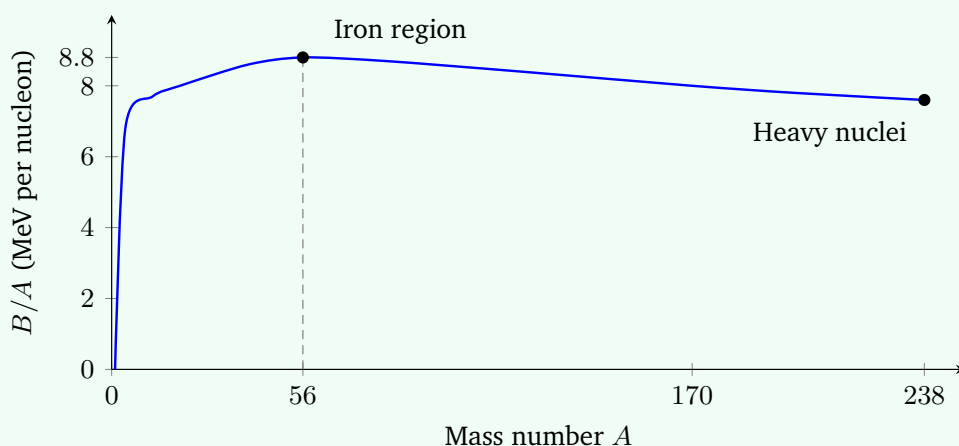
20(a). Draw a graph showing the variation of binding energy per nucleon as a function of mass number A . The binding energy per nucleon for heavy nuclei ($A > 170$) decreases with the increase in mass number. Explain. [2 marks]

Solution:

Concept:

- Binding energy per nucleon is B/A , where B is the energy required to separate a nucleus completely into its nucleons and A is its mass number.
- Nuclear attraction is short-ranged and saturates: a nucleon interacts strongly mainly with nearby nucleons. Electrostatic repulsion between protons is long-ranged.

Step 1: Sketch the binding-energy curve Plot mass number A on the horizontal axis and B/A , in MeV per nucleon, on the vertical axis. The curve rises rapidly for light nuclei, with fluctuations, reaches its broad maximum of about 8.8 MeV near $A \approx 56$, and then decreases slowly for heavier nuclei. The heavy end near uranium has about 7.6 MeV per nucleon. The sketch shows the overall trend, not individual light-nucleus fluctuations.



Schematic variation of binding energy per nucleon with mass number

Step 2: Explain the fall for heavy nuclei For heavy nuclei, adding nucleons does not give each nucleon attractive interactions with all the others, because nuclear forces act only over a short range. The attractive contribution per nucleon therefore remains approximately saturated. However, the increasing number of protons increases long-range Coulomb repulsion throughout the nucleus. Its growing repulsive contribution reduces the net binding per nucleon as A increases, explaining the downward trend for $A > 170$.

Step 3: Conclusion Binding energy per nucleon peaks near the iron region and slowly decreases for heavy nuclei because increasing proton repulsion competes with short-range, saturated nuclear attraction.

Quick Tip to Solve: Label both axes and the peak near $A \approx 56$; explain the heavy-nucleus fall by Coulomb repulsion together with nuclear-force saturation.

OR

20(b). Using Bohr's postulates, obtain the expression for radius of n^{th} stable orbit in a hydrogen atom. [2 marks]

Solution:

Concept:

- In Bohr's hydrogen model, the electron moves in a permitted circular stationary orbit without radiating energy. Electrostatic attraction supplies its centripetal force.
- Angular momentum is quantised: $m_e v_n r_n = n\hbar = nh/(2\pi)$, with positive integer n , electron mass m_e , orbital speed v_n and radius r_n .

Step 1: Write the force equation The hydrogen nucleus has charge $+e$, while the electron has charge $-e$. Equating the magnitude of Coulomb attraction to the centripetal force gives

$$\frac{e^2}{4\pi\epsilon_0 r_n^2} = \frac{m_e v_n^2}{r_n}.$$

Here ϵ_0 is the permittivity of free space. The standard Bohr model treats the much heavier nucleus as stationary.

Step 2: Apply angular-momentum quantisation From Bohr's allowed angular momenta,

$$v_n = \frac{n\hbar}{m_e r_n}.$$

Substitute this speed into the force equation:

$$\begin{aligned}\frac{e^2}{4\pi\epsilon_0 r_n^2} &= \frac{n^2 \hbar^2}{m_e r_n^3}, \\ \frac{e^2 r_n}{4\pi\epsilon_0} &= \frac{n^2 \hbar^2}{m_e}.\end{aligned}$$

This eliminates the unmeasured orbital speed and relates each allowed radius directly to its quantum number.

Step 3: Conclusion The radius of the n^{th} stable hydrogen orbit is

$$r_n = \frac{4\pi\epsilon_0 \hbar^2}{m_e e^2} n^2 = \frac{\epsilon_0 h^2}{\pi m_e e^2} n^2 = a_0 n^2,$$

where $a_0 \approx 5.29 \times 10^{-11} \text{ m}$ is the Bohr radius and $n = 1, 2, 3, \dots$

Quick Tip to Solve: Eliminate v_n using $m_e v_n r_n = n\hbar$; check that the resulting radius grows as n^2 , not as n .

21. What is meant by the term 'displacement current'? Briefly explain how this current is different from a conduction current. [2 marks]

Solution:

Concept:

- A time-varying electric field produces a magnetic field, just as an electric current does. Its contribution is represented by displacement current.
- In vacuum, $I_d = \epsilon_0 d\Phi_E/dt$, where $\Phi_E = \int \vec{E} \cdot d\vec{A}$ is electric flux. Conduction current is $I_c = dq/dt$, the rate of charge flow through a surface.

Step 1: Define displacement current Displacement current is the current associated with a changing electric flux. For example, while a capacitor is charging, the electric field between its plates changes, so there is a displacement current in the gap. It can exist even in vacuum, where no material charge carriers cross the gap.

$$I_d = \epsilon_0 \frac{d\Phi_E}{dt}.$$

Step 2: Compare it with conduction current Conduction current involves the actual directed motion of free charges through a material, such as electrons in a metallic wire. Displacement current does not require such transport of free charge; it arises from a changing electric field. Both contribute to the magnetic field. In an ideal charging capacitor, the displacement current in the gap equals the conduction current in the connecting wires, ensuring current continuity.

Step 3: Conclusion Displacement current is $\epsilon_0 d\Phi_E/dt$; unlike conduction current, it is associated with changing electric flux rather than the flow of free charges.

Quick Tip to Solve: Use a charging capacitor to distinguish the two: free charges flow in the wires, while changing electric flux supplies displacement current across the gap.

22. A wire of length L is bent round in the form of (i) a square, and then (ii) an equilateral triangle. If current I is passed through each of them, find the ratio of magnetic moment of the square loop to that of the triangle. [2 marks]

Solution:

Concept:

- The magnitude of the magnetic dipole moment of a single-turn planar loop is $m = IA$, where I is current and A is the enclosed area.
- Bending the same wire into different shapes keeps the perimeter L fixed. With the same current, the ratio of magnetic moments equals the ratio of enclosed areas.

Step 1: Calculate the square's magnetic moment A square has four equal sides, so each side is $L/4$. Its enclosed area and magnetic moment are

$$A_s = \left(\frac{L}{4}\right)^2 = \frac{L^2}{16}, \quad m_s = IA_s = \frac{IL^2}{16}.$$

Step 2: Calculate the triangle's magnetic moment and compare An equilateral triangle has three equal sides, each of length $L/3$. For side length a , its altitude is $\sqrt{3}a/2$, so its area is $\sqrt{3}a^2/4$. Therefore,

$$A_t = \frac{\sqrt{3}}{4} \left(\frac{L}{3}\right)^2 = \frac{\sqrt{3}L^2}{36}, \quad m_t = \frac{\sqrt{3}IL^2}{36}.$$

Cancelling the common factors I and L^2 gives

$$\frac{m_s}{m_t} = \frac{36}{16\sqrt{3}} = \frac{3\sqrt{3}}{4}.$$

Step 3: Conclusion The magnetic-moment ratio of the square to the equilateral triangle is $m_s : m_t = 3\sqrt{3} : 4$. The square encloses the larger area and hence has the larger moment.

Quick Tip to Solve: For loops made from the same wire carrying the same current, compare areas at fixed perimeter; the current and wire length cancel from the ratio.

23(a). State Huygens' principle. How did Huygens explain the absence of the backwave? [2 marks]

Solution:

Concept:

- A wavefront is a surface joining points of the wave that are in the same phase. In a homogeneous isotropic medium, secondary wavelets travel with the wave speed v .
- Huygens' construction obtains the later wavefront as the forward envelope, or common tangent

surface, of the secondary wavelets.

Step 1: State Huygens' principle Every point on a given wavefront acts as a source of secondary spherical wavelets. These wavelets spread through the medium with the speed of the wave. After a time interval Δt , each wavelet has radius $v\Delta t$; their common forward envelope gives the position of the new wavefront.

Step 2: Explain the absence of the backwave A purely geometrical construction using complete spherical wavelets would also allow a backward envelope. Huygens assumed that the amplitude of a secondary wavelet is maximum in the forward direction and zero in the backward direction. Thus the backward wavelets make no contribution, and a backwave is absent. This directional assumption supplements the geometrical wavefront construction; merely drawing the envelope does not by itself rule out a backward wave.

Step 3: Conclusion Each wavefront point generates secondary wavelets whose forward envelope is the next wavefront. Huygens excluded the backwave by assuming zero secondary-wavelet amplitude in the backward direction.

Quick Tip to Solve: State both parts of the principle: secondary sources and the forward envelope; then name the zero backward-amplitude assumption to explain the missing backwave.

OR

23(b). Use Huygens' principle to show reflection/refraction of a plane wave by (i) concave mirror, and (ii) a convex lens.

[2 marks]

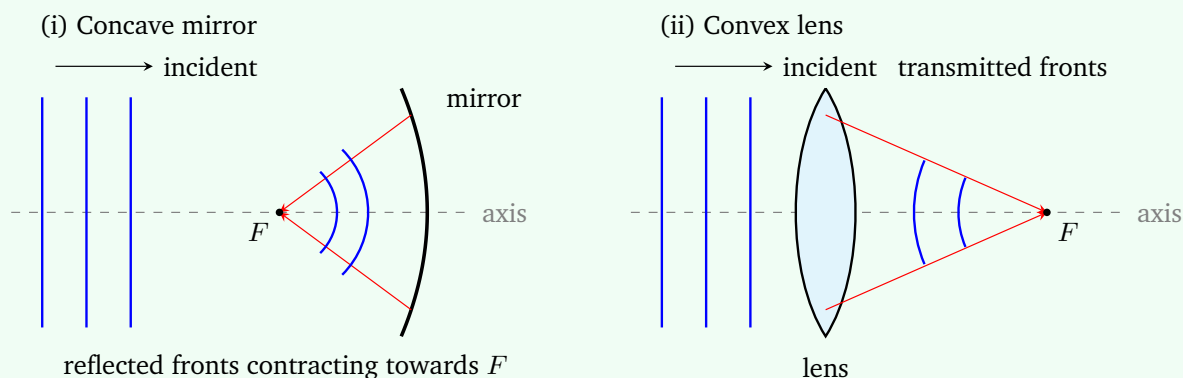
Solution:

Concept:

- By Huygens' principle, every point of a wavefront produces secondary wavelets. Their forward common envelope is the new wavefront; rays are normal to it.
- A plane wave incident parallel to the principal axis becomes a converging, approximately spherical wave after reflection at a concave mirror or refraction through a convex lens, in the paraxial approximation.

Step 1: Construct the reflected wavefront for a concave mirror Consider a plane wave approaching the concave reflecting surface parallel to its principal axis. Different parts of the curved mirror are reached at different times. At a common later instant, construct reflected secondary wavelets from the points already reached, allowing each to expand for the time since incidence. Their envelope is a converging spherical wavefront with its centre at the principal focus F . The reflected wave moves back towards F ; normals to successive wavefronts are the converging reflected rays.

Step 2: Construct the refracted wavefront for a convex lens For a plane wave incident normally on a thin convex lens, the central portion passes through more glass than the edge portions. Since light travels more slowly in glass, the centre is delayed more. The common envelope of the emergent secondary wavelets is therefore curved, with its centre at the principal focus F on the other side of the lens. It advances as a converging spherical wavefront and contracts to the focus. The diagrams show representative wavefronts and their normal rays; the construction assumes a small aperture.



Plane wavefronts become converging spherical wavefronts; arrows show propagation.

Step 3: Conclusion A concave mirror converts the incident plane wave into a converging reflected spherical wave; a convex lens converts it into a converging transmitted spherical wave. In each case the wavefront contracts towards the principal focus.

Quick Tip to Solve: Draw rays perpendicular to every wavefront: the mirror reverses propagation, while the lens transmits it; both converging fronts must be centred at their respective focus.

24. The refractive indices of two media A and B are 2 and $\sqrt{2}$ respectively. What is the critical angle for their interface? [2 marks]

Solution:

Concept:

- The critical angle C is the angle of incidence in the optically denser medium for which the refracted ray in the rarer medium makes 90° with the normal.
- Snell's law is $n_1 \sin i = n_2 \sin r$, where refractive indices are measured relative to vacuum. Thus $\sin C = n_{\text{rarer}}/n_{\text{denser}}$.

Step 1: Identify the permitted direction of incidence The given indices are $n_A = 2$ and $n_B = \sqrt{2}$. Since $2 > \sqrt{2}$, medium A is optically denser. A critical angle is therefore defined for light travelling from A into B. Light travelling from B into A cannot undergo total internal reflection at this interface.

Step 2: Apply Snell's law at the critical condition At critical incidence the refracted ray grazes the interface, so its refraction angle, measured from the normal, is $r = 90^\circ$. Substitution gives

$$\begin{aligned} n_A \sin C &= n_B \sin 90^\circ, \\ \sin C &= \frac{\sqrt{2}}{2} = \frac{1}{\sqrt{2}}, \\ C &= \sin^{-1} \left(\frac{1}{\sqrt{2}} \right). \end{aligned}$$

Step 3: Conclusion The critical angle is $C = 45^\circ$, measured from the normal in medium A for light incident towards medium B.

Quick Tip to Solve: Put the smaller refractive index in the numerator: the critical-angle sine must be less than one, and incidence must be from the denser medium.

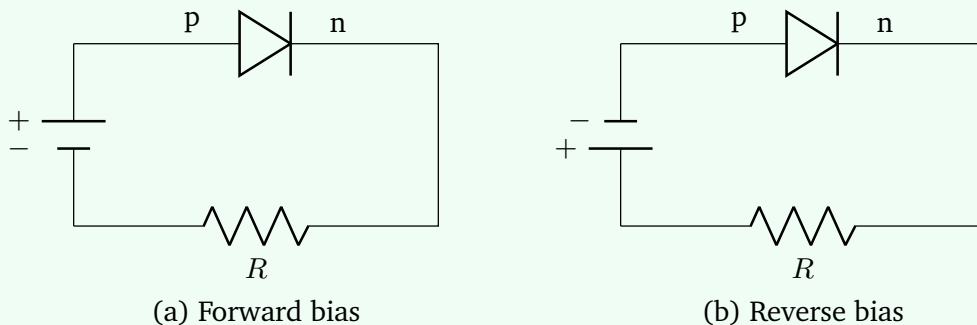
25. Draw a circuit diagram of a p-n junction diode in (a) forward biasing, and (b) reverse biasing. Draw the V-I characteristics for each case. [2 marks]

Solution:

Concept:

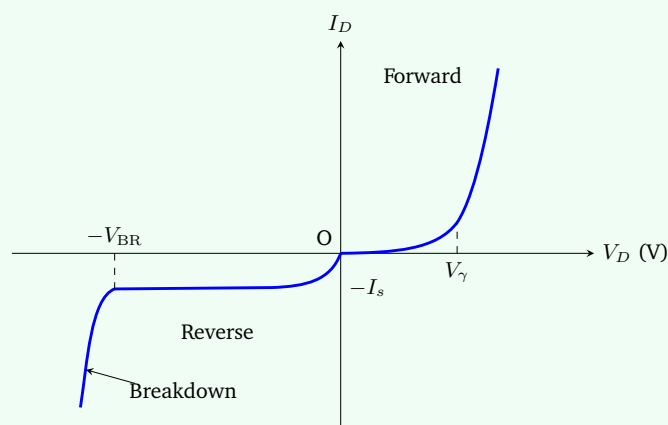
- A p-n diode is forward biased when its p-side is connected to the positive terminal and its n-side to the negative terminal of the supply; reversing these connections produces reverse bias.
- Define diode voltage as $V_D = V_p - V_n$ and conventional diode current I_D as positive from p to n. A series resistance R limits the current.

Step 1: Connect the diode in both bias conditions The circuits below use a variable dc supply and a protective resistor. In (a), the positive supply terminal feeds the p-side (anode), while the n-side (cathode, the barred end of the diode symbol) returns to the negative terminal. This reduces the junction barrier. In (b), the battery polarity is reversed: the n-side is positive relative to the p-side, increasing the barrier and widening the depletion region.



Bias circuits; R limits the current and the dc supply is variable.

Step 2: Sketch the current-voltage characteristics In forward bias the current is initially small, then rises rapidly beyond the knee voltage V_γ . In reverse bias only a small, nearly constant reverse saturation current I_s flows until breakdown at reverse voltage magnitude V_{BR} , where the reverse current rises sharply. The reverse-current scale is enlarged in this schematic so that its small magnitude is visible; it is normally much smaller than forward current.



Schematic V-I characteristic; the reverse-current scale is enlarged.

Step 3: Conclusion Forward bias: p to positive, n to negative, with appreciable current beyond the knee. Reverse bias: p to negative, n to positive, with only a small leakage current before breakdown. The labelled circuits and characteristic above show both cases.

Quick Tip to Solve: Check the cathode bar first: connecting that n-side to the positive terminal makes the diode reverse biased.

Section C (15 marks)

26(a). An ac source $V = V_m \sin \omega t$ is connected across an ideal capacitor. Derive the expression for the (i) current flowing in the circuit, and (ii) reactance of the capacitor. Plot a graph of current i versus ωt . [3 marks]

Solution:

Concept:

- For an ideal capacitor of capacitance C , the instantaneous charge on its positive-reference plate is $q = CV$, and the current entering that plate is $i = dq/dt$.
- Capacitive reactance X_C measures opposition to alternating current and is defined by the ratio of voltage amplitude to current amplitude: $X_C = V_m/I_m$. Its SI unit is the ohm.

Step 1: Express the charge as a function of time The applied voltage is $V = V_m \sin \omega t$, where V_m is its maximum value and ω is its angular frequency. Since the capacitor is ideal, its capacitance is constant and the voltage-charge relation applies at every instant:

$$q(t) = CV(t) = CV_m \sin \omega t.$$

As the source voltage changes, the plates alternately charge and discharge; this changing charge produces current in the external circuit.

Step 2: Differentiate to obtain the current Differentiating with respect to time gives

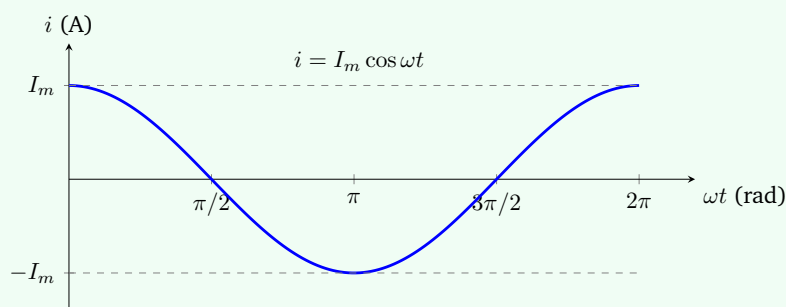
$$\begin{aligned} i(t) &= \frac{dq}{dt} = \omega CV_m \cos \omega t, \\ &= I_m \sin \left(\omega t + \frac{\pi}{2} \right), \quad I_m = \omega CV_m. \end{aligned}$$

Thus current leads the applied voltage by $\pi/2$ rad. In particular, current is maximum when voltage passes upward through zero, because the rate of change of charge is then greatest; it is zero when voltage and plate charge are at their extrema.

Step 3: Find the reactance and plot the current Dividing the voltage amplitude by the current amplitude yields

$$X_C = \frac{V_m}{I_m} = \frac{V_m}{\omega CV_m} = \frac{1}{\omega C} = \frac{1}{2\pi fC}.$$

The same ratio holds for rms values because both amplitudes are divided by $\sqrt{2}$. Reactance decreases as frequency or capacitance increases. The required graph is a cosine wave: at $\omega t = 0, \pi/2, \pi, 3\pi/2, 2\pi$, the current is respectively $I_m, 0, -I_m, 0, I_m$.



Current versus phase angle for an ideal capacitor.

Step 4: Conclusion The current is $i = \omega C V_m \cos \omega t$, leading the voltage by $\pi/2$; the capacitive reactance is $X_C = 1/(\omega C)$. The current graph starts at its positive maximum.

Quick Tip to Solve: For a capacitor, differentiate the given voltage: a sine voltage gives a cosine current, so start the current graph at its maximum.

OR

26(b). A series combination of an inductor L , a capacitor C and a resistor R is connected across an ac source of voltage in a circuit. Obtain an expression for the average power consumed by the circuit. Find power factor for (i) purely inductive circuit, and (ii) purely resistive circuit. [3 marks]

Solution:

Concept:

- A series LCR circuit has impedance $Z = \sqrt{R^2 + (X_L - X_C)^2}$, where $X_L = \omega L$ and $X_C = 1/(\omega C)$. Its phase angle satisfies $\cos \phi = R/Z$.
- Instantaneous electric power is $p = vi$. Average power is its mean over a complete cycle; ideal inductors and capacitors store and return energy, while resistance dissipates energy.

Step 1: Write the voltage and current with their phase difference Choose the source voltage as $v = V_m \sin \omega t$. In steady state the current is

$$i = I_m \sin(\omega t - \phi), \quad I_m = \frac{V_m}{Z}.$$

Here ϕ is positive for a net inductive circuit and negative for a net capacitive circuit. The resistance-voltage component is in phase with current, while the net reactive-voltage component is perpendicular to it, giving $\cos \phi = R/Z$.

Step 2: Average the instantaneous power over one cycle Multiply voltage and current, and use $2 \sin A \sin B = \cos(A - B) - \cos(A + B)$:

$$\begin{aligned} p(t) &= V_m I_m \sin \omega t \sin(\omega t - \phi) \\ &= \frac{V_m I_m}{2} [\cos \phi - \cos(2\omega t - \phi)]. \end{aligned}$$

The cosine term averages to zero over a full cycle, whereas $\cos \phi$ is constant. Hence, with $V_{\text{rms}} =$

$$V_m/\sqrt{2} \text{ and } I_{\text{rms}} = I_m/\sqrt{2},$$

$$\begin{aligned} P_{\text{av}} &= \frac{V_m I_m}{2} \cos \phi = V_{\text{rms}} I_{\text{rms}} \cos \phi \\ &= I_{\text{rms}}^2 R = \frac{V_{\text{rms}}^2 R}{R^2 + (X_L - X_C)^2}. \end{aligned}$$

Only the resistor consumes net energy in the ideal series circuit; the reactive elements exchange energy with the source during different parts of the cycle.

Step 3: Evaluate the two requested power factors (i) In a purely inductive circuit, current lags voltage by $\phi = \pi/2$. Thus the power factor is $\cos \phi = 0$ and the average power is zero, even though the instantaneous current need not vanish.

(ii) In a purely resistive circuit, current and voltage are in phase: $\phi = 0$. Thus the power factor is $\cos \phi = 1$, and $P_{\text{av}} = V_{\text{rms}} I_{\text{rms}}$.

Step 4: Conclusion Average power is $P_{\text{av}} = V_{\text{rms}} I_{\text{rms}} \cos \phi = I_{\text{rms}}^2 R$, with power factor R/Z . The power factors for purely inductive and purely resistive circuits are respectively 0 and 1.

Quick Tip to Solve: Use rms values in $VI \cos \phi$; if peak values are given, include the factor $1/2$. A pure reactance has zero average power.

27(a). (i) Prove that the nuclear density is same for all nuclei.

(ii) Draw a plot of potential energy of a pair of nucleons as a function of their separation. Draw two inferences from this plot. [3 marks]

Solution:

Concept:

- The empirical nuclear radius is $R = R_0 A^{1/3}$, where A is the mass number and R_0 is approximately $1.2 \times 10^{-15} \text{ m}$.
- Nuclear mass is approximately $M = Am_N$, with m_N the average nucleon mass. Density is mass divided by volume.
- The radial nuclear force is related to the nucleon potential energy by $F_r = -dU/dr$; the zero of energy is chosen at infinite separation.

Step 1: (i) Express the nuclear volume in terms of mass number Treating a nucleus as a sphere and using the radius law gives

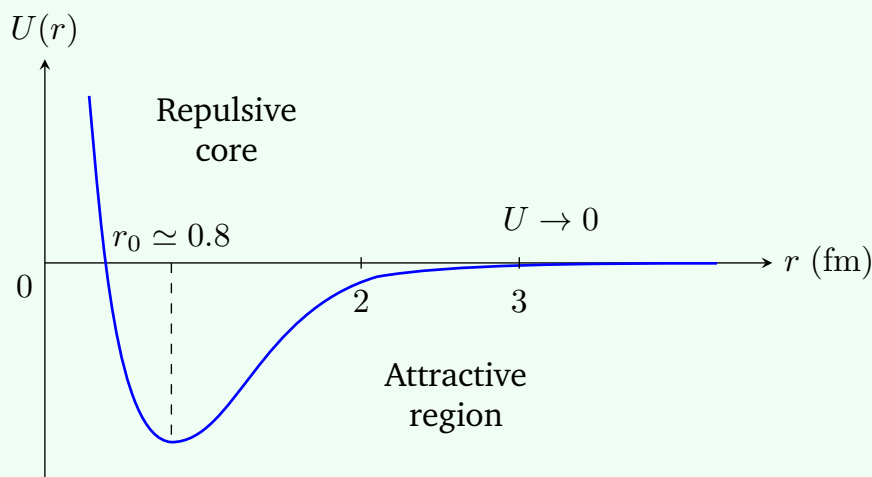
$$V = \frac{4\pi}{3} R^3 = \frac{4\pi}{3} R_0^3 A.$$

Thus both nuclear volume and nuclear mass increase in direct proportion to the number of nucleons. Their ratio is

$$\rho = \frac{Am_N}{(4\pi/3)R_0^3 A} = \frac{3m_N}{4\pi R_0^3}.$$

The mass number cancels. Using $m_N \simeq 1.67 \times 10^{-27} \text{ kg}$ gives $\rho \simeq 2.3 \times 10^{17} \text{ kg m}^{-3}$. The statement of equal density holds within this standard approximate radius law.

Step 2: (ii) Sketch the nucleon potential energy At very small separation the potential rises steeply to positive values. It falls to a negative minimum near $r_0 \simeq 0.8 \text{ fm}$, then rises towards zero, becoming negligible beyond a few femtometres. The sketch is qualitative; $1 \text{ fm} = 10^{-15} \text{ m}$.



Qualitative nuclear potential energy versus nucleon separation.

Step 3: Read two inferences from the slopes and range First, the force has a strongly repulsive core at $r < r_0$, where $dU/dr < 0$ and hence $F_r > 0$. For separations just greater than r_0 , the positive slope gives $F_r < 0$, an attractive force that binds nucleons. At the potential minimum the net radial force vanishes. Second, the nuclear interaction is short ranged: since the potential becomes nearly constant at zero beyond about 2–3 fm, its slope and therefore the nuclear force become negligible there.

Step 4: Conclusion Nuclear density is approximately the same for all nuclei, $\rho = 3m_N/(4\pi R_0^3)$, independent of A . The potential plot shows an attractive well with a repulsive core and a very short interaction range.

Quick Tip to Solve: Cube $R = R_0 A^{1/3}$ before taking mass divided by volume; infer attraction or repulsion from $-dU/dr$, not from the sign of U alone.

OR

27(b). (i) Draw a graph to show the variation of the number of scattered particles detected (N) in Geiger-Marsden experiment as a function of scattering angle (θ).

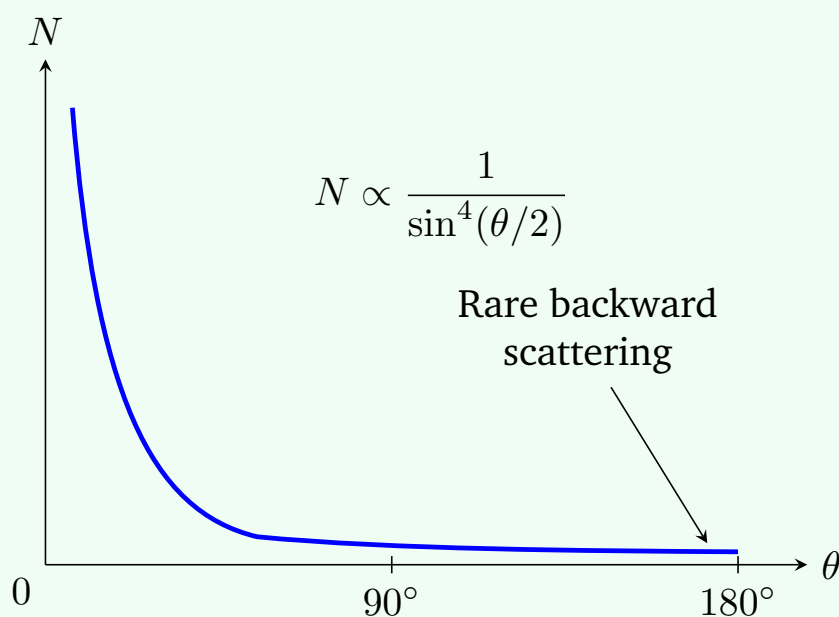
(ii) Discuss briefly two conclusions that can be drawn from this graph and how they lead to the discovery of nucleus in an atom. [3 marks]

Solution:

Concept:

- In the Geiger–Marsden experiment, fast positively charged α -particles strike a thin metal foil and the detector counts particles scattered through angle θ .
- For the same incident beam, foil and detector solid angle, Rutherford scattering gives $N(\theta) \propto 1/\sin^4(\theta/2)$. Thus large-angle scattering is far less frequent than small-angle scattering.

Step 1: (i) Draw the angular distribution Put scattering angle θ on the horizontal axis and the number of detected scattered particles N on the vertical axis. The curve is very high near the forward direction, drops steeply as the angle increases, and has a small but nonzero value even near 180° . The graph is schematic and shows the relative trend; the ideal scattering formula is not assigned a finite value at exactly $\theta = 0$.



Schematic angular distribution: very many forward events and rare backward events.

Step 2: (ii) Infer the mostly empty interior of the atom The overwhelming concentration near the forward direction means that most incident particles pass through the foil without appreciable deflection. Therefore most of the volume of each atom is empty space: along most trajectories an α -particle encounters no concentrated region capable of producing a large force.

Step 3: Infer a small, massive and positively charged nucleus The small but nonzero population scattered through large angles, including nearly backward scattering, shows that a few particles encounter a very strong repulsive force. Since an α -particle is positive, this implies a concentrated positive charge. A diffuse charge distribution could not give such a large deflection in a single close encounter. Such encounters are rare, so the charged region occupies only a tiny fraction of the atomic volume. It must also be massive compared with an electron to reverse a fast α -particle without simply recoiling away. Rutherford therefore placed essentially all the atomic positive charge and nearly all its mass in a small central nucleus, surrounded by mostly empty space containing electrons.

Step 4: Conclusion The N -versus- θ curve falls rapidly with angle and retains a tiny backward-scattered population. These observations establish a mostly empty atom with a very small, massive, positively charged nucleus.

Quick Tip to Solve: Link the tall forward part of the curve to empty space and its tiny backward tail to the concentrated positive charge and mass of the nucleus.

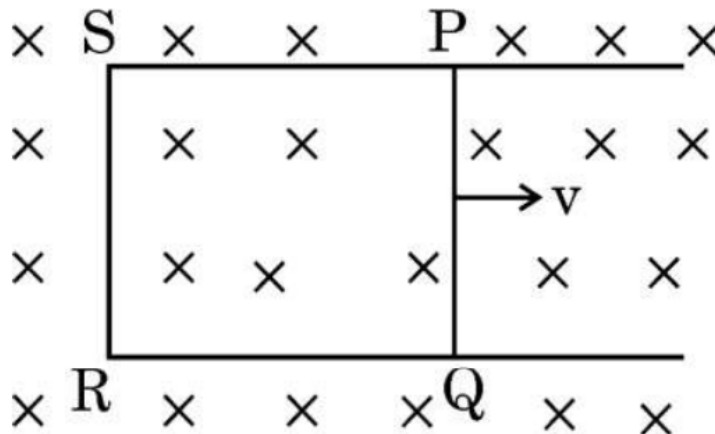
28. The figure shows a rectangular conductor $PQRS$ in which the arm PQ of length 10 cm and resistance $0.4\ \Omega$ is free to move. It is kept in a uniform magnetic field $B = 0.2\ \text{T}$ acting perpendicular into the plane of $PQRS$. If arm PQ is moved with a velocity v of 5 cm/s as shown, find:

(a) the current induced in the loop, and

(b) the power required to move the arm.

(Resistances of arms PS , SR and RQ are negligible.)

[3 marks]



Solution:

Concept:

- A rod of length l moving at speed v perpendicular to itself and a uniform magnetic field B develops motional emf $\varepsilon = Blv$.
- The loop current is $I = \varepsilon/R$, where R is the total loop resistance. Its direction opposes the change of magnetic flux, by Lenz's law.
- A current-carrying rod experiences magnetic force $F_B = BIl$. To maintain constant speed, the external force balances this drag and supplies power $P = F_B v = I^2 R$.

Step 1: Convert the given data to SI units The moving arm has length $l = 10\ \text{cm} = 0.10\ \text{m}$ and speed $v = 5\ \text{cm s}^{-1} = 0.050\ \text{m s}^{-1}$. The magnetic field is $B = 0.20\ \text{T}$. Since the other three arms have negligible resistance, the total resistance is $R = 0.40\ \Omega$.

Step 2: (a) Calculate the induced current and its direction As the rod moves right, the area of the loop increases at rate $dA/dt = lv$. Faraday's law therefore gives the magnitude

$$\varepsilon = B \frac{dA}{dt} = Blv = (0.20)(0.10)(0.050) = 1.0 \times 10^{-3}\ \text{V}.$$

Ohm's law then gives

$$I = \frac{1.0 \times 10^{-3}}{0.40} = 2.5 \times 10^{-3}\ \text{A}.$$

Into-the-page flux is increasing, so the induced current produces an out-of-the-page magnetic field. It is anticlockwise around $P \rightarrow S \rightarrow R \rightarrow Q \rightarrow P$; in the moving arm it flows upward from Q to P .

Step 3: (b) Calculate the power needed to maintain the motion The upward current in the rod and the magnetic field into the page give a magnetic force to the left, opposing its motion. The required external force is therefore to the right with magnitude

$$F_{\text{ext}} = BIl = (0.20)(2.5 \times 10^{-3})(0.10) = 5.0 \times 10^{-5}\ \text{N}.$$

Hence the mechanical power supplied is

$$P = F_{\text{ext}}v = (5.0 \times 10^{-5})(0.050) = 2.5 \times 10^{-6} \text{ W}.$$

This equals the Joule heating rate $I^2R = (2.5 \times 10^{-3})^2(0.40) = 2.5 \times 10^{-6} \text{ W}$, as required by conservation of energy at constant speed.

Step 4: Conclusion (a) The induced current is 2.5 mA, anticlockwise in the loop and from Q to P in the moving arm. (b) The required power is $2.5 \times 10^{-6} \text{ W} = 2.5 \mu\text{W}$.

Quick Tip to Solve: Convert both centimetre quantities before using Blv ; then check the mechanical power with $P = I^2R$ and use increasing inward flux to fix the current direction.

29. Obtain a relation between the current flowing in a conductor and drift velocity of electrons in it. Hence, obtain Ohm's law. [3 marks]

Solution:

Concept:

- Electric current is the charge crossing a conductor's cross-section per unit time: $I = \Delta Q / \Delta t$.
- Drift speed v_d is the magnitude of the average velocity acquired by free electrons in an electric field. Their random thermal velocities have zero average.
- In the relaxation-time model, $v_d = eE\tau/m$, where e is the electron charge magnitude, m its mass, E the field magnitude and τ the mean relaxation time.

Step 1: Count the electrons crossing a section Consider a uniform conductor of cross-sectional area A , length ℓ , and free-electron number density n . In time Δt , the electrons drift through a distance $v_d\Delta t$. The volume that contributes electrons across a section is $Av_d\Delta t$, so the number crossing it is $nAv_d\Delta t$. Hence the magnitude of charge transported and the current are

$$\Delta Q = neAv_d\Delta t, \quad I = \frac{\Delta Q}{\Delta t} = neAv_d.$$

Conventional current is opposite to the electron drift direction; the displayed relation uses magnitudes.

Step 2: Relate drift speed to the applied voltage The force on an electron in the field is $-e\vec{E}$, giving acceleration $-e\vec{E}/m$. Averaging over collisions gives $\vec{v}_d = -e\tau\vec{E}/m$. For a uniform wire with potential difference V , the field magnitude is $E = V/\ell$, and therefore

$$v_d = \frac{eE\tau}{m} = \frac{e\tau V}{m\ell}.$$

Collisions limit the drift speed: the electron does not accelerate indefinitely through the whole conductor.

Step 3: Obtain the voltage-current relation Substitute the drift speed in the current relation and rearrange:

$$I = neA \left(\frac{e\tau V}{m\ell} \right) = \frac{ne^2\tau A}{m\ell} V, \\ V = IR, \quad R = \frac{m\ell}{ne^2\tau A} = \rho \frac{\ell}{A}, \quad \rho = \frac{m}{ne^2\tau}.$$

At constant temperature and unchanged physical conditions, n , τ , ℓ and A remain constant. Thus R is

independent of the applied voltage, establishing the proportionality required by Ohm's law.

Step 4: Conclusion The current magnitude is $I = neAv_d$. The drift model gives $V = IR$, with $R = m\ell/(ne^2\tau A)$, at constant temperature and physical conditions.

Quick Tip to Solve: First count electrons in the swept volume $Av_d\Delta t$; then insert $v_d = eE\tau/m$ and $E = V/\ell$ to obtain Ohm's law.

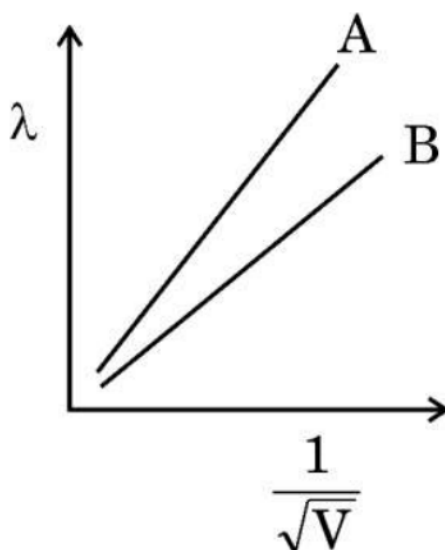
30. (a) The figure shows de Broglie wavelength (λ) for two particles A and B having same charges but different masses as a function of $\frac{1}{\sqrt{V}}$, where V is the potential through which the particles are accelerated.

(i) Which of them is heavier and why?

(ii) What does the slope of the line represent?

(b) Calculate the momentum of an electron having de Broglie wavelength of $3.0 \text{ \AA}$.

[3 marks]



Solution:

Concept:

- The de Broglie wavelength of a particle of momentum magnitude p is $\lambda = h/p$, where h is Planck's constant.
- A non-relativistic particle of mass m and charge magnitude q , accelerated from rest through potential difference V , gains kinetic energy $qV = p^2/(2m)$.
- A straight-line graph $y = sx$ has slope s . Here the ordinate is λ and the abscissa is $1/\sqrt{V}$.

Step 1: (a) Express the wavelength in graph form Equating the kinetic energy gained to the electric work gives $p = \sqrt{2mqV}$. Combining this with the de Broglie relation,

$$\lambda = \frac{h}{\sqrt{2mqV}} = \frac{h}{\sqrt{2mq}} \left(\frac{1}{\sqrt{V}} \right).$$

The proportionality predicts the straight lines shown. The charge q is the common magnitude of the charge of the two particles, and need not equal the electron charge for this comparison.

Step 2: (a)(i) Compare the masses using the inclinations The printed line for A is steeper than that

for B , so their slopes satisfy $s_A > s_B$. Since the particles have the same charge, the expression above shows $s \propto 1/\sqrt{m}$. Thus a smaller slope corresponds to a larger mass:

$$\frac{m_B}{m_A} = \left(\frac{s_A}{s_B} \right)^2 > 1.$$

Particle B is heavier. At the same accelerating voltage both particles gain the same kinetic energy, but the heavier particle has greater momentum and hence a shorter wavelength, consistent with its lower line.

Step 3: (a)(ii) Identify the slope Comparing the graph equation with $y = sx$, the slope represents

$$s = \frac{\Delta\lambda}{\Delta(1/\sqrt{V})} = \frac{h}{\sqrt{2mq}}.$$

It depends on mass and charge, but not on the accelerating voltage. Its units are metre times square root of volt.

Step 4: (b) Convert the wavelength and calculate momentum One angstrom is 10^{-10} m, so the given electron wavelength is $\lambda = 3.0 \times 10^{-10}$ m. Using $h = 6.63 \times 10^{-34}$ J s,

$$p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{3.0 \times 10^{-10}} = 2.21 \times 10^{-24} \text{ kg m s}^{-1}.$$

The de Broglie relation gives momentum directly, so the electron mass is not required for this calculation. To two significant figures the value is $2.2 \times 10^{-24} \text{ kg m s}^{-1}$.

Step 5: Conclusion (a)(i) B is heavier because its slope is smaller. (a)(ii) The slope is $h/\sqrt{2mq}$. (b) The electron momentum is $2.2 \times 10^{-24} \text{ kg m s}^{-1}$.

Quick Tip to Solve: Read the horizontal axis before comparing slopes: for λ against $1/\sqrt{V}$, a smaller slope means a larger mass when charges are equal.

Section D (15 marks)

31(a). (i) Draw a ray diagram showing the formation of a real image of an object placed at a distance u in front of a concave mirror of radius of curvature R . Hence, obtain the relation for the image distance v in terms of u and R .

(ii) A 1.8 m tall person stands in front of a convex lens of focal length 1 m, at a distance of 5 m. Find the position and height of the image formed. [5 marks]

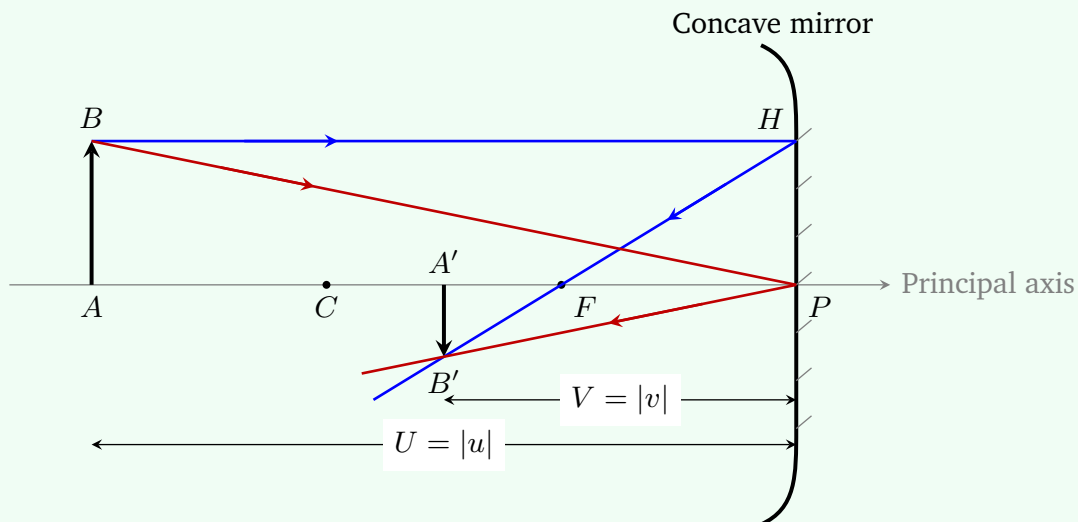
Solution:

Concept:

- A concave spherical mirror forms a real, inverted image when the object lies beyond its principal focus. For paraxial rays, its focal length is half its radius of curvature.
- In the Cartesian convention, distances measured from the pole or optical centre opposite to incident light are negative. The mirror formula is $1/v + 1/u = 2/R$, where u, v, R are signed distances.
- For a thin lens, $1/f = 1/v - 1/u$ and transverse magnification $m = h_i/h_o = v/u$. Here h_o and h_i are signed object and image heights.

Step 1: (i) Construct the real-image ray diagram Place the upright object AB beyond the centre

of curvature C as one example of real-image formation. A ray from B parallel to the principal axis strikes the mirror at H and is reflected through F . A second ray travels from B to the pole P ; it reflects with equal angles to the principal axis, which is the normal at P . The reflected rays meet at B' , giving an inverted image $A'B'$ between C and F . The drawing uses the paraxial approximation, with H vertically above P .



Paraxial ray diagram: a concave mirror forms a real, inverted image between C and F for an object beyond C .

Step 2: (i) Derive the relation using similar triangles First use positive length magnitudes $U = AP$, $V = A'P$, and $F_0 = FP$. Let $h_o = AB$ and let $h' = A'B'$ denote the positive magnitude of the inverted image height. The equal angles at the pole give similar triangles ABP and $A'B'P$, so

$$\frac{h'}{h_o} = \frac{V}{U}.$$

For a small mirror aperture, $HP \simeq AB = h_o$. The triangles HFP and $B'FA'$ are also similar, because the reflected ray passes through F . Since $A'F = V - F_0$,

$$\frac{h'}{h_o} = \frac{V - F_0}{F_0}.$$

Equating these two ratios and dividing by V yields

$$\begin{aligned} \frac{V}{U} &= \frac{V - F_0}{F_0}, \\ \frac{1}{U} &= \frac{1}{F_0} - \frac{1}{V}, \\ \frac{1}{U} + \frac{1}{V} &= \frac{1}{F_0} = \frac{2}{r}, \end{aligned}$$

where $r = CP$ is the positive radius magnitude. Thus $V = Ur/(2U - r)$. This relation holds for the real-image arrangements, not just the illustrated object position.

Step 3: (i) Express the result with signed distances The object, real image and centre of curvature all lie to the left of the pole. Hence $u = -U$, $v = -V$, and $R = -r$. Substitution into the magnitude relation gives

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{R}, \quad \frac{1}{v} = \frac{2u - R}{uR}.$$

If the printed distances are understood as positive magnitudes, use $V = Ur/(2U - r)$; the image is in

front of the mirror. The signed and magnitude forms describe the same geometry.

Step 4: (ii) Apply the lens formula For the convex lens, $f = +1 \text{ m}$, $u = -5 \text{ m}$, and $h_o = +1.8 \text{ m}$. Substitute the distances with their signs:

$$\frac{1}{v} = \frac{1}{f} + \frac{1}{u} = 1 - \frac{1}{5} = \frac{4}{5} \text{ m}^{-1},$$

$$v = \frac{5}{4} \text{ m} = +1.25 \text{ m}.$$

A positive lens image distance places the image on the opposite side of the lens from the person. Since the person is beyond twice the focal length, a diminished real image between the focus and twice the focal length is consistent with the calculation.

Step 5: (ii) Calculate the image height Lens magnification includes the sign of the object distance:

$$m = \frac{v}{u} = \frac{1.25}{-5} = -0.25, \quad h_i = mh_o = (-0.25)(1.8) = -0.45 \text{ m}.$$

The negative height indicates inversion; its magnitude gives the actual height of the image.

Step 6: Conclusion (i) The mirror relation is $v = uR/(2u - R)$ in the Cartesian convention; with positive distance magnitudes it is $V = Ur/(2U - r)$, with the real image in front of the mirror. (ii) The lens forms a real, inverted image 1.25 m beyond the lens, of height 0.45 m (signed height -0.45 m).

Quick Tip to Solve: Keep mirror and lens formulae distinct: mirrors use $1/v + 1/u$, lenses use $1/v - 1/u$. For the lens, a negative v/u immediately checks that the calculated image is inverted.

OR

31(b). (i) Draw a ray diagram showing refraction of a ray of light through a triangular glass prism. Hence, obtain the relation for the refractive index (μ) in terms of angle of prism (A) and angle of minimum deviation (δ_m).

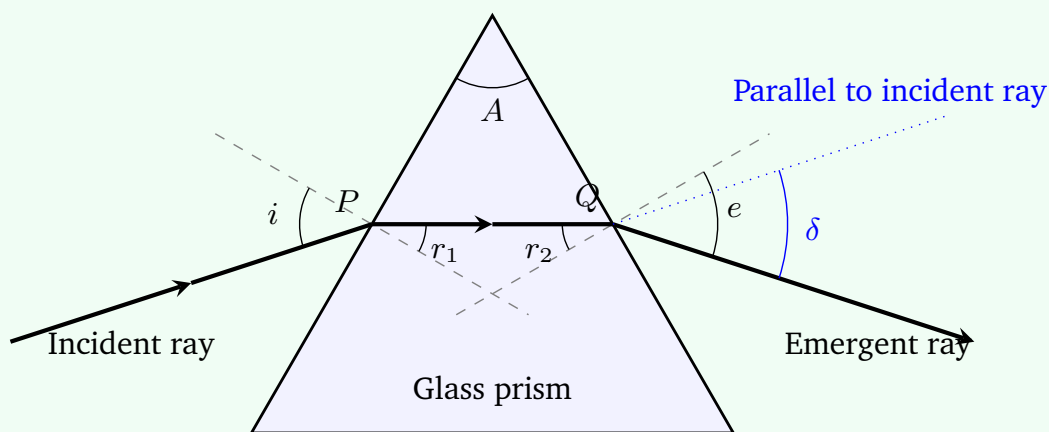
(ii) The radii of curvature of the two surfaces of a concave lens are 20 cm each. Find the refractive index of the material of the lens if its power is -5.0 D . [5 marks]

Solution:

Concept:

- Snell's law at an air-glass boundary is $\mu = \sin i / \sin r_1$, where i is the angle of incidence and r_1 is the angle of refraction, measured from the normal.
- For a prism of angle A , the internal angles satisfy $r_1 + r_2 = A$, and the total deviation is $\delta = i + e - A$, with e the angle of emergence.
- At minimum deviation the path is symmetric: $i = e$ and $r_1 = r_2$. For a thin lens in air, $P = (\mu - 1)(1/R_1 - 1/R_2)$, where P is in dioptres when the signed radii are in metres.

Step 1: (i) Draw and identify the refracted path The incident ray enters the glass prism at P , bends towards the normal and travels along PQ . At Q , it enters air and bends away from the normal. The overall deviation is towards the base of the prism. Dashed black lines are the normals; the dotted line through Q is parallel to the incident ray, so the angle between it and the emergent ray represents δ . The sketch shows the symmetric path used at minimum deviation.



Refraction through a prism; the symmetric ray path corresponds to minimum deviation.

Step 2: Relate the prism angle to the internal angles Each normal is perpendicular to its refracting face. The angle between the two inward normals is therefore $180^\circ - A$. Applying the angle sum of the triangle formed by the internal ray and the two normals gives

$$r_1 + r_2 + (180^\circ - A) = 180^\circ, \quad r_1 + r_2 = A.$$

At the first face the ray turns through $i - r_1$, and at the second through $e - r_2$, both towards the base. Hence the total deviation is

$$\delta = (i - r_1) + (e - r_2) = i + e - A.$$

Step 3: Apply the minimum-deviation condition As the angle of incidence is varied, the deviation decreases to a minimum and then increases. At the minimum the forward and reversed paths coincide by symmetry, so the incidence and emergence angles are equal. Thus

$$r_1 = r_2 = \frac{A}{2}, \quad \delta_m = 2i - A, \quad i = \frac{A + \delta_m}{2}.$$

Substituting these angles into Snell's law at the first face yields

$$\mu = \frac{\sin i}{\sin r_1} = \frac{\sin((A + \delta_m)/2)}{\sin(A/2)}.$$

This relation gives the refractive index of the prism material relative to air for the wavelength used.

Step 4: (ii) Assign signed radii to the concave lens Take light travelling from left to right and use the Cartesian sign convention. For the first concave surface its centre of curvature lies to the left, while that of the second surface lies to the right. Therefore

$$R_1 = -20 \text{ cm} = -0.20 \text{ m}, \quad R_2 = +20 \text{ cm} = +0.20 \text{ m}.$$

The given power is $P = -5.0 \text{ D}$, corresponding to a negative focal length $f = 1/P = -0.20 \text{ m}$, as expected for a diverging lens.

Step 5: Substitute in the lens-maker formula Using radii in metres, the lens-maker formula gives

$$\begin{aligned}-5.0 &= (\mu - 1) \left(\frac{1}{-0.20} - \frac{1}{+0.20} \right), \\ -5.0 &= -10(\mu - 1), \\ \mu - 1 &= 0.50, \quad \mu = 1.50.\end{aligned}$$

The negative curvature factor and positive value of $\mu - 1$ reproduce the specified negative power, providing a sign check.

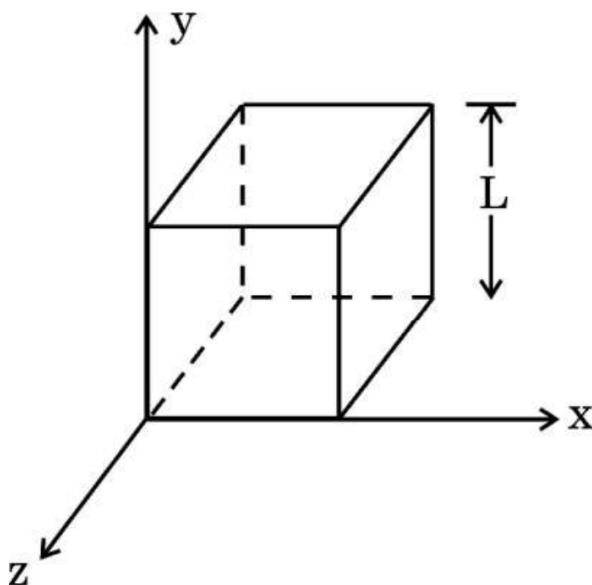
Step 6: Conclusion (i) The prism relation is $\mu = \frac{\sin((A + \delta_m)/2)}{\sin(A/2)}$. (ii) The refractive index of the concave-lens material is $\boxed{1.50}$, a dimensionless quantity.

Quick Tip to Solve: At minimum deviation, first put $r = A/2$ and $i = (A + \delta_m)/2$. For the biconcave lens use opposite signed radii and convert centimetres to metres before substituting the power in dioptres.

32(a). (i) Define electric flux and write its SI unit.

(ii) Use Gauss' law to obtain the expression for the electric field due to a uniformly charged infinite plane sheet.

(iii) A cube of side L is kept in space, as shown in the figure. An electric field $\vec{E} = (Ax + B)\hat{i}$ N/C exists in the region. Find the net charge enclosed by the cube. [5 marks]



Solution:

Concept:

- Electric flux through an oriented surface is $\Phi_E = \int_S \vec{E} \cdot d\vec{S}$, where $d\vec{S}$ is the normal area vector. For a closed surface the normal is outward.
- Gauss' law states $\oint_S \vec{E} \cdot d\vec{S} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the algebraic enclosed charge and ϵ_0 is the permittivity of free space.
- An infinite uniformly charged plane has translational and reflection symmetry: its electric field is perpendicular to the plane and has the same magnitude on its two sides.

Step 1: (i) Define flux and obtain its unit Electric flux is the surface integral of the normal component

of the electric field over the surface. For a uniform field through a plane area S ,

$$\Phi_E = \vec{E} \cdot \vec{S} = ES \cos \theta,$$

where θ is the angle between the field and the chosen area normal, not the plane itself. Since the field has unit N/C and area has unit m^2 , the SI unit of flux is $\text{N m}^2\text{C}^{-1}$, equivalently V m.

Step 2: (ii) Choose a Gaussian pillbox across the sheet Let the sheet carry uniform surface charge density σ . Choose a short cylindrical Gaussian surface with its axis normal to the sheet and equal flat end faces of area S , one on each side. The enclosed charge is σS . By symmetry the field has no component parallel to the sheet, and its magnitude is the same at corresponding points on opposite sides. For $\sigma > 0$, the field points away from the sheet. It is tangent to the curved surface, giving zero curved-surface flux, and parallel to the outward normals at both end faces. Each face therefore contributes ES .

Step 3: Apply Gauss' law to the pillbox Adding the two end-face contributions gives

$$2ES = \frac{\sigma S}{\epsilon_0} \Rightarrow E = \frac{\sigma}{2\epsilon_0} \quad (\sigma > 0).$$

In general the magnitude is $|\sigma|/(2\epsilon_0)$. The field is normal to the sheet, away from a positively charged sheet and towards a negatively charged sheet. It does not depend on distance from the infinite sheet. This result is for an isolated charged plane sheet; the two sides both contribute to its Gaussian flux.

Step 4: (iii) Compute the flux through the cube The cube extends from $x = 0$ to $x = L$, and each face has area L^2 . Since $\vec{E} = (Ax + B)\hat{i}$, its dot product with the normals of the four faces parallel to the x -axis is zero. On the left face the outward normal is $-\hat{i}$, whereas on the right it is $+\hat{i}$. Hence the signed fluxes are

$$\begin{aligned}\Phi_{x=0} &= -BL^2, \\ \Phi_{x=L} &= (AL + B)L^2, \\ \Phi_{\text{net}} &= (AL + B)L^2 - BL^2 = AL^3.\end{aligned}$$

Gauss' law now gives $Q_{\text{enc}} = \epsilon_0 \Phi_{\text{net}}$. The uniform part $B\hat{i}$ cancels between the two opposite faces; only the spatial variation contributes to the enclosed charge.

Step 5: Conclusion (i) $\Phi_E = \int_S \vec{E} \cdot d\vec{S}$, with SI unit $\text{N m}^2\text{C}^{-1}$. (ii) $E = |\sigma|/(2\epsilon_0)$, perpendicular to the sheet, away for positive charge and towards it for negative charge. (iii) The net charge inside the cube is $Q_{\text{enc}} = \epsilon_0 AL^3$, with its sign set by A .

Quick Tip to Solve: For a field along one coordinate axis, use only the two faces normal to that axis: net flux equals face area times the difference of the field components at the two faces.

32(b). (i) Define electric potential at a point and write its SI unit.

(ii) Two capacitors are connected in series. Derive an expression of the equivalent capacitance of the combination.

(iii) Two point charges $+q$ and $-q$ are located at points $(3a, 0)$ and $(0, 4a)$ respectively in x - y plane. A third charge Q is kept at the origin. Find the value of Q , in terms of q and a , so that the electrostatic potential energy of the system is zero. [5 marks]

Solution:

Concept:

- Electric potential is potential energy per unit positive test charge: $V = U/q_0$. With zero potential at infinity, it equals the external work per unit charge needed to bring a test charge slowly from infinity to the point.
- A capacitor obeys $C = Q_c/V$, where Q_c is the magnitude of charge on either plate and V is the potential difference between the plates.
- For point charges assembled from infinity, the system's electrostatic potential energy is $U = \sum_{i < j} kq_i q_j / r_{ij}$, where $k = 1/(4\pi\epsilon_0)$; each distinct pair is counted once with its algebraic charge signs.

Step 1: (i) Define electric potential and state its unit Electric potential at a point is the work done by an external agent per unit positive test charge in bringing that charge from infinity to the point without changing its kinetic energy. The test charge is sufficiently small that it does not disturb the existing source charges. Taking potential at infinity as zero,

$$V = \frac{W_{\text{ext}}}{q_0}.$$

Its SI unit is the volt, with $1 \text{ V} = 1 \text{ J C}^{-1}$. Potential is a scalar and can be positive or negative relative to the chosen reference.

Step 2: (ii) Relate the charges and voltages in series Consider two initially uncharged capacitors of capacitances C_1 and C_2 connected in series across a potential difference V . Their isolated connecting conductor remains electrically neutral, so equal and opposite charges appear on its two connected plates. Thus both capacitors carry the same charge magnitude Q_c , although their potential differences need not be equal. Using the definition of capacitance separately gives

$$V_1 = \frac{Q_c}{C_1}, \quad V_2 = \frac{Q_c}{C_2}.$$

The applied voltage is the sum of these drops: $V = V_1 + V_2$.

Step 3: Derive the equivalent capacitance Let C_{eq} be the single capacitance which draws the same charge Q_c under the same applied voltage. Then

$$\begin{aligned} \frac{Q_c}{C_{\text{eq}}} &= \frac{Q_c}{C_1} + \frac{Q_c}{C_2}, \\ \frac{1}{C_{\text{eq}}} &= \frac{1}{C_1} + \frac{1}{C_2}, \\ C_{\text{eq}} &= \frac{C_1 C_2}{C_1 + C_2}. \end{aligned}$$

For positive capacitances this is smaller than either constituent capacitance, which provides a useful check on a series-combination result.

Step 4: (iii) Determine all three pair separations The origin is a distance $3a$ from $+q$ at $(3a, 0)$ and a distance $4a$ from $-q$ at $(0, 4a)$, taking $a > 0$. By Pythagoras, the separation of the two fixed charges is

$$r_{+-} = \sqrt{(3a)^2 + (4a)^2} = 5a.$$

There are three distinct interacting pairs. Their energies are $-kq^2/(5a)$, $kqQ/(3a)$ and $-kqQ/(4a)$. The first term must be retained because the question asks for the energy of the entire three-charge system.

Step 5: Set the total potential energy to zero Summing the pair energies with their signs gives

$$\begin{aligned} U &= -\frac{kq^2}{5a} + \frac{kqQ}{3a} - \frac{kqQ}{4a} \\ &= \frac{k}{a} \left(-\frac{q^2}{5} + \frac{qQ}{12} \right). \end{aligned}$$

For $U = 0$ and nonzero q ,

$$\frac{qQ}{12} = \frac{q^2}{5} \Rightarrow Q = \frac{12q}{5}.$$

The required third charge is positive: its net interaction with the fixed pair is positive and cancels their negative mutual energy. The scale a cancels because every separation is proportional to it.

Step 6: Conclusion (i) Electric potential is external work per unit positive test charge brought from infinity without change of kinetic energy; its SI unit is the volt. (ii) $C_{\text{eq}} = C_1 C_2 / (C_1 + C_2)$. (iii) The required charge is $Q = +12q/5$, independent of a .

Quick Tip to Solve: For three charges, write exactly three pair-energy terms before simplifying. Here the origin's potential is positive, but the fixed pair's negative mutual energy must also be included.

33(a). (i) Write the principle and explain the working of a moving coil galvanometer. A galvanometer as such cannot be used to measure the current in a circuit. Why?

(ii) Why is the magnetic field made radial in a moving coil galvanometer? How is it achieved?

[5 marks]

Solution:

Concept:

- A current-carrying coil experiences a magnetic torque. For a coil of N turns and area A , carrying current I , the torque magnitude is $\tau_m = NIAB \sin \alpha$, where B is the magnetic field and α is its angle with the coil's normal.
- The suspension or spring supplies a restoring torque $\tau_r = k\theta$, where k is the torsional constant and θ is the angular deflection. Equilibrium requires equal opposing torques.
- A radial magnetic field keeps the field in the plane of the coil throughout its rotation, so that $\alpha = 90^\circ$ and the magnetic torque is always $NIAB$.

Step 1: (i) State the principle and describe the arrangement The moving coil galvanometer works on the principle that a current-carrying coil placed in a magnetic field experiences a torque. A light

rectangular coil of many turns of insulated wire is suspended, or pivoted with control springs, between the concave pole faces of a strong permanent magnet. A cylindrical soft-iron core is placed inside the coil. The suspension or springs carry current into and out of the coil and provide the restoring torque. A pointer or a mirror arrangement indicates the angular deflection.

Step 2: Explain the working and obtain the current-deflection relation When current flows, magnetic forces on the opposite sides of the coil form a couple and turn it. As the coil rotates, the suspension twists or the spring winds up, producing an opposing restoring torque. In the radial field, the magnetic torque has its maximum value at every allowed coil position. When the coil comes to rest,

$$\begin{aligned}\tau_m &= \tau_r, \\ NIAB &= k\theta, \\ I &= \frac{k}{NAB}\theta.\end{aligned}$$

Thus deflection is directly proportional to current, giving a uniformly graduated scale. Reversing the current reverses the torque and hence the direction of deflection.

Step 3: Explain why the galvanometer cannot directly measure ordinary circuit current A galvanometer is a sensitive detector of small currents. Its fine coil can carry only a small current safely; a larger circuit current may damage it. Also, its appreciable resistance, when inserted in series, changes the current that is to be measured. It is therefore converted into an ammeter by connecting a suitably small shunt resistance in parallel. Most of the current then passes through the shunt, protecting the coil and making the effective resistance of the instrument small.

Step 4: (ii) Explain the purpose and production of the radial field With a radial field, the coil's plane remains parallel to the local field and its normal remains perpendicular to it. Therefore $\sin \alpha = 1$: the torque has no additional dependence on the coil's angular position. This makes $\theta \propto I$, increases the torque for a given current, and produces a linear scale. The field is made radial using cylindrically concave magnet pole faces and a coaxial cylindrical soft-iron core inside the coil. The high permeability of the core also strengthens the field in the narrow air gap.

Step 5: Conclusion A moving coil galvanometer balances magnetic and restoring torques, giving $I = k\theta/(NAB)$. Its small current capacity and appreciable resistance prevent direct use for ordinary circuit currents. Concave pole faces with a cylindrical soft-iron core provide the radial field needed for maximum torque and a linear scale.

Quick Tip to Solve: Distinguish the deflection θ from the field-normal angle α : the radial field fixes $\alpha = 90^\circ$, while θ varies with current.

- 33(b).** (i) Derive an expression for magnetic field on the axis of a current-carrying circular loop.
 (ii) Write any two points of difference between a diamagnetic and a paramagnetic substance.

[5 marks]

Solution:**Concept:**

- Biot–Savart law gives the field of a current element: $d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{\ell} \times \hat{r}}{r^2}$, where $\vec{r}$ points from the element to the observation point.
- For a circular loop, symmetry cancels the field components perpendicular to its axis at an axial point; the axial components add. The field direction follows the right-hand grip rule.
- Magnetic susceptibility χ_m relates magnetisation to applied field through $\vec{M} = \chi_m \vec{H}$. Diamagnetic substances have a small negative susceptibility, whereas paramagnetic substances have a small positive susceptibility.

Step 1: (i) Define the geometry of the circular loop Consider a circular loop of radius R , carrying a steady current I , in vacuum. Let O be its centre and let P be a point on its axis, a distance x from O . The distance from every element of the loop to P is

$$r = \sqrt{R^2 + x^2}.$$

The tangent element $d\vec{\ell}$ is perpendicular to the plane containing the loop radius and the axis, and hence is perpendicular to $\vec{r}$. Thus the sine factor in Biot–Savart law is unity for every element.

Step 2: Resolve the field of an element along the axis The magnitude of the element's field at P is

$$dB = \frac{\mu_0 I d\ell}{4\pi r^2}.$$

Let β be the angle between $\vec{r}$ and the axis. From the right triangle, $\sin \beta = R/r$. Since $d\vec{B}$ is perpendicular to $\vec{r}$ in that same axial plane, its axial component is

$$dB_{\text{axis}} = dB \sin \beta = \frac{\mu_0 I R d\ell}{4\pi r^3}.$$

For diametrically opposite elements, the components perpendicular to the axis are equal and opposite, whereas their axial components have the same direction. Only the axial components therefore survive in the sum.

Step 3: Integrate around the complete loop Both R and r are constant around the loop, and its circumference is $2\pi R$. Therefore,

$$\begin{aligned} B(x) &= \oint dB_{\text{axis}} \\ &= \frac{\mu_0 I R}{4\pi (R^2 + x^2)^{3/2}} \oint d\ell \\ &= \frac{\mu_0 I R}{4\pi (R^2 + x^2)^{3/2}} (2\pi R) \\ &= \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}. \end{aligned}$$

The field is directed along the axis in the direction of the right thumb when the curled fingers follow the current. At the centre, setting $x = 0$ gives $B(0) = \mu_0 I / (2R)$. For N identical closely wound turns, the expression is multiplied by N .

Step 4: (ii) State two differences between the substances Response to a non-uniform magnetic field: A diamagnetic substance is weakly repelled and tends to move from a stronger to a weaker field region. A paramagnetic substance is weakly attracted and tends to move from a weaker to a stronger field region.

Susceptibility and magnetisation: A diamagnetic substance has a small negative χ_m , so its induced magnetisation is opposite to the applied field. A paramagnetic substance has a small positive χ_m , so its magnetisation is along the applied field. Correspondingly, $\mu_r = 1 + \chi_m$ is slightly less than unity for a diamagnet and slightly greater than unity for a paramagnet.

Step 5: Conclusion The axial field of a single circular current loop is $B(x) = \mu_0 I R^2 / [2(R^2 + x^2)^{3/2}]$, with direction given by the right-hand rule. Diamagnets are weakly repelled and have negative susceptibility; paramagnets are weakly attracted and have positive susceptibility.

Quick Tip to Solve: Cancel the transverse components before integrating the loop field, and check the result at $x = 0$: it must reduce to $\mu_0 I / (2R)$.

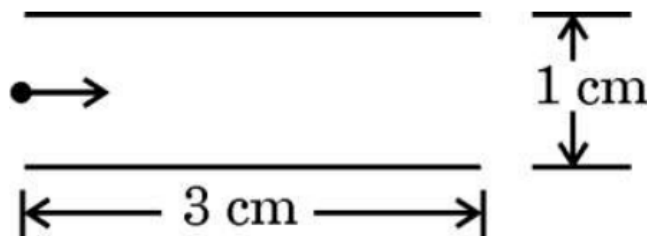
Section E (8 marks)

34(a). A beam of electrons moving horizontally with a velocity of 3×10^7 m/s enters a region between two plates as shown in the figure. A suitable potential difference is applied across the plates such that the electron beam just strikes the edge of the lower plate.

Answer the following questions based on the above:

How long does an electron take to strike the edge?

[1 mark]



Solution:

Concept:

- The electric field between parallel plates acts vertically, so the horizontal velocity remains constant at $v_x = 3 \times 10^7$ m s⁻¹.
- For constant horizontal velocity, the travel time is $t = L/v_x$, where L is the horizontal length of the plates.

Step 1: Identify the horizontal travel distance The electron reaches the far edge after travelling the plate length horizontally. From the figure, $L = 3$ cm = 3×10^{-2} m. The vertical deflection changes the path length, but does not change the horizontal component of velocity.

Step 2: Calculate the transit time Use the horizontal displacement, rather than the curved path

length:

$$t = \frac{3 \times 10^{-2}}{3 \times 10^7} = 10^{-9} \text{ s.}$$

The vertical force determines where the electron strikes, while horizontal motion determines when it reaches that edge.

Step 3: Conclusion The electron takes $1.0 \times 10^{-9} \text{ s}$, or 1.0 ns, to strike the edge.

Quick Tip to Solve: Use the 3 cm plate length with the horizontal speed; the 1 cm plate separation is not the distance for this time calculation.

34(b). What is the shape of the path followed by the electron and why?

[1 mark]

Solution:

Concept:

- In a uniform electric field, an electron experiences constant force $\mathbf{F} = -e\mathbf{E}$, hence constant vertical acceleration.
- Horizontal motion is uniform and vertical motion starts from rest: $x = v_x t$ and $y = \frac{1}{2} a_y t^2$, with downward y taken positive.

Step 1: Resolve the motion into two directions The beam enters horizontally, so its initial vertical velocity is zero. The field between the plates provides a constant downward force on the electrons. With no horizontal force, v_x stays constant while the downward velocity increases uniformly.

Step 2: Eliminate the travel time From horizontal motion, $t = x/v_x$. Substitution into the vertical displacement gives

$$y = \frac{a_y}{2v_x^2} x^2.$$

Thus vertical displacement is proportional to the square of horizontal displacement, the defining relation of a parabola.

Step 3: Conclusion The path is **parabolic**, because uniform horizontal motion combines with uniformly accelerated vertical motion.

Quick Tip to Solve: Whenever a constant force is perpendicular to the initial velocity, eliminate time from the two component equations to recognize the parabola.

34(c). Find the potential difference applied.

[2 marks]

Solution:

Concept:

- Between parallel plates, the uniform electric field has magnitude $E = V/d$, where V is their potential difference and d their separation.
- An electron has acceleration magnitude $a = eE/m_e$. Starting with zero vertical velocity, its vertical displacement is $y = \frac{1}{2} at^2$.

Step 1: Find the transit time and vertical displacement The figure shows the beam entering midway between the plates. Their separation is $d = 1 \text{ cm} = 10^{-2} \text{ m}$, so reaching the lower plate requires a downward displacement $y = d/2 = 5 \times 10^{-3} \text{ m}$. The horizontal speed is unchanged and the plate

length is $L = 3 \times 10^{-2}$ m, giving

$$t = \frac{L}{v_x} = \frac{3 \times 10^{-2}}{3 \times 10^7} = 10^{-9} \text{ s.}$$

Step 2: Calculate the field and potential difference Using $m_e = 9.1 \times 10^{-31}$ kg and $e = 1.6 \times 10^{-19}$ C,

$$\begin{aligned} a &= \frac{2y}{t^2} = 10^{16} \text{ m s}^{-2}, \\ E &= \frac{m_e a}{e} = 5.6875 \times 10^4 \text{ V m}^{-1}, \\ V &= Ed = (5.6875 \times 10^4)(10^{-2}) = 568.75 \text{ V.} \end{aligned}$$

The force on a negative electron is opposite to the electric field. Downward deflection therefore requires an upward field, from the positive lower plate towards the negative upper plate.

Step 3: Conclusion The required potential difference is $V \approx 5.69 \times 10^2 \text{ V}$, with the lower plate at higher potential.

Quick Tip to Solve: The electron falls only half the 1 cm separation; use that displacement for acceleration, then the full separation in $V = Ed$.

OR

34(c). Find the magnitude and direction of the magnetic field which should be created in the space between the plates so that the electron beam goes straight undeviated. [2 marks]

Solution:

Concept:

- For an undeviated charged particle, the net Lorentz force vanishes: $q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = 0$.
- With mutually perpendicular fields and velocity, electric and magnetic forces cancel when $eE = evB$, giving $B = E/v$.

Step 1: Determine the electric field from the original deflection The plate length is $L = 0.03$ m and the speed is $v = 3 \times 10^7$ m s⁻¹, so the transit time is $t = L/v = 10^{-9}$ s. The beam starts midway across the 0.01 m gap, giving $y = 0.005$ m. Before adding the magnetic field,

$$\begin{aligned} a &= \frac{2y}{t^2} = 10^{16} \text{ m s}^{-2}, \\ E &= \frac{m_e a}{e} = \frac{(9.1 \times 10^{-31})(10^{16})}{1.6 \times 10^{-19}} \\ &= 5.6875 \times 10^4 \text{ V m}^{-1}. \end{aligned}$$

Step 2: Balance the forces and establish the field direction The magnetic force must act upward to cancel the downward electric force. Equating their magnitudes gives

$$B = \frac{E}{v} = \frac{5.6875 \times 10^4}{3 \times 10^7} = 1.896 \times 10^{-3} \text{ T.}$$

For velocity to the right and magnetic field out of the page, $\mathbf{v} \times \mathbf{B}$ points downward. Since the electron charge is negative, $-(\mathbf{v} \times \mathbf{B})$ points upward, as required.

Step 3: Conclusion The required perpendicular magnetic field is $B \approx 1.90 \times 10^{-3} \text{ T}$, directed out of the plane of the page, towards the observer.

Quick Tip to Solve: First find $B = E/v$; then reverse the right-hand-rule force direction because the moving particle is an electron.

35(a). Diffraction of light is bending of light around the corners of an object whose size is comparable with the wavelength of light. Diffraction actually defines the limits of ray optics. This limit for optical instruments is set by the wavelength of light. An experimental arrangement is set up to observe the diffraction pattern due to a single slit.

Answer the following questions based on the above:

How will the width of central maximum be affected if the wavelength of light is increased? [1 mark]

Solution:

Concept:

- For a single slit of width a , the first minima satisfy $a \sin \theta = \pm \lambda$, where λ is the wavelength.
- For small diffraction angles on a screen at distance D , the central maximum has width $W = 2D\lambda/a$.

Step 1: Locate the boundaries of the central maximum The central maximum lies between the first dark fringes on either side of the axis. With the small-angle approximation, these occur at $y = \pm D\lambda/a$, so their separation is

$$W = \frac{2D\lambda}{a}.$$

Step 2: Compare the widths at fixed geometry The slit width and the screen distance are unchanged when only the wavelength is increased. Hence

$$\frac{W_2}{W_1} = \frac{\lambda_2}{\lambda_1}.$$

A larger wavelength moves both first minima farther from the centre; for example, doubling the wavelength doubles the central width within the small-angle approximation.

Step 3: Conclusion The width of the central maximum increases; for fixed slit width and screen distance, it is directly proportional to wavelength.

Quick Tip to Solve: For a wavelength change alone, use $W_2/W_1 = \lambda_2/\lambda_1$; longer wavelengths spread the single-slit pattern more.

35(b). Under what condition is the first minimum obtained? [1 mark]

Solution:

Concept:

- The path difference between secondary waves from the two edges of a slit of width a is $a \sin \theta$.
- Destructive interference gives a dark fringe when corresponding contributions across the slit cancel in pairs.

Step 1: Pair the contributions from the two half-slits Divide the slit into two equal halves. Pair each

point in the upper half with a corresponding point a distance $a/2$ away in the lower half. Their path difference is $(a/2) \sin \theta$.

Step 2: Apply the cancellation condition For the first minimum, each pair must differ in path by $\lambda/2$, so its waves arrive in opposite phase:

$$\frac{a}{2} \sin \theta = \frac{\lambda}{2} \implies a \sin \theta = \lambda.$$

All such pairs then cancel. The symmetric first minimum occurs on the other side of the central maximum at the negative angle.

Step 3: Conclusion The first minima satisfy $a \sin \theta = \pm \lambda$, or $|\sin \theta| = \lambda/a$, where a is the slit width.

Quick Tip to Solve: For the first minimum, the full-slit edge-to-edge path difference is one wavelength; the paired half-slit difference is half a wavelength.

35(c). Write two points of difference between interference and diffraction patterns.

[2 marks]

Solution:

Concept:

- Interference results from the superposition of coherent waves. For two equally illuminated narrow slits, the ideal interference fringes have width $\beta = \lambda D/d$, where λ is wavelength, D is screen distance and d is slit separation.
- Single-slit diffraction results from superposition of secondary wavelets from different parts of the same slit. Its minima satisfy $a \sin \theta = n\lambda$, where a is slit width and $n = 1, 2, \dots$

Step 1: Compare the widths of the fringes In the ideal two-slit interference pattern, bright and dark fringes are equally spaced and have the same width $\lambda D/d$. In a single-slit diffraction pattern, the central bright maximum extends between the first minima on either side and has width $2\lambda D/a$. Each secondary bright fringe lies between successive minima and has approximately half this width, $\lambda D/a$, in the small-angle approximation.

Step 2: Compare the intensities of the bright fringes For two coherent sources of equal intensity, the ideal interference bright fringes have the same maximum intensity. In single-slit diffraction, the central maximum is the brightest; the secondary maxima are much weaker and their intensities decrease as their distance from the centre increases. The ideal interference comparison neglects the diffraction envelope caused by finite slit width.

Step 3: Conclusion The two differences are: interference fringes have equal widths and equal peak intensities in the ideal equal-source case; diffraction has a central maximum twice as wide as its secondary bright fringes, with successively weaker secondary maxima.

Quick Tip to Solve: Compare width and peak intensity: the broad, brightest central maximum is the key signature of single-slit diffraction.

35(c). Two students are separated by a 7 m partition wall in a room 10 m high. If both light and sound waves can bend around obstacles, how is it that the students are unable to see each other even though they can converse easily? [2 marks]

Solution:

Concept:

- Diffraction is the spreading of waves around an obstacle or through an opening. The spreading is appreciable when the wavelength is comparable with the relevant size of the opening or obstacle.
- For an opening of width a , the angular spread scales as λ/a . Thus a longer wavelength λ produces greater diffraction for the same geometry; a very small ratio gives an almost straight path.

Step 1: Compare sound wavelengths with the room dimensions The 7 m partition leaves a $10 - 7 = 3$ m gap below the ceiling. Audible sound has wavelengths ranging from centimetres to metres; the longer wavelengths present in speech are sufficiently large for appreciable spreading around the partition edges and through the available opening. Sound therefore reaches the student behind the wall, allowing conversation.

Step 2: Compare visible-light wavelengths with the same opening Visible-light wavelengths are only about 4×10^{-7} to 7×10^{-7} m, enormously smaller than the metre-scale wall and gap. Consequently, the diffraction angle for light is extremely small, and light does not bend appreciably into the region behind the wall. The partition blocks the direct light paths needed to see the other student; the existence of diffraction does not imply a large bending angle.

Step 3: Conclusion Sound diffracts appreciably around the partition because of its much longer wavelength, whereas visible-light diffraction is negligible on this scale. Hence the students can hear each other but cannot see each other through the partition.

Quick Tip to Solve: Compare wavelength with the opening size: sound wavelengths are much closer to room dimensions than visible-light wavelengths are.