

CBSE Class 12 Physics Question Paper 2023 with Solution PDF-Set 55/2/1



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) Question paper is divided into **FIVE** sections – Section **A, B, C, D** and **E**.
- (iii) In **Section A** : Question number **1** to **18** are Multiple Choice (MCQ) type questions carrying **1** mark each.
- (iv) In **Section B** : Question number **19** to **25** are Short Answer-1 (SA-1) type questions carrying **2** marks each.
- (v) In **Section C** : Question number **26** to **30** are Short Answer-2 (SA-2) type questions carrying **3** marks each.
- (vi) In **Section D** : Question number **31** to **33** are Long Answer (LA) type questions carrying **5** marks each.
- (vii) In **Section E** : Question number **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.

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

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

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

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

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

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

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

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

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

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

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

Section A (18 marks)

1. The magnitude of the electric field due to a point charge object at a distance of 4.0 m is 9 N/C. From the same charged object the electric field of magnitude, 16 N/C will be at a distance of [1 mark]

- (A) 1 m
- (B) 2 m
- (C) 3 m
- (D) 6 m

Correct Answer: (C) 3 m

Solution:

Concept:

- For a fixed point charge, $E = k|q|/r^2$, where r is distance and $k = 1/(4\pi\epsilon_0)$.
- Thus Er^2 remains constant at different distances from the same charge in the same medium.

Step 1: Relate the two field values The charge is unchanged, so $E_1 r_1^2 = E_2 r_2^2$. Substituting $E_1 = 9 \text{ N/C}$, $r_1 = 4.0 \text{ m}$, and $E_2 = 16 \text{ N/C}$ gives

$$r_2^2 = \frac{9 \times (4.0)^2}{16} = 9 \text{ m}^2.$$

Step 2: Check the possible distances Take the positive square root because distance is nonnegative. The field is stronger at the second point, so its distance must be smaller than 4.0 m. At 1, 2, and 6 m, the fields would instead be 144, 36, and 4 N/C, respectively.

Step 3: Conclusion The required distance is $r_2 = 3 \text{ m}$. Hence, the correct option is (C).

Quick Tip to Solve: Use $r_2 = r_1 \sqrt{E_1/E_2}$; the square root is essential for an inverse-square field.

2. A point P lies at a distance x from the mid point of an electric dipole on its axis. The electric potential at point P is proportional to [1 mark]

- (A) $\frac{1}{x^2}$
- (B) $\frac{1}{x^3}$
- (C) $\frac{1}{x^4}$
- (D) $\frac{1}{x^{1/2}}$

Correct Answer: (A) $\frac{1}{x^2}$

Solution:

Concept:

- For a short electric dipole, $V = kp \cos \theta / r^2$, where p is dipole moment and θ is measured from its axis.
- On the dipole axis, $|\cos \theta| = 1$, so the magnitude of the potential varies as $1/r^2$.

Step 1: Apply the axial dipole formula At the axial point P , the distance from the midpoint is x . In

the usual ideal or short-dipole approximation,

$$V = \pm \frac{kp}{x^2}.$$

The sign depends on the side of the dipole; it does not change the distance dependence.

Step 2: Distinguish potential from field The $1/x^3$ dependence belongs to the far-field electric field of a dipole, not its potential. Neither $1/x^4$ nor $1/\sqrt{x}$ is the dipole-potential law. For charges separated by $2a$, the exact axial expression is $V = \pm kp/(x^2 - a^2)$; the printed choices implicitly use $x \gg a$.

Step 3: Conclusion In the standard short-dipole approximation, $V \propto 1/x^2$. Hence, the correct option is (A).

Quick Tip to Solve: Remember the dipole pair: potential falls as r^{-2} , while electric field falls as r^{-3} .

3. A current of 0.8 A flows in a conductor of $40\ \Omega$ for 1 minute. The heat produced in the conductor will be [1 mark]

- (A) 1445 J
- (B) 1536 J
- (C) 1569 J
- (D) 1640 J

Correct Answer: (B) 1536 J

Solution:

Concept:

- Joule heating is $H = I^2Rt$, where I is current, R is resistance and t is elapsed time.
- With amperes, ohms and seconds, the heat H is obtained in joules.

Step 1: Convert the time to SI units The current and resistance are already in SI units: $I = 0.8\text{ A}$ and $R = 40\ \Omega$. Convert 1 minute to $t = 60\text{ s}$ before substituting. Keeping the time as 1 would calculate only one second of heating.

Step 2: Calculate heat and compare the choices First square the current, then multiply by resistance and time:

$$H = (0.8)^2 \times 40 \times 60 = 0.64 \times 2400 = 1536\text{ J}.$$

The dissipated power is $I^2R = 25.6\text{ W}$. Over 60 s this gives the same energy; the other three listed energies do not satisfy Joule's law for these data.

Step 3: Conclusion The heat produced is 1536 J. Hence, the correct option is (B).

Quick Tip to Solve: Convert minutes to seconds first and square the full current value: $(0.8)^2 = 0.64$.

4. A cell of emf E is connected across an external resistance R . When current I is drawn from the cell, the potential difference across the electrodes of the cell drops to V . The internal resistance ' r ' of the cell is [1 mark]

(A) $\left(\frac{E - V}{E}\right) R$

(B) $\frac{E - V}{R}$

(C) $\frac{(E - V)R}{I}$

(D) $\left(\frac{E - V}{V}\right) R$

Correct Answer: (D) $\left(\frac{E - V}{V}\right) R$

Solution:

Concept:

- A cell supplying current satisfies $E = V + Ir$, where E is emf, V terminal voltage and r internal resistance.
- Across the external resistance, Ohm's law gives $V = IR$.

Step 1: Express the internal voltage drop The loss of terminal voltage while the cell delivers current is the drop across its internal resistance:

$$Ir = E - V, \quad r = \frac{E - V}{I}.$$

The total emf must not be used as the voltage across the external resistor.

Step 2: Eliminate the current using the external circuit Since $I = V/R$, substitution gives

$$r = \frac{E - V}{V/R} = \left(\frac{E - V}{V}\right) R.$$

Option (A) incorrectly replaces the terminal voltage in the denominator by emf. Option (B) has units of current, and option (C) has units of resistance squared; neither can represent r .

Step 3: Conclusion The internal resistance is $r = \left(\frac{E - V}{V}\right) R$. Hence, the correct option is (D).

Quick Tip to Solve: Use $E - V = Ir$ together with $V = IR$; the external resistor has voltage V , not E .

5. Beams of electrons and protons move parallel to each other in the same direction. They [1 mark]

- (A) attract each other.
- (B) repel each other.
- (C) neither attract nor repel.
- (D) force of attraction or repulsion depends upon speed of beams.

Correct Answer: (A) attract each other.

Solution:

Concept:

- Electron and proton beams carry opposite electric charges, so their electric interaction is attractive.
- Their conventional currents are opposite for motion in the same direction; the magnetic interaction is repulsive.

Step 1: Identify the two contributions to force Electrons have negative charge and protons positive charge, giving electric attraction between the beams. Conventional current follows proton motion and opposes electron motion. Consequently, the two current directions are antiparallel, which produces magnetic repulsion.

Step 2: Compare electric attraction with magnetic repulsion For parallel thin beams with speeds v_e and v_p , the ratio of force magnitudes is

$$\frac{F_B}{F_E} = \mu_0 \epsilon_0 v_e v_p = \frac{v_e v_p}{c^2} < 1.$$

Both particles are massive, so their speeds are below c . Electric attraction therefore exceeds magnetic repulsion. Option (B) would describe the magnetic force alone; (C) would require exact cancellation, and (D) incorrectly suggests that changing subluminal speeds can reverse the net force.

Step 3: Conclusion The net electromagnetic interaction of the charged beams is attractive. Hence, the correct option is (A).

Quick Tip to Solve: Distinguish total force from magnetic force: opposite moving charges attract electrically even when their currents repel.

6. A long straight wire of radius ' a ' carries a steady current ' I '. The current is uniformly distributed across its area of cross-section. The ratio of magnitude of magnetic field $\vec{B}_1$ at $\frac{a}{2}$ and $\vec{B}_2$ at distance $2a$ is [1 mark]

- (A) $\frac{1}{2}$
- (B) 1
- (C) 2
- (D) 4

Correct Answer: (B) 1

Solution:

Concept:

- Ampere's law gives $B(2\pi r) = \mu_0 I_{\text{enc}}$, where I_{enc} is the enclosed current.
- For uniform current density inside radius a , $I_{\text{enc}} = Ir^2/a^2$; outside the wire the full current I is

enclosed.

Step 1: Find the field inside the conductor At $r = a/2$, only one quarter of the total current lies inside the circular Amperian path. Therefore

$$B_1 = \frac{\mu_0 I(a/2)}{2\pi a^2} = \frac{\mu_0 I}{4\pi a}.$$

Using the outside-wire formula here would incorrectly count all the current.

Step 2: Find the outside field and form the ratio At $r = 2a$, the whole current is enclosed:

$$B_2 = \frac{\mu_0 I}{2\pi(2a)} = \frac{\mu_0 I}{4\pi a}, \quad \frac{B_1}{B_2} = 1.$$

The ratios 1/2, 2, and 4 fail because the interior field increases linearly with radius while the exterior field decreases inversely with radius.

Step 3: Conclusion The two field magnitudes are equal, so $B_1/B_2 = 1$. Hence, the correct option is (B).

Quick Tip to Solve: Use $B \propto r$ inside a uniformly conducting wire and $B \propto 1/r$ outside it.

7. $\vec{E}$ and $\vec{B}$ represent the electric and the magnetic field of an electromagnetic wave respectively. The direction of propagation of the wave is along [1 mark]

- (A) $\vec{B}$
- (B) $\vec{E}$
- (C) $\vec{E} \times \vec{B}$
- (D) $\vec{B} \times \vec{E}$

Correct Answer: (C) $\vec{E} \times \vec{B}$

Solution:

Concept:

- The electric field, magnetic field and propagation direction of a plane electromagnetic wave are mutually perpendicular.
- The energy-flow direction is given by the Poynting vector $\vec{S} = (1/\mu_0)\vec{E} \times \vec{B}$ in vacuum.

Step 1: Use the direction of energy transport An electromagnetic wave transports energy along its direction of propagation. Since the factor $1/\mu_0$ is positive, the Poynting vector points along the ordered cross product $\vec{E} \times \vec{B}$. The right-hand rule applied from $\vec{E}$ towards $\vec{B}$ determines this direction.

Step 2: Check the alternative directions Neither $\vec{E}$ nor $\vec{B}$ is along propagation because both are transverse to it. Reversing the cross-product order changes its sign:

$$\vec{B} \times \vec{E} = -\vec{E} \times \vec{B}.$$

Thus option (D) points opposite to propagation, whereas options (A) and (B) lie perpendicular to propagation.

Step 3: Conclusion The propagation direction is along $\vec{E} \times \vec{B}$. Hence, the correct option is (C).

Quick Tip to Solve: Keep the order electric field then magnetic field when using the right-hand rule for wave propagation.

8. A ray of monochromatic light propagating in air, is incident on the surface of water. Which of the following will be the same for the reflected and refracted rays? [1 mark]

- (A) Energy carried
- (B) Speed
- (C) Frequency
- (D) Wavelength

Correct Answer: (C) Frequency

Solution:

Concept:

- At a stationary interface, reflected and transmitted waves retain the frequency of the incident light.
- Wave speed and wavelength satisfy $v = f\lambda$; the refractive index changes speed and therefore wavelength.

Step 1: Apply frequency continuity at the interface The oscillations at the air-water boundary are driven by the same incident monochromatic wave. Both the reflected and refracted waves therefore have its frequency f . Reflection and refraction do not create a new oscillation frequency at this stationary boundary.

Step 2: Compare the remaining quantities The reflected ray travels in air while the refracted ray travels in water, where its speed is lower. Since $\lambda = v/f$, their wavelengths also differ. The incident energy is divided between reflected and transmitted light, and the two energy portions are not generally equal. Therefore energy carried, speed and wavelength are not the common quantity sought.

Step 3: Conclusion The frequency is the same for both rays. Hence, the correct option is (C).

Quick Tip to Solve: At a stationary boundary keep f unchanged, then use $\lambda = v/f$ to determine how wavelength changes.

9. A beam of light travels from air into a medium. Its speed and wavelength in the medium are $1.5 \times 10^8 \text{ m s}^{-1}$ and 230 nm respectively. The wavelength of light in air will be [1 mark]

- (A) 230 nm
- (B) 345 nm
- (C) 460 nm
- (D) 690 nm

Correct Answer: (C) 460 nm

Solution:

Concept:

- The frequency ν of light remains unchanged at the boundary between two stationary media.
- Wave speed satisfies $v = \nu\lambda$, where λ is the wavelength in that medium; hence wavelength is proportional to speed at fixed frequency.

Step 1: Compare the speeds In air, take $c = 3.0 \times 10^8 \text{ m s}^{-1}$. The ratio of the speed in air to that in the medium is

$$\frac{c}{v} = \frac{3.0 \times 10^8}{1.5 \times 10^8} = 2.$$

Step 2: Apply the unchanged frequency Since $c/\lambda_{\text{air}} = v/\lambda_{\text{medium}}$,

$$\lambda_{\text{air}} = \frac{c}{v} \lambda_{\text{medium}} = 2(230 \text{ nm}) = 460 \text{ nm}.$$

Option (A) incorrectly leaves wavelength unchanged, while (B) and (D) use speed ratios of 1.5 and 3 instead of the actual ratio 2.

Step 3: Conclusion The wavelength of light in air is 460 nm. Hence, the correct option is (C).

Quick Tip to Solve: Keep frequency fixed at a boundary: if light travels twice as fast in air, its wavelength in air is twice as large.

10. Which one of the following metals does not exhibit emission of electrons from its surface when irradiated by visible light? [1 mark]

- (A) Rubidium
- (B) Sodium
- (C) Cadmium
- (D) Caesium

Correct Answer: (C) Cadmium

Solution:

Concept:

- Photoelectric emission requires the photon energy $h\nu$ to be at least the metal's work function ϕ , the minimum energy needed to remove an electron.
- The threshold frequency is $\nu_0 = \phi/h$; light of frequency below ν_0 cannot eject electrons, however intense it is.

Step 1: Compare the thresholds of the metals Rubidium, sodium and caesium are alkali metals with sufficiently low work functions that light in an appropriate part of the visible spectrum can cause

photoelectric emission. Therefore options (A), (B) and (D) do not answer the question.

Step 2: Identify the metal needing ultraviolet light Cadmium has a higher work function than the energies of visible photons. Its threshold lies in the ultraviolet region, so visible illumination cannot supply the minimum energy needed for an electron to escape. Increasing visible-light intensity does not overcome this energy deficit per photon.

Step 3: Conclusion Cadmium does not exhibit photoelectric emission under visible light. Hence, the correct option is (C).

Quick Tip to Solve: For visible-light photoemission, identify low-work-function alkali metals first; the non-alkali metal cadmium requires ultraviolet photons.

11. A hydrogen atom makes a transition from $n = 5$ to $n = 1$ orbit. The wavelength of photon emitted is λ . The wavelength of photon emitted when it makes a transition from $n = 5$ to $n = 2$ orbit is [1 mark]

- (A) $\frac{8}{7}\lambda$
- (B) $\frac{16}{7}\lambda$
- (C) $\frac{24}{7}\lambda$
- (D) $\frac{32}{7}\lambda$

Correct Answer: (D) $\frac{32}{7}\lambda$

Solution:

Concept:

- For hydrogen, the Rydberg formula is $1/\lambda = R_H(1/n_f^2 - 1/n_i^2)$, where n_i and n_f are the initial and final quantum numbers.
- Photon energy is $E = hc/\lambda$, so a smaller energy difference produces a longer wavelength.

Step 1: Write the two transition equations For the given transition from $n = 5$ to $n = 1$,

$$\frac{1}{\lambda} = R_H \left(1 - \frac{1}{25} \right) = \frac{24R_H}{25}.$$

If λ' is the wavelength for the transition from $n = 5$ to $n = 2$,

$$\frac{1}{\lambda'} = R_H \left(\frac{1}{4} - \frac{1}{25} \right) = \frac{21R_H}{100}.$$

Step 2: Take the inverse-wavelength ratio Dividing the first equation by the second gives

$$\frac{\lambda'}{\lambda} = \frac{24/25}{21/100} = \frac{96}{21} = \frac{32}{7}.$$

The common Rydberg constant cancels. Options (A), (B) and (C) do not equal this ratio of the two energy differences; using the quantum numbers directly instead of their inverse squares is incorrect.

Step 3: Conclusion The wavelength of the second photon is $\lambda' = \frac{32}{7}\lambda$. Hence, the correct option is (D).

Quick Tip to Solve: For two hydrogen transitions, divide their Rydberg expressions and invert the wavenumber ratio to obtain the wavelength ratio.

12. The curve of binding energy per nucleon as a function of atomic mass number has a sharp peak for helium nucleus. This implies that helium nucleus is [1 mark]

- (A) radioactive
- (B) unstable
- (C) easily fissionable
- (D) more stable nucleus than its neighbours

Correct Answer: (D) more stable nucleus than its neighbours

Solution:

Concept:

- Binding energy is the energy required to separate a nucleus completely into its constituent protons and neutrons.
- Binding energy per nucleon, B/A , is the average binding energy per constituent nucleon; a larger value indicates stronger binding and greater relative nuclear stability.

Step 1: Interpret the local peak A sharp peak at the helium nucleus means that its binding energy per nucleon is larger than that of nuclei with nearby mass numbers. Its nucleons are therefore more strongly bound on average than those in its neighbours.

Step 2: Relate binding to stability Stronger binding makes the nucleus relatively more stable. A peak does not signify radioactivity or instability, so (A) and (B) are inappropriate. Nor does it indicate that the nucleus is easily fissionable, as in (C): breaking a tightly bound light nucleus into less tightly bound fragments requires energy.

Step 3: Conclusion The helium nucleus is more stable than its neighbours. Hence, the correct option is (D).

Quick Tip to Solve: Read a local peak of the binding-energy-per-nucleon curve as enhanced stability relative to nearby nuclei, not as the largest total binding energy.

13. In an extrinsic semiconductor, the number density of holes is $4 \times 10^{20} \text{ m}^{-3}$. If the number density of intrinsic carriers is $1.2 \times 10^{15} \text{ m}^{-3}$, the number density of electrons in it is [1 mark]

- (A) $1.8 \times 10^9 \text{ m}^{-3}$
(B) $2.4 \times 10^{10} \text{ m}^{-3}$
(C) $3.6 \times 10^9 \text{ m}^{-3}$
(D) $3.2 \times 10^{10} \text{ m}^{-3}$

Correct Answer: (C) $3.6 \times 10^9 \text{ m}^{-3}$

Solution:

Concept:

- At thermal equilibrium, the mass-action law is $n_e n_h = n_i^2$, where n_e , n_h and n_i denote electron, hole and intrinsic carrier number densities at the same temperature.
- In a p-type semiconductor, holes are the majority carriers and electrons are the minority carriers; the two densities are not equal after doping.

Step 1: Rearrange the mass-action law Given $n_h = 4 \times 10^{20} \text{ m}^{-3}$ and $n_i = 1.2 \times 10^{15} \text{ m}^{-3}$, the required electron density is

$$n_e = \frac{n_i^2}{n_h}.$$

Squaring the intrinsic density is essential; merely dividing n_i by the hole density would be dimensionally incorrect.

Step 2: Substitute and simplify

$$\begin{aligned} n_e &= \frac{(1.2 \times 10^{15})^2}{4 \times 10^{20}} \text{ m}^{-3} \\ &= \frac{1.44 \times 10^{30}}{4 \times 10^{20}} \text{ m}^{-3} \\ &= 0.36 \times 10^{10} \text{ m}^{-3} = 3.6 \times 10^9 \text{ m}^{-3}. \end{aligned}$$

Only option (C) has both the correct coefficient and exponent; (A), (B) and (D) fail the product relation with the given hole density.

Step 3: Conclusion The electron number density is $3.6 \times 10^9 \text{ m}^{-3}$. Hence, the correct option is (C).

Quick Tip to Solve: Square both the coefficient and the power of ten in the intrinsic density before dividing by the majority-carrier density.

14. Pieces of copper and of silicon are initially at room temperature. Both are heated to temperature T . The conductivity of [1 mark]

- (A) both increases.
- (B) both decreases.
- (C) copper increases and silicon decreases.
- (D) copper decreases and silicon increases.

Correct Answer: (D) copper decreases and silicon increases.

Solution:

Concept:

- Conductivity depends on the number of mobile charge carriers and their mobility; for a metal, $\sigma = ne^2\tau/m$, where τ is the mean relaxation time.
- Heating increases lattice vibrations. In a semiconductor, it also creates additional electron-hole pairs by thermally exciting electrons across the band gap.

Step 1: Examine the copper sample In copper, the free-electron density changes very little on heating. Stronger lattice vibrations increase scattering and reduce the relaxation time τ . Thus its resistivity increases and its conductivity decreases.

Step 2: Examine the silicon sample In silicon, heating increases the number of electrons in the conduction band and holes in the valence band. The increase in carrier density dominates the reduction in mobility, so conductivity increases. Therefore the two materials show opposite trends: (A) and (B) incorrectly give the same trend, and (C) reverses the actual trends.

Step 3: Conclusion On heating, the conductivity of copper decreases and that of silicon increases. Hence, the correct option is (D).

Quick Tip to Solve: Distinguish a metal's nearly fixed carrier population from a semiconductor's thermally generated carriers when predicting temperature effects.

15. The formation of depletion region in a p-n junction diode is due to [1 mark]

- (A) movement of dopant atoms
- (B) diffusion of both electrons and holes
- (C) drift of electrons only
- (D) drift of holes only

Correct Answer: (B) diffusion of both electrons and holes

Solution:

Concept:

- Diffusion is carrier motion from a region of higher carrier concentration to a region of lower concentration.
- The depletion region contains exposed, immobile ionised donors and acceptors and is depleted of mobile majority carriers near the junction.

Step 1: Follow majority-carrier diffusion When a p-n junction is formed, electrons diffuse from the n-side to the p-side and holes diffuse from the p-side to the n-side. They recombine near the junction, removing mobile charge carriers from this region.

Step 2: Identify what remains near the junction Recombination leaves fixed positive donor ions on the n-side and fixed negative acceptor ions on the p-side. These charges form the depletion layer and set up its electric field. Dopant atoms do not migrate, ruling out (A). The resulting field drives drift currents that oppose further diffusion; drift of only electrons or only holes, as in (C) or (D), is not the mechanism that initially forms the layer.

Step 3: Conclusion The depletion region forms due to diffusion of both electrons and holes followed by recombination. Hence, the correct option is (B).

Quick Tip to Solve: Remember the junction sequence: diffusion, recombination, exposed fixed ions, then the electric field and opposing drift.

16. Assertion (A): Diamagnetic substances exhibit magnetism.

Reason (R): Diamagnetic materials do not have permanent magnetic dipole moment. [1 mark]

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

Correct Answer: (B) Both Assertion (A) and Reason (R) are true and Reason (R) is NOT the correct explanation of Assertion (A).

Solution:

Concept:

- Diamagnetic materials acquire a weak induced magnetic moment opposite to an applied magnetic field; their magnetic susceptibility is negative.
- A permanent magnetic dipole moment exists without an external field, whereas an induced moment appears because of the applied field.

Step 1: Evaluate the assertion The assertion is true. Diamagnetic substances do exhibit magnetism when placed in an external magnetic field: they develop an opposing induced magnetisation and are weakly repelled by regions of stronger field. They need not retain magnetism after the field is removed.

Step 2: Evaluate the reason The reason is also true. Diamagnetic atoms or molecules have no permanent net magnetic dipole moment because the constituent magnetic moments cancel in the absence of an external field.

Step 3: Test the explanatory link The absence of a permanent moment does not itself explain the appearance of magnetism. Diamagnetism arises because the external field changes electronic orbital motion and induces a moment opposite to the field. This induction mechanism is missing from the reason. Thus (A) incorrectly treats the reason as sufficient explanation, while (C) and (D) incorrectly call true statements false.

Step 4: Conclusion Both A and R are true, but R is not the correct explanation of A. Hence, the correct option is (B).

Quick Tip to Solve: Separate permanent moments from induced moments: having no permanent dipole does not prevent a material from responding magnetically to a field.

17. Assertion (A): Work done in moving a charge around a closed path, in an electric field is always zero.

Reason (R): Electrostatic force is a conservative force.

[1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
(B) Both Assertion (A) and Reason (R) are true and Reason (R) is NOT the correct explanation of Assertion (A).
(C) Assertion (A) is true and 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 Assertion (A).

Solution:

Concept:

- In electrostatics, the work done by the electric force is $W = q(V_i - V_f)$, where q is the charge and V_i, V_f are the initial and final potentials.
- A conservative force does work independent of the path; consequently its work over a closed path is zero.

Step 1: Judge the assertion In the electrostatic context indicated by the reason, a closed path returns the charge to its initial point. Thus $V_i = V_f$, giving $W = q(V_i - V_f) = 0$. Assertion (A) is true in this context. The statement is not a general claim about electric fields induced by changing magnetic flux.

Step 2: Judge the reason The electrostatic force is conservative: its work depends only on the end points, and $\oint \vec{E} \cdot d\vec{l} = 0$. Reason (R) is therefore true.

Step 3: Check the explanatory connection Conservativeness directly gives zero work when the initial and final points coincide. The reason therefore explains the assertion, ruling out (B). Options (C) and (D) incorrectly reject the true reason.

Step 4: Conclusion Both statements are true in the electrostatic setting, and R correctly explains A. Hence, the correct option is (A).

Quick Tip to Solve: For a closed path in an electrostatic field, set the initial and final potentials equal before evaluating work.

18. Assertion (A): In Young's double slit experiment all fringes are of equal width.

Reason (R): The fringe width depends upon wavelength of light (λ) used, distance of screen from plane of slits (D) and slits separation (d). [1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
(B) Both Assertion (A) and Reason (R) are true and Reason (R) is NOT the correct explanation of Assertion (A).
(C) Assertion (A) is true and 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 Assertion (A).

Solution:

Concept:

- In the usual small-angle treatment of Young's double-slit experiment, the fringe width is $\beta = \lambda D/d$, where λ is wavelength, D the screen distance and d the slit separation.
- Successive bright fringes occur at $y_n = n\lambda D/d$; successive dark fringes also have separation $\lambda D/d$.

Step 1: Judge the assertion The separation of adjacent bright fringes is $y_{n+1} - y_n = \lambda D/d$, independent of the order n . The same result follows for adjacent dark fringes. Thus all fringe widths are equal in the standard experimental approximation, and Assertion (A) is true.

Step 2: Judge the reason The formula $\beta = \lambda D/d$ shows that fringe width depends on the three quantities stated: the wavelength, screen distance and slit separation. Reason (R) is true.

Step 3: Check the explanation In a fixed arrangement using monochromatic light, λ , D and d are constant. Hence the reason, through the fringe-width relation, accounts for the constant width. Option (B) misses this connection, whereas (C) and (D) wrongly call the reason false.

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

Quick Tip to Solve: Check whether the expression for fringe width contains the fringe order; its absence gives equal spacing.

Section B (14 marks)

19. Briefly explain why and how a galvanometer is converted into an ammeter. [2 marks]

Solution:

Concept:

- A galvanometer is sensitive to small currents and has a finite resistance G . Let I_g be its full-scale current.
- An ammeter must carry the circuit current while producing very little voltage drop, so its effective resistance should be very small.

Step 1: Explain why conversion is needed A galvanometer alone cannot measure a large current: it reaches full-scale deflection at the small current I_g , and an excessive current may damage its coil. Its resistance would also appreciably change the current being measured. Conversion extends its range and reduces the effective resistance of the measuring instrument.

Step 2: Connect a low-resistance shunt Connect a small resistance S , called a shunt, in parallel with the galvanometer. For a desired maximum current I , the galvanometer carries only I_g while the shunt carries $I - I_g$. Equal potential differences across the parallel branches give

$$I_g G = (I - I_g) S, \quad S = \frac{I_g G}{I - I_g}.$$

The combination has resistance $GS/(G + S)$, which is small. Calibrate the scale to read the total current and connect this combination in series with the circuit.

Step 3: Conclusion A galvanometer is converted into an ammeter to measure larger currents safely with little circuit disturbance, by connecting a suitable low-resistance shunt in parallel.

Quick Tip to Solve: For ammeter conversion, put the shunt in parallel and equate branch voltages; the shunt current is $I - I_g$.

20(a). How are infrared waves produced? Why are these waves referred to as heat waves? Give any two uses of infrared waves. [2 marks]

Solution:

Concept:

- Infrared radiation is electromagnetic radiation with wavelengths longer than visible red light; hot bodies and molecular vibrations are common sources.
- When matter absorbs infrared radiation, molecular motion increases and the absorbed energy appears as internal thermal energy.

Step 1: State how infrared waves are produced Infrared waves are emitted by hot bodies and by vibrating molecules. Thermal motion excites molecular vibrational and rotational modes, and suitable transitions emit radiation in the infrared region. Thus heated objects are familiar sources of infrared radiation.

Step 2: Explain the name heat waves Water molecules and many other substances readily absorb infrared radiation. Absorption increases the energy of molecular motion and raises the temperature of the absorbing body. Their pronounced heating effect is why these waves are commonly called heat waves; the name describes their interaction with matter.

Step 3: Give two uses Infrared lamps provide local heating in physiotherapy for relief of muscular pain. Infrared emitters are also used in television remote controls, where modulated infrared pulses transmit commands to a detector in the television.

Step 4: Conclusion Infrared waves are produced by hot bodies and vibrating molecules, and are called heat waves because of their heating effect on absorption. Two uses are physiotherapy heating and television remote controls.

Quick Tip to Solve: Link the name heat waves to absorption and increased molecular motion, then give two distinct applications.

20(b). How are X-rays produced? Give any two uses of these.

[2 marks]

Solution:

Concept:

- X-rays are high-frequency electromagnetic waves produced when energetic electrons are rapidly decelerated in matter.
- Their ability to penetrate matter and their short wavelengths enable radiography and the study of crystal structure.

Step 1: Describe production in an X-ray tube Electrons released from a heated cathode are accelerated through a large potential difference towards a heavy-metal target, such as tungsten. On striking the target they suffer rapid deceleration, and part of their kinetic energy is emitted as X-rays. Most of the energy heats the target. Characteristic X-rays can also be emitted when inner-shell vacancies created in target atoms are filled by electrons from higher energy levels.

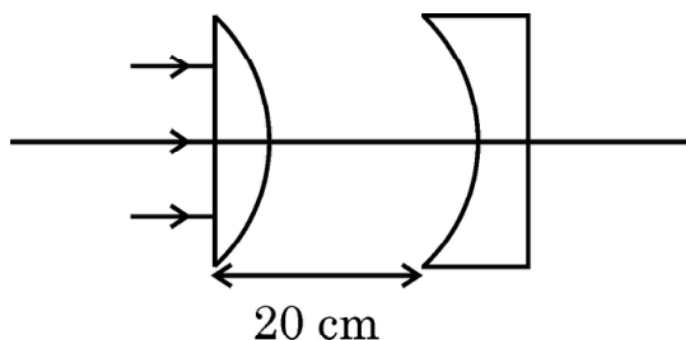
Step 2: State two uses and their basis First, X-ray radiography is used to detect bone fractures: bones absorb X-rays more strongly than surrounding soft tissue and therefore produce contrast in the image. Second, X-ray diffraction is used to determine crystal structure, since X-ray wavelengths are comparable with the spacing between atomic planes in crystals.

Step 3: Conclusion X-rays are produced by the rapid deceleration of high-speed electrons striking a heavy-metal target. Two uses are detecting bone fractures and determining crystal structure by diffraction.

Quick Tip to Solve: Describe both acceleration towards the target and sudden deceleration at it; connect each X-ray use to a physical property.

21. In the given figure the radius of curvature of curved face in the plano-convex and the plano-concave lens is 15 cm each. The refractive index of the material of the lenses is 1.5. Find the final position of the image formed.

[2 marks]



Solution:

Concept:

- For a thin lens in air, $1/f = (\mu - 1)(1/R_1 - 1/R_2)$, where μ is its refractive index and R_1, R_2 are signed radii of curvature.
- Use $1/v - 1/u = 1/f$, with distances positive along the incident light direction. A converging beam reaching a lens has a virtual object on its outgoing side, so $u > 0$.

Step 1: Find the two focal lengths Each plane surface has infinite radius. The plano-convex lens has positive power and the plano-concave lens has negative power. Therefore

$$\frac{1}{f_1} = \frac{1.5 - 1}{15 \text{ cm}}, \quad \frac{1}{f_2} = -\frac{1.5 - 1}{15 \text{ cm}},$$

giving $f_1 = +30 \text{ cm}$ and $f_2 = -30 \text{ cm}$.

Step 2: Locate the object for the second lens The figure shows parallel rays entering from the left. The first lens alone would focus them 30 cm to its right. The second lens is 20 cm to the right of the first, so the rays reaching it are converging towards a point 10 cm to its right. This point is a virtual object for the second lens: $u_2 = +10 \text{ cm}$.

Step 3: Apply the lens formula to the concave lens Substituting the signed distances gives

$$\frac{1}{v_2} = \frac{1}{f_2} + \frac{1}{u_2} = -\frac{1}{30} + \frac{1}{10} = \frac{1}{15} \text{ cm}^{-1}.$$

The positive image distance indicates that the emerging rays actually converge on the outgoing side of the second lens.

Step 4: Conclusion The final image is real and lies 15 cm to the right of the plano-concave lens, or 35 cm to the right of the first lens.

Quick Tip to Solve: Locate the first lens's would-be focus relative to the second lens; a focus beyond it gives a positive virtual-object distance.

22. What happens to the interference pattern when two coherent sources are

(a) infinitely close, and

(b) far apart from each other?

[2 marks]

Solution:

Concept:

- For two coherent sources separated by d , the fringe width on a screen at distance D is $\beta = \lambda D/d$, where λ is the wavelength; this is the usual small-angle interference result.
- With wavelength and screen distance fixed, the fringe width is inversely proportional to source separation. Fringes require the relative phase to vary across the screen.

Step 1: (a) Bring the sources infinitely close As $d \rightarrow 0$, the fringe width $\beta \rightarrow \infty$. The bright and dark bands become increasingly broad, so distinct alternating fringes cannot be observed on a finite screen. For coincident sources, the geometrical path difference is the same everywhere. In the usual in-phase arrangement the screen is uniformly bright; more generally its uniform intensity depends on their fixed relative phase.

Step 2: (b) Separate the sources widely Increasing d decreases β , so the fringes become narrower and lie closer together. If the separation is very large, the fringes become too closely spaced to resolve with the eye or a detector of finite resolution, and the pattern appears uniform. This is loss of visibility

due to small fringe spacing, even though the sources remain coherent.

Step 3: Conclusion (a) The fringe width tends to infinity and distinct fringes disappear. (b) The fringe width decreases; for widely separated sources the very fine fringes may be unresolved.

Quick Tip to Solve: Keep λ and D fixed and read both limits directly from $\beta \propto 1/d$.

23(a). What is meant by ionisation energy? Write its value for hydrogen atom.

[2 marks]

Solution:

Concept:

- Ionisation energy is the minimum energy required to remove an electron completely from an isolated gaseous atom in its ground state, leaving a positive ion. Complete removal means taking the electron to infinity with zero final kinetic energy.
- For hydrogen the allowed energies are $E_n = -13.6/n^2$ eV, measured relative to the energy of a free electron and proton at infinite separation.

Step 1: Identify the initial and final states The electron in a ground-state hydrogen atom has principal quantum number $n = 1$, so $E_1 = -13.6$ eV. For complete ionisation the final state is the continuum limit $n \rightarrow \infty$, for which $E_\infty = 0$. Merely raising the electron to another finite orbit is excitation, not ionisation.

Step 2: Calculate the energy that must be supplied The required input is the increase in energy:

$$E_{\text{ion}} = E_\infty - E_1 = 0 - (-13.6) = 13.6 \text{ eV.}$$

In joules, using $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$, this is $13.6 \times 1.602 \times 10^{-19} = 2.18 \times 10^{-18} \text{ J}$ per atom. The ionisation energy is positive because energy must be supplied to overcome the electron-proton attraction.

Step 3: Conclusion Ionisation energy is the minimum energy needed to remove an electron completely from an isolated ground-state gaseous atom. For hydrogen it is $13.6 \text{ eV} = 2.18 \times 10^{-18} \text{ J}$ per atom.

Quick Tip to Solve: Set the free-electron energy to zero and subtract the negative ground-state energy; ionisation energy is positive.

OR

23(b). Define the term, mass defect. How is it related to stability of the nucleus?

[2 marks]

Solution:

Concept:

- Mass defect is the difference between the sum of the masses of the free constituent nucleons and the actual mass of the bound nucleus.
- Binding energy is related to mass defect by Einstein's relation $B = \Delta mc^2$, where c is the speed of light. Binding energy per nucleon, B/A , measures the average binding of a nucleon.

Step 1: Express the mass defect For a nucleus of mass number A , atomic number Z and nuclear mass

M , there are Z protons and $A - Z$ neutrons. Hence

$$\Delta m = Zm_p + (A - Z)m_n - M,$$

where m_p and m_n are the masses of a free proton and neutron. A bound nucleus has less mass than its separated constituents because energy is released when it forms.

Step 2: Relate the defect to nuclear stability The released energy is the binding energy $B = \Delta mc^2$. The same energy must be supplied to separate the nucleus completely into free nucleons. To compare the binding of nuclei with different mass numbers, use

$$\frac{B}{A} = \frac{\Delta mc^2}{A}.$$

A greater binding energy per nucleon generally indicates a more tightly bound, more stable nucleus. Total mass defect alone is insufficient for such a comparison, because a larger nucleus contains more nucleons. For nuclei with the same A , a larger mass defect means a larger binding energy per nucleon.

Step 3: Conclusion $\Delta m = Zm_p + (A - Z)m_n - M$, and $B = \Delta mc^2$. Nuclear binding and relative stability generally increase with binding energy per nucleon, or equivalently with mass defect per nucleon.

Quick Tip to Solve: When comparing nuclei of different sizes, divide Δmc^2 by A ; do not compare total mass defects alone.

24. Draw energy band diagram for an n-type and p-type semiconductor at $T > 0$ K.

[2 marks]

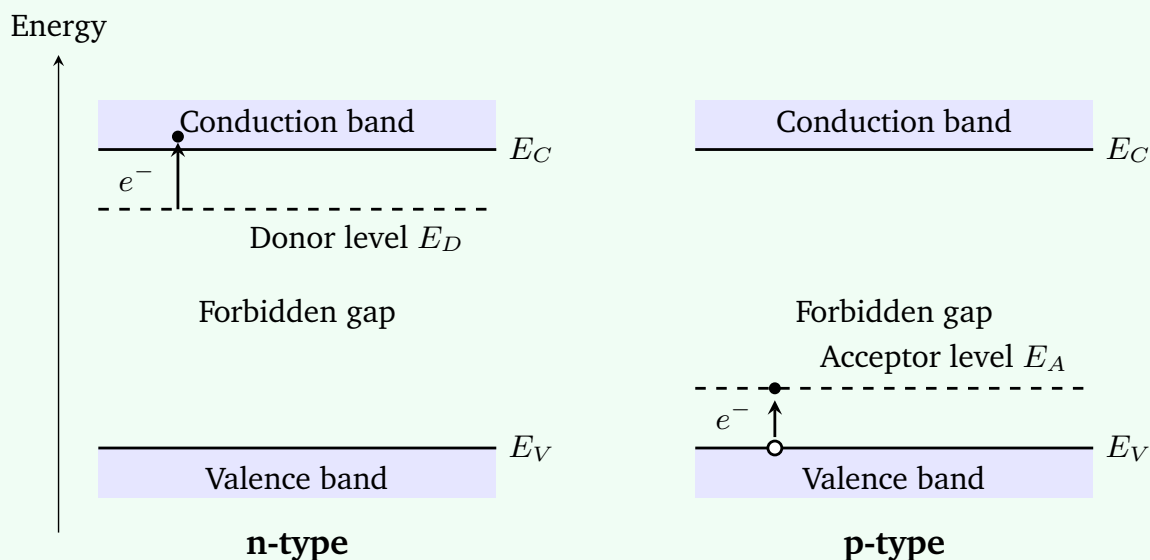
Solution:

Concept:

- The valence-band edge E_V and conduction-band edge E_C enclose the forbidden energy gap $E_g = E_C - E_V$. Doping introduces impurity levels inside this gap.
- An n-type semiconductor has a donor level E_D just below E_C ; a p-type semiconductor has an acceptor level E_A just above E_V . At finite temperature thermal energy can activate carriers.

Step 1: n-type semiconductor: donor electrons enter the conduction band Pentavalent donor impurities introduce a level close to the conduction band. The small energy $E_C - E_D$ allows donor electrons to be thermally excited into the conduction band at $T > 0$ K, leaving ionised positive donors. Electrons are the majority carriers. The left-hand diagram shows a representative donor-to-conduction-band transition; it does not imply that every donor is ionised at every nonzero temperature.

Step 2: p-type semiconductor: acceptors create holes in the valence band Trivalent acceptor impurities introduce an empty level just above the valence band. A valence electron can gain the small energy $E_A - E_V$ and occupy an acceptor level, leaving a mobile hole in the valence band and a negatively ionised acceptor. Holes are the majority carriers. The right-hand diagram shows this upward electron transition and the hole left behind. The sketches show relative level positions schematically, not to energy scale.



Energy bands at $T > 0\text{ K}$: filled dots are electrons and the open circle is a hole. Impurity spacings are enlarged for clarity.

Step 3: Conclusion For n-type material, E_D lies just below E_C ; for p-type material, E_A lies just above E_V . Thermal excitation supplies conduction electrons and valence-band holes respectively, as shown in the energy-band diagrams.

Quick Tip to Solve: Place the donor level near the conduction band and the acceptor level near the valence band; electron excitation arrows always point upward in energy.

25. Answer the following giving reasons:

(i) A p-n junction diode is damaged by a strong current.

(ii) Impurities are added in intrinsic semiconductors.

[2 marks]

Solution:

Concept:

- A diode dissipates electrical power as heat, with $P = VI$, where V is its voltage and I is the current through it.
- Doping adds a small controlled amount of suitable impurity to increase the density of mobile charge carriers and hence the conductivity of a semiconductor.

Step 1: Explain damage by a strong current (i) A large current produces excessive heating at the p-n junction. When heat is generated faster than it can be removed, the junction temperature rises beyond the safe limit. The resulting thermal damage destroys the junction's normal rectifying action. Thus a diode needs a current limit; a strong current can permanently damage it.

Step 2: Explain the purpose of doping (ii) An intrinsic semiconductor has a small concentration of free charge carriers and hence low conductivity at ordinary temperatures. A suitable impurity supplies additional carriers: a pentavalent donor produces an n-type semiconductor with electrons as majority carriers, while a trivalent acceptor produces a p-type semiconductor with holes as majority carriers. Controlled doping therefore increases conductivity and allows it to be adjusted for devices.

Step 3: Conclusion (i) Excessive junction heating due to a strong current damages the diode. (ii)

Suitable impurities are added to increase and control the semiconductor's charge-carrier concentration and electrical conductivity.

Quick Tip to Solve: Link diode damage to excessive heat, and link doping to extra mobile carriers; dopants need only be present in a small controlled concentration.

Section C (15 marks)

26(a). Two charged conducting spheres of radii a and b are connected to each other by a wire. Find the ratio of the electric fields at their surfaces. [3 marks]

Solution:

Concept:

- Conductors connected by a conducting wire reach the same electrostatic potential at equilibrium; charge flows until their potential difference vanishes.
- For a conducting sphere of radius r and charge Q , $V = kQ/r$ and the field just outside its surface has magnitude $E = k|Q|/r^2$, where $k = 1/(4\pi\epsilon_0)$.

Step 1: Equate the final potentials Let the final charges on the spheres of radii a and b be Q_a and Q_b . Use the usual spherical-conductor approximation: the spheres are sufficiently far apart that their mutual distortion of the surface charge can be neglected, and the thin connecting wire holds negligible charge. At electrostatic equilibrium, the wire enforces

$$V_a = V_b, \quad \frac{kQ_a}{a} = \frac{kQ_b}{b}.$$

Therefore the final charges obey $Q_a/Q_b = a/b$. Equal potentials do not imply equal charges when the radii differ.

Step 2: Compare the surface electric fields The requested fields are those immediately outside the conducting surfaces; the field inside either conductor is zero. Applying the surface-field formula to each sphere gives

$$E_a = \frac{k|Q_a|}{a^2}, \quad E_b = \frac{k|Q_b|}{b^2}.$$

On dividing and using the charge ratio,

$$\frac{E_a}{E_b} = \frac{|Q_a|}{|Q_b|} \frac{b^2}{a^2} = \frac{a}{b} \frac{b^2}{a^2} = \frac{b}{a}.$$

Thus, for a nonzero common potential, the smaller sphere has the stronger surface field. This also follows directly from $E = |V|/r$.

Step 3: Conclusion The surface-field ratio, in the order sphere of radius a to sphere of radius b , is $E_a : E_b = b : a$.

Quick Tip to Solve: A connecting wire equalises potential. Then use $E = |V|/r$: the surface field is inversely proportional to the sphere's radius.

26(b). A parallel plate capacitor (A) of capacitance C is charged by a battery to voltage V . The battery is disconnected and an uncharged capacitor (B) of capacitance $2C$ is connected across A. Find the ratio of

(i) final charges on A and B.

(ii) total electrostatic energy stored in A and B finally and that stored in A initially.

[3 marks]

Solution:

Concept:

- A capacitor stores charge $Q = CV$ and electrostatic energy $U = \frac{1}{2}CV^2$, where C is capacitance and V is its potential difference.
- After the battery is disconnected, connecting the capacitors in parallel conserves the charge on each connected pair of plates and makes their final potential differences equal.

Step 1: Determine the common final voltage Initially capacitor A has charge $Q_{A,i} = CV$, while B is uncharged. With the battery removed, there is no external supply of charge. Let V_f be the common voltage after charge redistribution. The equivalent capacitance of the parallel pair is $C + 2C = 3C$. Conservation of charge gives

$$CV = (C + 2C)V_f = 3CV_f, \quad V_f = \frac{V}{3}.$$

Here charge means the magnitude on a plate; the other plate of each capacitor has equal and opposite charge.

Step 2: Calculate the final charges (i) Each capacitor has the same final voltage, but their capacitances differ. Thus

$$Q_{A,f} = CV_f = \frac{CV}{3}, \quad Q_{B,f} = 2CV_f = \frac{2CV}{3}.$$

Their sum is CV , as required. Therefore the charge ratio follows the capacitance ratio, not its inverse.

Step 3: Compare the final and initial stored energies (ii) Initially only A stores energy:

$$U_i = \frac{1}{2}CV^2.$$

The final energy is the sum of the energies of both capacitors:

$$\begin{aligned} U_f &= \frac{1}{2}C \left(\frac{V}{3}\right)^2 + \frac{1}{2}(2C) \left(\frac{V}{3}\right)^2 \\ &= \frac{CV^2}{18} + \frac{CV^2}{9} = \frac{CV^2}{6}. \end{aligned}$$

The decrease in electrostatic energy is released during the transient redistribution, mainly as heat in the connecting circuit. Charge conservation therefore does not imply conservation of stored electrostatic energy alone.

Step 4: Conclusion (i) $Q_{A,f} : Q_{B,f} = 1 : 2$. (ii) The final total electrostatic energy to the initial energy ratio is $U_f : U_i = 1 : 3$.

Quick Tip to Solve: Disconnecting the battery fixes the available charge. First find the common voltage from total charge, then add both final capacitor energies.

27. Define current density and relaxation time. Derive an expression for resistivity of a conductor in terms of number density of charge carriers in the conductor and relaxation time. [3 marks]

Solution:

Concept:

- Current density $\vec{J}$ is current per unit area normal to the flow, directed along conventional current; for uniform flow, $J = I/A$. Its SI unit is A m^{-2} .
- Relaxation time τ is the average time between successive collisions of a conduction electron with the lattice ions. Its SI unit is the second.
- The microscopic Ohm law is $\vec{J} = \sigma \vec{E} = \vec{E}/\rho$, where σ is conductivity and ρ is resistivity.

Step 1: Relate drift velocity to the applied field Consider a metallic conductor with n free electrons per unit volume, each of mass m and charge $-e$, where e denotes the positive elementary charge. In an electric field $\vec{E}$, the electron experiences force $-e\vec{E}$, giving acceleration

$$\vec{a} = -\frac{e}{m}\vec{E}.$$

Random thermal velocities have zero average. Between collisions the field adds a systematic velocity, so the average drift velocity in the relaxation-time model is

$$\vec{v}_d = \vec{a}\tau = -\frac{e\tau}{m}\vec{E}.$$

The negative sign shows that electrons drift opposite to the electric field.

Step 2: Express current density using carrier motion In time Δt , electrons within a length $|v_d|\Delta t$ cross a normal cross-sectional area A . Their number is $nA|v_d|\Delta t$, so the magnitude of charge crossing per unit time is $I = neA|v_d|$. In vector form, conventional current density is

$$\vec{J} = -ne\vec{v}_d = \frac{ne^2\tau}{m}\vec{E}.$$

Although the electron drift is opposite to the field, conventional current is along the field because the carriers are negatively charged.

Step 3: Identify the resistivity Compare the derived expression with $\vec{J} = \vec{E}/\rho$. Equating the coefficients of $\vec{E}$ gives

$$\sigma = \frac{ne^2\tau}{m}, \quad \rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}.$$

With the electron mass and charge fixed, more carriers or a longer relaxation time increases conductivity and therefore lowers resistivity.

Step 4: Conclusion Current density is current per unit normal area, and relaxation time is the mean time between successive collisions. The conductor's resistivity is $\boxed{\rho = m/(ne^2\tau)}$, measured in $\Omega \text{ m}$.

Quick Tip to Solve: Derive $J = ne|v_d|$ first and substitute $|v_d| = eE\tau/m$; the coefficient of E is conductivity, whose reciprocal is resistivity.

28. A series CR circuit with $R = 200\ \Omega$ and $C = (50/\pi)\ \mu\text{F}$ is connected across an ac source of peak voltage $\varepsilon_0 = 100\ \text{V}$ and frequency $\nu = 50\ \text{Hz}$. Calculate

(a) impedance of the circuit (Z),

(b) phase angle (φ), and

(c) voltage across the resistor.

[3 marks]

Solution:

Concept:

- Capacitive reactance is $X_C = 1/(\omega C)$, where $\omega = 2\pi\nu$ is the angular frequency and C is capacitance in farads.
- For a series CR circuit, $Z = \sqrt{R^2 + X_C^2}$. The current leads the applied voltage, and the resistor voltage is in phase with the current.
- Consistent peak values obey $I_0 = \varepsilon_0/Z$ and $V_{R0} = I_0 R$; rms values are the corresponding peak values divided by $\sqrt{2}$.

Step 1: (a) Convert the capacitance and calculate the impedance Here $C = (50/\pi) \times 10^{-6}\ \text{F}$ and $\omega = 2\pi(50) = 100\pi\ \text{rad s}^{-1}$. Thus

$$X_C = \frac{1}{(100\pi)(50/\pi) \times 10^{-6}} = 200\ \Omega,$$
$$Z = \sqrt{200^2 + 200^2} = 200\sqrt{2}\ \Omega.$$

The resistance and capacitive reactance enter in quadrature because their voltage drops differ in phase by a quarter cycle.

Step 2: (b) Determine the phase difference and identify the lead With current as the phase reference, the source-voltage phase satisfies

$$\tan \varphi = \frac{-X_C}{R} = -1, \quad \varphi = -45^\circ.$$

Equivalently, the phase-difference magnitude is 45° , with current leading the applied voltage by 45° . The negative sign above refers specifically to voltage relative to current.

Step 3: (c) Calculate the voltage across the resistor The stated source voltage is a peak value, so first calculate the peak current and resistor voltage:

$$I_0 = \frac{100}{200\sqrt{2}} = \frac{1}{2\sqrt{2}}\ \text{A},$$
$$V_{R0} = I_0 R = \frac{100}{\sqrt{2}} = 50\sqrt{2}\ \text{V}.$$

If voltage is quoted as an rms reading, $V_{R,\text{rms}} = V_{R0}/\sqrt{2} = 50\ \text{V}$. For a source $\varepsilon(t) = 100 \sin(100\pi t)\ \text{V}$, the resistor voltage is $v_R(t) = 50\sqrt{2} \sin(100\pi t + \pi/4)\ \text{V}$.

Step 4: Conclusion $Z = 200\sqrt{2}\ \Omega \approx 282.8\ \Omega$; current leads the source voltage by 45° . The resistor voltage has peak value $50\sqrt{2}\ \text{V} \approx 70.7\ \text{V}$ and rms value $50\ \text{V}$.

Quick Tip to Solve: When $R = X_C$, use $Z = \sqrt{2}R$ and a 45° current lead; retain peak values until the final rms conversion.

29. Define critical angle for a given pair of media and total internal reflection. Obtain the relation between the critical angle and refractive index of the medium. [3 marks]

Solution:

Concept:

- Snell's law at an interface is $n_1 \sin i = n_2 \sin r$, where n_1, n_2 are the refractive indices and i, r are measured from the normal.
- The critical-angle condition applies when light travels from an optically denser medium into an optically rarer medium, so $n_1 > n_2$.

Step 1: Define the critical angle for the two media The critical angle i_c is the angle of incidence in the denser medium for which the angle of refraction in the rarer medium becomes 90° . At this limiting condition the refracted ray travels along the interface. The angle depends on the pair of media and on the wavelength of light; it is not a property of the denser medium alone unless the outside medium is specified.

Step 2: Define total internal reflection and its conditions Total internal reflection is the complete reflection of incident light back into the denser medium at its boundary with a rarer medium, with no propagating refracted ray in the rarer medium. It occurs only when light is incident from the denser side and the incidence angle exceeds the critical angle: $i > i_c$. At $i = i_c$, the refracted ray is grazing the surface; total internal reflection requires an angle greater than this limiting value.

Step 3: Apply Snell's law at the limiting angle Substituting $i = i_c$ and $r = 90^\circ$ in Snell's law gives

$$n_1 \sin i_c = n_2 \sin 90^\circ = n_2, \quad \sin i_c = \frac{n_2}{n_1}.$$

If $\mu = n_1/n_2$ denotes the refractive index of the denser medium relative to the rarer medium, then $\mu = 1/\sin i_c$. For the rarer medium air, $n_2 \approx 1$, so the same relation gives the denser medium's refractive index relative to air.

Step 4: Conclusion The critical angle produces a 90° refracted ray; incidence beyond it from the denser side produces total internal reflection. The required relation is $\mu = 1/\sin i_c$, with $\mu = n_1/n_2$.

Quick Tip to Solve: Set the refraction angle to 90° , not the incidence angle, when using Snell's law to obtain the critical-angle formula.

30(a). (i) Distinguish between nuclear fission and fusion giving an example of each.

(ii) Explain the release of energy in nuclear fission and fusion on the basis of binding energy per nucleon curve. [3 marks]

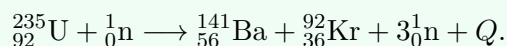
Solution:

Concept:

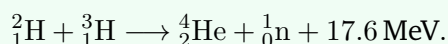
- Nuclear binding energy is the energy needed to separate a nucleus into free nucleons. Binding energy per nucleon B/A measures how tightly the nucleons are bound on average.
- Energy is released when the products have greater total binding energy than the reactants:
 $Q = B_{\text{products}} - B_{\text{reactants}} = \Delta mc^2 > 0$.

Step 1: (i) Distinguish fission and fusion with examples In nuclear fission, a heavy nucleus splits into two lighter nuclei, generally with emission of neutrons and release of energy. A neutron-induced

example is



In nuclear fusion, two light nuclei combine to form a heavier nucleus, releasing energy for suitable light nuclei. For example,



Both examples conserve charge and nucleon number. Fission starts with a heavy nucleus; fusion starts with light nuclei and requires them to approach closely despite their electrostatic repulsion.

Step 2: (ii) Explain fission using the binding-energy curve The binding energy per nucleon rises steeply among light nuclei, reaches a broad maximum near iron and nickel in the mass-number region $A \approx 56\text{--}62$, and then decreases slowly for very heavy nuclei. A heavy uranium nucleus has about 7.6 MeV binding energy per nucleon, whereas typical intermediate-mass fission fragments have about 8.5 MeV per nucleon. The fragments are therefore more tightly bound. The increase in total binding energy appears mainly as fragment kinetic energy and other emitted energy.

Step 3: (ii) Explain fusion using the same curve On the rising portion of the curve, the heavier nucleus formed by fusion of suitable light nuclei has a greater binding energy per nucleon than the initial light nuclei. Accounting for every product, the total binding energy increases while the total rest mass decreases. This mass decrease supplies the released energy through $Q = \Delta mc^2$. Thus both processes move their bound products toward the more tightly bound region of the curve.

Step 4: Conclusion Fission splits a heavy nucleus; fusion combines light nuclei. Both release energy when the products gain total binding energy, corresponding to a decrease in total rest mass.

Quick Tip to Solve: Locate the starting nuclei on the B/A curve: heavy nuclei release energy by splitting, while suitable light nuclei release it by combining toward the peak.

OR

30(b). (i) How is the size of a nucleus found experimentally? Write the relation between the radius and mass number of a nucleus.

(ii) Prove that the density of a nucleus is independent of its mass number.

[3 marks]

Solution:

Concept:

- Nuclear radii are measured through scattering experiments using energetic particles. The empirical radius relation is $R = R_0 A^{1/3}$, where A is the mass number and $R_0 \approx 1.2 \times 10^{-15} \text{ m}$.
- Approximating the nucleus as a sphere gives volume $V = 4\pi R^3/3$. Its mass is approximately $M = Am_N$, where m_N is the mean nucleon mass.

Step 1: (i) Describe the experimental determination of nuclear size Nuclear size is found by scattering energetic particles, such as alpha particles or electrons, from nuclei and studying their angular scattering pattern. High-energy electron scattering probes the finite distribution of nuclear charge, and the diffraction pattern allows the radius to be inferred. In an alpha-particle experiment, a head-on approach converts kinetic energy into electrostatic potential energy at the distance of closest approach:

$$K = \frac{1}{4\pi\epsilon_0} \frac{2Ze^2}{r_{\min}}.$$

Here Z is the target atomic number and target recoil is neglected. Pure Rutherford scattering gives an upper bound on nuclear size; sufficiently energetic scattering that resolves the finite nucleus gives its size more directly. Experiments establish

$$R = R_0 A^{1/3}, \quad R_0 \approx 1.2 \times 10^{-15} \text{ m}.$$

Step 2: (ii) Express the nuclear mass and volume in terms of mass number Since the proton and neutron have nearly equal masses, the mass of a nucleus containing A nucleons is approximately Am_N . Ignoring the small binding-energy correction and substituting the radius relation, its volume is

$$V = \frac{4\pi}{3} (R_0 A^{1/3})^3 = \frac{4\pi}{3} R_0^3 A.$$

Thus both nuclear mass and nuclear volume are proportional to the mass number.

Step 3: (ii) Divide mass by volume and cancel the mass number The mean nuclear density therefore becomes

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

There is no factor of A left. Using $m_N \approx 1.67 \times 10^{-27} \text{ kg}$ gives $\rho \approx 2.3 \times 10^{17} \text{ kg m}^{-3}$. The near constancy describes average nuclear density within the empirical spherical-nucleus approximation.

Step 4: Conclusion Particle-scattering experiments give $R = R_0 A^{1/3}$. Consequently $\rho = 3m_N/(4\pi R_0^3)$, which is approximately independent of the nuclear mass number.

Quick Tip to Solve: Cube $A^{1/3}$ before forming the density: nuclear volume is proportional to A , so the same factor in the mass cancels.

Section D (15 marks)

31(a). (i) Use Gauss' law to obtain an expression for the electric field due to an infinitely long thin straight wire with uniform linear charge density λ .

(ii) An infinitely long positively charged straight wire has a linear charge density λ . An electron is revolving in a circle with a constant speed v such that the wire passes through the centre, and is perpendicular to the plane, of the circle. Find the kinetic energy of the electron in terms of magnitudes of its charge and linear charge density λ on the wire.

(iii) Draw a graph of kinetic energy as a function of linear charge density λ .

[5 marks]

Solution:

Concept:

- Gauss' law states that $\oint \vec{E} \cdot d\vec{S} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the enclosed charge and ϵ_0 is the permittivity of free space.
- Cylindrical symmetry makes the field of an infinite uniformly charged wire radial, with its magnitude depending only on the perpendicular distance r from the wire.
- For uniform circular motion, the inward force is mv^2/r . An electron of mass m and charge $-e$, where $e > 0$, has kinetic energy $K = mv^2/2$.

Step 1: (i) Choose a cylindrical Gaussian surface Take a closed cylinder of radius r and length L , coaxial with the wire. Its enclosed charge is $Q_{\text{enc}} = \lambda L$. For a positive wire, the electric field points

radially outward and is constant in magnitude over the curved surface. The outward area vector there is parallel to the field. On each flat end cap the area vector is along the wire, perpendicular to the field, so the flux through both end caps is zero.

Step 2: (i) Evaluate the flux and apply Gauss' law Only the curved area $2\pi rL$ contributes to the total outward flux. Therefore,

$$\oint \vec{E} \cdot d\vec{S} = E(2\pi rL) + 0 + 0,$$

$$E(2\pi rL) = \frac{\lambda L}{\epsilon_0},$$

$$\vec{E}(r) = \frac{\lambda}{2\pi\epsilon_0 r} \hat{r}.$$

Here $\hat{r}$ points radially away from the wire. Thus the field is outward for $\lambda > 0$, inward for $\lambda < 0$, and its magnitude is $|\lambda|/(2\pi\epsilon_0 r)$. The arbitrary length L cancels, as expected for an infinite uniform wire.

Step 3: (ii) Equate electric attraction to the centripetal force Let the electron's circular orbit have radius r . Since the wire is positively charged, $\lambda > 0$, and the force on the negative electron is toward the wire. It is perpendicular to the instantaneous velocity and supplies the centripetal force without changing the speed:

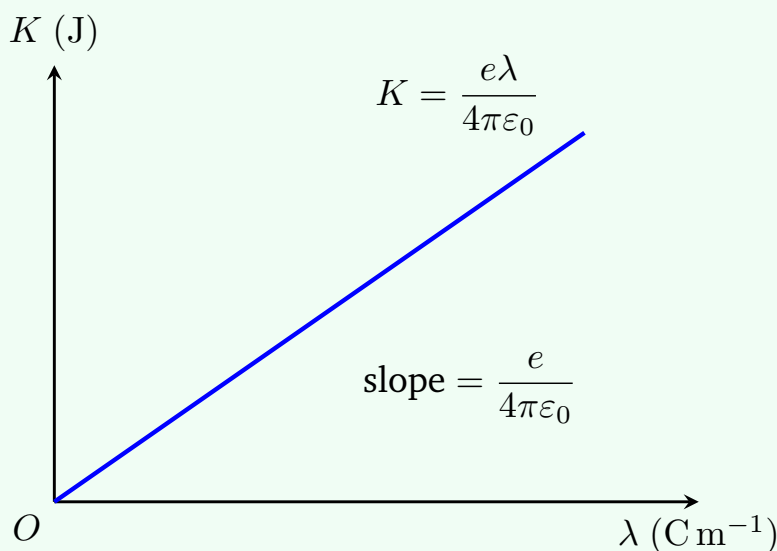
$$\frac{mv^2}{r} = eE = \frac{e\lambda}{2\pi\epsilon_0 r},$$

$$mv^2 = \frac{e\lambda}{2\pi\epsilon_0},$$

$$K = \frac{1}{2}mv^2 = \frac{e\lambda}{4\pi\epsilon_0}.$$

The radius cancels because both the required centripetal force and the field force vary as $1/r$. For a given linear charge density, the kinetic energy is therefore independent of the orbit radius and the electron mass.

Step 4: (iii) Plot kinetic energy against linear charge density With e and ϵ_0 fixed, the relation has the form $K = s\lambda$, where the positive constant slope is $s = e/(4\pi\epsilon_0)$. Put λ on the horizontal axis and K on the vertical axis. The graph is a straight line through the origin in the first quadrant; doubling λ doubles K . The origin represents the zero-density limiting value, not a nonzero-speed bound circular orbit.



Kinetic energy increases linearly with positive linear charge density.

Step 5: Conclusion (i) $\vec{E} = \frac{\lambda}{2\pi\epsilon_0 r} \hat{r}$. (ii) $K = \frac{e\lambda}{4\pi\epsilon_0}$, with e the magnitude of the electron's charge and $\lambda > 0$. (iii) The K -versus- λ graph is a straight line through the origin with slope $e/(4\pi\epsilon_0)$.

Quick Tip to Solve: For this orbit, multiply $eE = mv^2/r$ by $r/2$: since $Er = \lambda/(2\pi\epsilon_0)$, the kinetic energy follows immediately and the radius cancels.

OR

31(b). (i) Consider two identical point charges located at points $(0, 0)$ and $(a, 0)$.

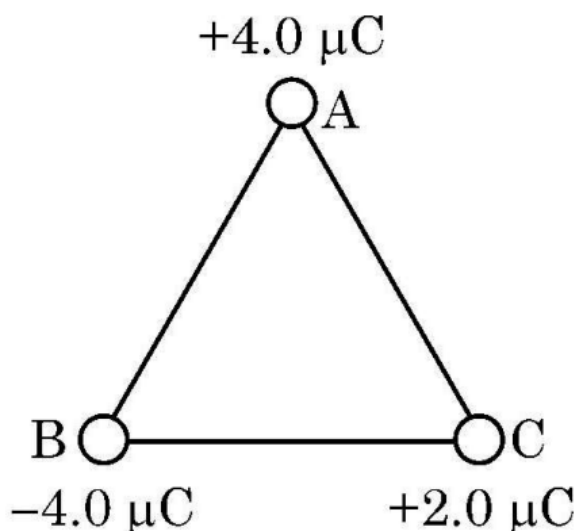
(1) Is there a point on the line joining them at which the electric field is zero?

(2) Is there a point on the line joining them at which the electric potential is zero?

Justify your answers for each case.

(ii) State the significance of negative value of electrostatic potential energy of a system of charges.

Three charges are placed at the corners of an equilateral triangle ABC of side 2.0 m as shown in figure. Calculate the electric potential energy of the system of three charges. [5 marks]



Solution:

Concept:

- Electric field obeys vector superposition: $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$. A point charge q produces a field of magnitude $k|q|/r^2$, where $k = 1/(4\pi\epsilon_0)$.
- With potential zero at infinity, potentials add algebraically: $V = k \sum_i q_i/r_i$. Equal like charges have potentials of the same sign.
- The electrostatic potential energy relative to infinitely separated charges is $U = k \sum_{i < j} q_i q_j / r_{ij}$; each distinct pair is counted once.

Step 1: (i)(1) Compare the two electric fields Let the identical nonzero charges be q , separated by $a > 0$. At a point $(x, 0)$ between them, the two fields point in opposite directions. Their magnitudes can therefore cancel when

$$\frac{k|q|}{x^2} = \frac{k|q|}{(a-x)^2}, \quad 0 < x < a.$$

Since both distances are positive, $x = a - x$, giving the midpoint $(a/2, 0)$. The fields there have equal

magnitudes $4k|q|/a^2$ and opposite directions, so their vector sum vanishes. Outside the segment both fields point in the same direction and cannot cancel. The field at either charge itself is undefined.

Step 2: (i)(2) Add the scalar potentials At any finite point on the line other than the charge locations, the distances r_1 and r_2 are positive, and

$$V = kq \left(\frac{1}{r_1} + \frac{1}{r_2} \right).$$

Both terms have the sign of q , so there is no cancellation and no finite point with zero potential. In particular the midpoint has $V = 4kq/a$, despite its zero electric field. Potential approaches zero only infinitely far away under the chosen reference convention. Reversing both charges reverses the potential's sign but does not create a finite zero.

Step 3: (ii) Interpret a negative potential energy A negative value of U means that the system lies below the energy of the same charges infinitely separated, whose energy is defined as zero. Assembly from infinity releases energy. Conversely, an external agent must supply positive work $-U$ to separate all charges to infinity quasistatically. This signifies an energetically bound arrangement relative to complete separation; it does not by itself assert that the given geometry is a stable mechanical equilibrium.

Step 4: (ii) Sum the three pair energies From the printed triangle, $q_A = +4.0 \mu\text{C}$, $q_B = -4.0 \mu\text{C}$ and $q_C = +2.0 \mu\text{C}$. Each pair is separated by $r = 2.0 \text{ m}$. Hence

$$U = \frac{k}{r}(q_A q_B + q_B q_C + q_C q_A).$$

Converting each microcoulomb to 10^{-6} C , the three contributions are

$$\begin{aligned} U_{AB} &= \frac{9 \times 10^9}{2.0} (-16 \times 10^{-12}) = -0.072 \text{ J}, \\ U_{BC} &= \frac{9 \times 10^9}{2.0} (-8 \times 10^{-12}) = -0.036 \text{ J}, \\ U_{CA} &= \frac{9 \times 10^9}{2.0} (8 \times 10^{-12}) = +0.036 \text{ J}. \end{aligned}$$

The two contributions involving C cancel because A and B have equal and opposite charges at equal distances from C .

Step 5: Conclusion (i) The electric field is zero at $(a/2, 0)$; the potential is zero at no finite point on the joining line. (ii) Negative energy means positive work is needed for complete separation to infinity. The triangle has $U = -7.2 \times 10^{-2} \text{ J}$.

Quick Tip to Solve: Distinguish vector cancellation of fields from scalar addition of potentials. For the triangle, list AB, BC and CA once each; the equal-and-opposite contributions involving C cancel immediately.

32(a). (i) Define coefficient of self-induction. Obtain an expression for self-inductance of a long solenoid of length l , area of cross-section A having N turns.

(ii) Calculate the self-inductance of a coil using the following data obtained when an AC source of frequency $\left(\frac{200}{\pi}\right)$ Hz and a DC source is applied across the coil.

AC Source		
S.No.	V (Volts)	I (A)
1	3.0	0.5
2	6.0	1.0
3	9.0	1.5

DC Source		
S.No.	V (Volts)	I (A)
1	4.0	1.0
2	6.0	1.5
3	8.0	2.0

[5 marks]

Solution:

Concept:

- The self-inductance L of a coil is its magnetic flux linkage per unit current: $N\Phi = LI$. Faraday's law gives $\varepsilon = -L dI/dt$ for constant L .
- A long air-core solenoid has approximately uniform internal field $B = \mu_0 nI$, where $n = N/l$ is its number of turns per unit length; end effects are neglected.
- A coil has resistance R and inductive reactance $X_L = \omega L$. Its AC impedance is $Z = \sqrt{R^2 + X_L^2}$, while its steady DC current is governed by resistance alone.

Step 1: (i) Define the coefficient of self-induction The coefficient of self-induction, or self-inductance, is the total magnetic flux linkage with a coil per unit current through it:

$$L = \frac{N\Phi}{I}.$$

Equivalently, its magnitude equals the induced emf when the current changes at unit rate. Thus a coil has inductance 1 H if a current change of 1 A s^{-1} induces an emf of magnitude 1 V. The negative sign in $\varepsilon = -L dI/dt$ expresses opposition to the change in current, rather than a negative inductance.

Step 2: (i) Derive the solenoid expression Consider a long solenoid of length l , cross-sectional area A , and N closely wound turns carrying current I . For an air or vacuum core, Ampere's law gives

$$B = \mu_0 \frac{N}{l} I.$$

The field is nearly uniform and parallel to the area vector of each turn. Neglecting fringing, the flux through one turn and the total flux linkage are

$$\Phi = BA = \frac{\mu_0 NIA}{l},$$

$$N\Phi = \frac{\mu_0 N^2 A}{l} I.$$

Comparing with $N\Phi = LI$ gives $L = \mu_0 N^2 A/l$. If the solenoid is uniformly filled with a linear magnetic material of relative permeability μ_r , replace μ_0 by $\mu_0 \mu_r$, obtaining $L = \mu_0 \mu_r N^2 A/l$.

Step 3: (ii) Extract resistance and impedance from the data After a DC current becomes steady, $dI/dt = 0$; there is no self-induced emf and the voltage drop is resistive. All three DC readings yield the same resistance:

$$R = \frac{4.0}{1.0} = \frac{6.0}{1.5} = \frac{8.0}{2.0} = 4.0 \Omega.$$

For AC, the voltage-to-current ratio gives impedance, using consistent rms readings. Every AC pair yields

$$Z = \frac{3.0}{0.5} = \frac{6.0}{1.0} = \frac{9.0}{1.5} = 6.0 \, \Omega.$$

Resistance and inductive reactance cannot be subtracted directly from impedance, because the resistive and inductive voltage components are in quadrature.

Step 4: (ii) Determine the reactance and inductance Using the series resistance-inductance model of the coil,

$$X_L = \sqrt{Z^2 - R^2} = \sqrt{6.0^2 - 4.0^2} = \sqrt{20} = 2\sqrt{5} \, \Omega.$$

The stated frequency is $f = (200/\pi) \, \text{Hz}$, so

$$\omega = 2\pi f = 400 \, \text{rad s}^{-1}.$$

Substituting into $X_L = \omega L$,

$$L = \frac{2\sqrt{5}}{400} = \frac{\sqrt{5}}{200} \, \text{H} \simeq 1.12 \times 10^{-2} \, \text{H}.$$

Step 5: Conclusion The coefficient of self-induction is flux linkage per unit current, measured in henry. For a long air-core solenoid, $L = \mu_0 N^2 A / l$. The given coil has $L \simeq 0.0112 \, \text{H} = 11.2 \, \text{mH}$.

Quick Tip to Solve: Use the DC data for R and the AC data for Z ; then apply $L = \sqrt{Z^2 - R^2} / (2\pi f)$. The printed frequency makes $2\pi f = 400$, so the factors of π cancel before calculation.

OR

32(b). (i) With the help of a labelled diagram, describe the principle and working of an ac generator. Hence, obtain an expression for the instantaneous value of the emf generated.

(ii) The coil of an ac generator consists of 100 turns of wire, each of area $0.5 \, \text{m}^2$. The resistance of the wire is $100 \, \Omega$. The coil is rotating in a magnetic field of $0.8 \, \text{T}$ perpendicular to its axis of rotation, at a constant angular speed of 60 radian per second. Calculate the maximum emf generated and power dissipated in the coil. [5 marks]

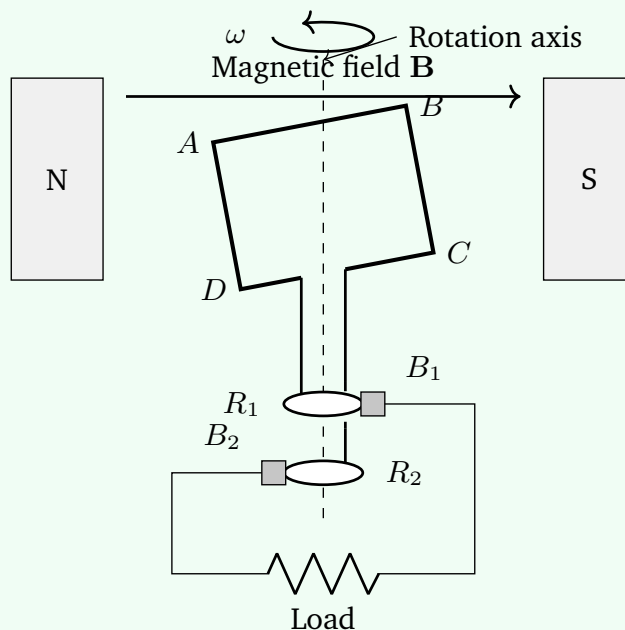
Solution:

Concept:

- Faraday's law gives the induced emf as $e = -d(N\Phi)/dt$, where $N\Phi$ is the magnetic flux linkage of a coil of N turns. The negative sign represents Lenz's law.
- For a plane coil of area A in a uniform magnetic field B , the flux through one turn is $\Phi = BA \cos \theta$, where θ is the angle between the field and the normal to the coil.
- In a purely resistive closed circuit, the average power is $P = E_{\text{rms}}^2 / R$, with $E_{\text{rms}} = E_0 / \sqrt{2}$ for sinusoidal emf of peak value E_0 .

Step 1: (i) Explain the principle and construction An ac generator converts mechanical energy into electrical energy by electromagnetic induction. A rectangular armature coil $ABCD$ is rotated mechanically between the north and south poles of a magnet. Its axis of rotation is perpendicular to the magnetic field. The coil ends connect to two separate, continuous slip rings R_1 and R_2 , insulated from one another and mounted on the rotating shaft. Stationary carbon brushes B_1 and B_2 touch the rings and connect the rotating coil to the external circuit. The diagram is schematic; the two rings

remain electrically separate.



Schematic ac generator: rotating coil, separate slip rings, stationary brushes and external load.

Step 2: Describe the working and derive the instantaneous emf Rotation changes the angle between the coil's area vector and the field, so the magnetic flux linkage changes and an emf is induced. Choose $t = 0$ when the normal to the coil is parallel to the magnetic field. For uniform angular speed ω , the angle is $\theta = \omega t$. Thus,

$$N\Phi = NBA \cos(\omega t).$$

Differentiating the flux linkage gives

$$\begin{aligned} e(t) &= -\frac{d}{dt} [NBA \cos(\omega t)] \\ &= NBA\omega \sin(\omega t) = E_0 \sin(\omega t), \\ E_0 &= NBA\omega. \end{aligned}$$

The emf is zero when the flux is maximum and reaches its greatest magnitude when the coil's plane is parallel to the field. After every half revolution the direction of motion of each active side reverses relative to the field, reversing the emf. The slip rings retain each coil end's connection to its brush, so the output is alternating. Lenz's law ensures that the induced current opposes the driving rotation; mechanical work is therefore required to maintain the speed.

Step 3: (ii) Calculate the maximum emf Here $N = 100$, $A = 0.5 \text{ m}^2$, $B = 0.8 \text{ T}$, and $\omega = 60 \text{ rad s}^{-1}$. The angular speed is already given in radians per second, so no factor of 2π is required:

$$E_0 = 100 \times 0.8 \times 0.5 \times 60 = 2400 \text{ V}.$$

With the chosen initial orientation the induced emf can therefore be written as $e(t) = 2400 \sin(60t) \text{ V}$, with t in seconds.

Step 4: Calculate the mean power dissipated in the coil Taking the coil resistance $R = 100 \Omega$ as the resistance of the closed circuit, as intended in the question, and neglecting inductive reactance, the

rms emf and current are

$$E_{\text{rms}} = \frac{2400}{\sqrt{2}} \text{ V}, \quad I_{\text{rms}} = \frac{24}{\sqrt{2}} \text{ A}.$$

Hence the average rate of Joule heating is

$$P = \frac{E_0^2}{2R} = \frac{(2400)^2}{2 \times 100} = 28800 \text{ W} = 28.8 \text{ kW}.$$

The factor $1/2$ is essential: $E_0^2/R = 57.6 \text{ kW}$ would be the peak instantaneous power, whereas power dissipated by an ac source normally denotes the cycle average. An open coil would carry no current and dissipate no Joule power.

Step 5: Conclusion The generator works by electromagnetic induction and produces $e = NBA\omega \sin(\omega t)$. The maximum emf is 2400 V , and the mean power dissipated in the resistive closed coil is 28.8 kW .

Quick Tip to Solve: Use the given angular speed directly in $E_0 = NBA\omega$; then divide E_0^2 by $2R$, not by R , to obtain mean ac power.

33(a). (i) State Huygen's principle. With the help of a diagram, show how a plane wave is reflected from a surface. Hence verify the law of reflection.

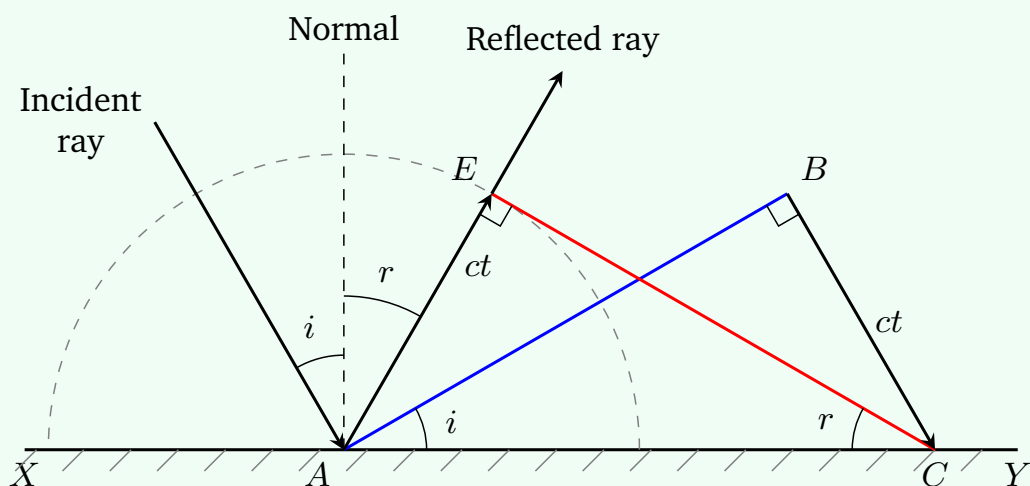
(ii) A concave mirror of focal length 12 cm forms a three times magnified virtual image of an object. Find the distance of the object from the mirror. [5 marks]

Solution:

Concept:

- Huygens' principle: every point on a wavefront acts as a source of secondary wavelets that spread forward with the speed of the wave in that medium. The forward envelope of these wavelets gives the new wavefront at a later instant.
- A ray in an isotropic medium is perpendicular to its wavefront. On reflection, the incident and reflected waves travel in the same medium and therefore have the same speed c .
- With the Cartesian sign convention, a spherical mirror obeys $\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$, and its linear magnification is $m = -v/u$. Here u , v and f are the signed object distance, image distance and focal length.

Step 1: (i) Construct the incident and reflected wavefronts Let AB be a plane incident wavefront approaching the reflecting surface XY . Point A reaches the surface first. In the time t taken by point B of the wavefront to reach C , the incident disturbance travels a distance $BC = ct$. During the same time, the secondary wavelet originating at A has radius $AE = ct$. Draw the tangent CE from C to this wavelet. By Huygens' construction, CE is the reflected plane wavefront, the envelope of the reflected secondary wavelets. The incident ray BC is perpendicular to AB , while the reflected ray AE is perpendicular to CE .



Huygens' reflection construction: AB is incident, CE is reflected, and $AE = BC = ct$. The normal and the ray angles at A are shown.

Step 2: (i) Verify the laws of reflection In right triangles ABC and AEC , $\angle ABC = \angle AEC = 90^\circ$, the hypotenuse AC is common, and $BC = AE = ct$. Hence the triangles are congruent by the right-angle–hypotenuse–side criterion, giving

$$\angle BAC = \angle ECA.$$

Since each ray is perpendicular to its wavefront and the normal is perpendicular to the reflecting surface, the angle between AB and AC equals the incidence angle i , and the angle between CE and CA equals the reflection angle r . Thus $i = r$. The construction lies in the plane containing the incident ray and the normal; the reflected ray lies in that same plane. Both laws of reflection therefore follow.

Step 3: (ii) Use the virtual-image magnification A virtual image formed by a concave mirror is erect, so the given magnification is positive: $m = +3$. Take the incident-light direction as positive. For the concave mirror, $f = -12$ cm, while a real object in front has $u < 0$ and its virtual image behind the mirror has $v > 0$. Therefore

$$3 = -\frac{v}{u} \Rightarrow v = -3u.$$

Substitute into the mirror formula:

$$-\frac{1}{12} = \frac{1}{-3u} + \frac{1}{u} = \frac{2}{3u},$$

$$3u = -24 \text{ cm}, \quad u = -8 \text{ cm}.$$

This gives $v = +24$ cm. The object lies between the pole and the focus, as required for an erect, magnified virtual image from a concave mirror.

Step 4: Conclusion Huygens' construction gives $i = r$, with the incident ray, reflected ray and normal coplanar. The object is 8 cm in front of the concave mirror ($u = -8$ cm).

Quick Tip to Solve: For a magnified virtual image of a concave mirror, use positive magnification but negative focal length; check that the object lies inside the focus.

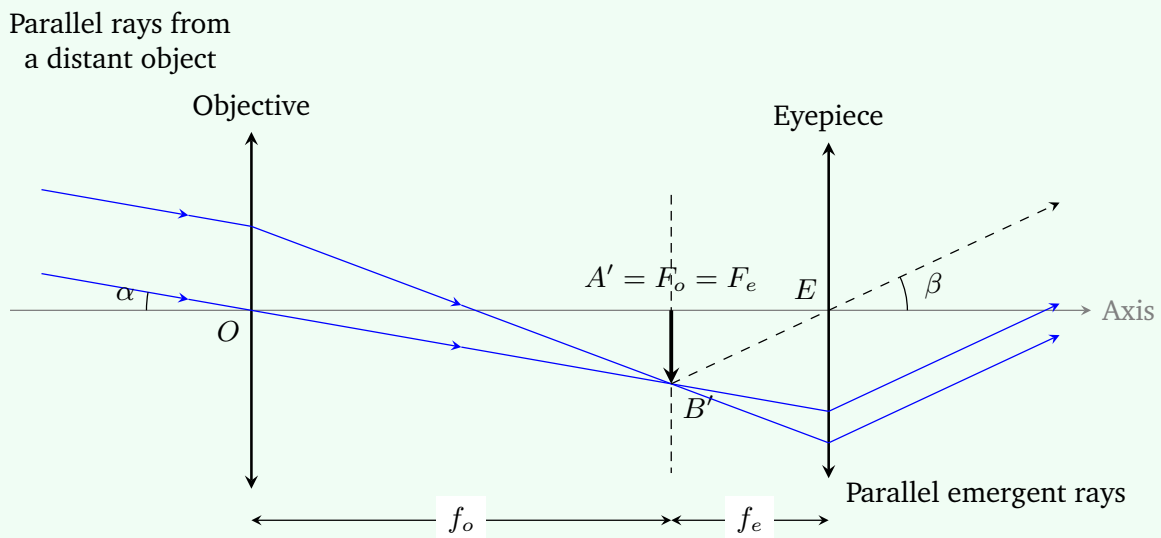
- 33(b).** (i) Draw a labelled ray diagram showing the image formation by a refracting telescope. Define its magnifying power. Write two limitations of a refracting telescope over a reflecting telescope.
- (ii) The focal lengths of the objective and the eye-piece of a compound microscope are 1.0 cm and 2.5 cm respectively. Find the tube length of the microscope for obtaining a magnification of 300.

[5 marks]

Solution:**Concept:**

- A refracting astronomical telescope uses a large-aperture, long-focal-length objective and a short-focal-length eyepiece. In normal adjustment their separation is $f_o + f_e$.
- Angular magnifying power is $M = \beta/\alpha$, where β is the angle subtended by the final image at the eye and α is the angle subtended by the distant object at the unaided eye.
- For a compound microscope, the usual tube-length approximation gives $|m_o| \simeq L/f_o$. The eyepiece magnification is $1 + D/f_e$ for a final image at the near point, and D/f_e for a final image at infinity; $D = 25$ cm.

Step 1: (i) Trace rays through the telescope Draw the telescope in normal adjustment. Parallel rays arriving from a distant off-axis object are focused by the objective at B' , in its focal plane. Thus $A'B'$ is a real, inverted intermediate image. Place this image in the first focal plane of the eyepiece: F_o and F_e coincide at A' . The eyepiece makes rays from B' emerge parallel, so the final image is virtual, inverted and at infinity. The dashed ray through the eyepiece centre shows the viewing direction.



Refracting telescope in normal adjustment; the final image is at infinity.

Step 2: (i) Define and obtain the magnifying power The magnifying power is the ratio of the angle subtended by the final image at the eye to the angle subtended by the distant object when viewed directly. For small angles and intermediate-image height h ,

$$|\alpha| \simeq \frac{h}{f_o}, \quad |\beta| \simeq \frac{h}{f_e}, \quad M = -\frac{f_o}{f_e}.$$

Its magnitude is f_o/f_e ; the negative sign denotes inversion of the final image relative to the object. The diagram labels the magnitudes of the two viewing angles.

Step 3: (i) State two limitations of refracting telescopes First, a refracting objective suffers from

chromatic aberration: different wavelengths have different refractive indices and hence different focal lengths, producing coloured fringes. A reflecting objective has no chromatic aberration. Second, making and supporting a large, optically uniform objective lens is difficult: the lens is heavy and can be supported only at its rim. A mirror can be supported from behind, so reflecting telescopes can have much larger apertures and greater light-gathering power.

Step 4: (ii) Calculate the microscope tube length Use the conventional maximum-magnification setting, with the final image at the least distance of distinct vision $D = 25$ cm. The total magnification is the product of the objective and eyepiece magnifications:

$$\begin{aligned}|M| &\simeq \frac{L}{f_o} \left(1 + \frac{D}{f_e}\right), \\ 300 &= \frac{L}{1.0 \text{ cm}} \left(1 + \frac{25}{2.5}\right) = \frac{11L}{1.0 \text{ cm}}, \\ L &= \frac{300}{11} \text{ cm} \simeq 27.3 \text{ cm}.\end{aligned}$$

Here L is the tube length in the standard school-level approximation. The printed question does not specify the final-image position. If normal adjustment (final image at infinity) is intended instead, the eyepiece factor is $25/2.5 = 10$, giving $L = 300(1.0)/10 = 30$ cm. Thus the image-position assumption must accompany the numerical answer.

Step 5: Conclusion The telescope in normal adjustment has $M = -f_o/f_e$; chromatic aberration and the difficulty of constructing a large objective are its two limitations. The microscope tube length is approximately 27.3 cm for near-point viewing, or 30 cm if the final image is at infinity.

Quick Tip to Solve: For the microscope, decide the final-image position first: use the eyepiece factor 11 at the near point or 10 at infinity for these focal lengths.

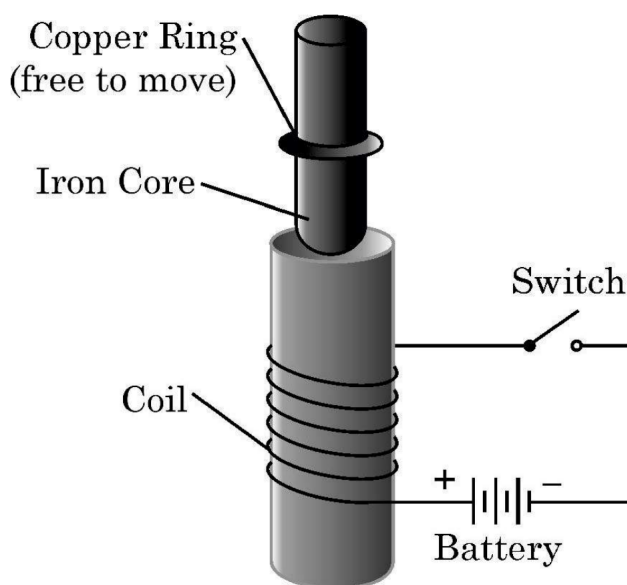
Section E (8 marks)

Note : Questions number 34 and 35 are Case Study based questions. Read the following paragraph and answer the questions.

34(a). Consider the experimental set up shown in the figure. This jumping ring experiment is an outstanding demonstration of some simple laws of Physics. A conducting non-magnetic ring is placed over the vertical core of a solenoid. When current is passed through the solenoid, the ring is thrown off.

Answer the following questions:

- Explain the reason of jumping of the ring when the switch is closed in the circuit.
- What will happen if the terminals of the battery are reversed and the switch is closed? Explain.
- Explain the two laws that help us understand this phenomenon. [4 marks]



Solution:

Concept:

- Faraday's law gives the induced emf: $\mathcal{E} = -d\Phi_B/dt$ for a single conducting ring, where Φ_B is the magnetic flux through it.
- Lenz's law fixes the direction of the induced current: its magnetic effect opposes the change of flux that produces it.
- A current-carrying ring has a magnetic moment. In the non-uniform field above the solenoid, the induced ring current experiences a force.

Step 1: (i) Trace the change immediately after closing the switch The solenoid current rises from zero, so the magnetic flux linked with the closed copper ring increases. This changing flux induces an emf and hence a current in the ring, even though the ring is non-magnetic. By Lenz's law, the ring produces a field opposing the increasing solenoid field. Its current therefore circulates opposite to that of the solenoid turns when both are viewed from the same end. The adjacent faces of the ring and solenoid behave as like magnetic poles and repel. In the field near the end of the solenoid, this gives an upward force; the sufficiently strong transient force throws the ring upwards. With a battery, the effect occurs during the rise of current. Once the solenoid current and flux become steady, the induced emf vanishes; steady direct current does not continuously drive the ring upwards.

Step 2: (ii) Reverse the battery and close the switch again Starting again from zero current, reversing the battery reverses the direction of the solenoid field and of its increasing flux. The induced current in the ring also reverses. It still produces a field opposing the new increase in flux. Thus the relative directions of the solenoid and ring currents remain opposite, and the adjacent magnetic faces are again like poles. The ring therefore jumps upwards in this case also, assuming the same initial conditions and battery strength.

Step 3: (iii) State the laws and their roles **Faraday's laws of electromagnetic induction:** Whenever the magnetic flux linked with a circuit changes, an emf is induced; its magnitude equals the rate of change of flux linkage. For a coil of N turns,

$$|\mathcal{E}| = N \left| \frac{d\Phi_B}{dt} \right|.$$

For this ring, $N = 1$; since it is a closed conductor, the emf drives a current. **Lenz's law:** The induced current has a direction such that its magnetic effect opposes the change in flux producing it. This explains the repulsion during switch-on and why reversing the battery does not reverse the upward force. The minus sign in $\mathcal{E} = -N d\Phi_B/dt$ expresses this direction rule.

Step 4: Conclusion The increasing flux at switch-on induces an opposing current in the ring and produces repulsion, making the ring jump. Reversing the battery reverses both currents, so the ring again jumps. Faraday's law explains induction and Lenz's law explains the direction and repulsion.

Quick Tip to Solve: At switch-on, oppose the increase of flux. If the battery is reversed, reverse both the solenoid field and the induced ring current before deciding the force.

OR

34(b). Briefly explain various ways to increase the strength of magnetic field produced by a given solenoid. [4 marks]

Solution:

Concept:

- The magnetic field well inside a long solenoid is approximately $B = \mu n I = \mu_0 \mu_r (N/L) I$, where I is the current, N the number of turns and L its length.
- The turn density is $n = N/L$. The core permeability is $\mu = \mu_0 \mu_r$, where μ_r is its relative permeability; a suitable ferromagnetic core strengthens the field.

Step 1: Increase the current through the solenoid For fixed winding and core, B increases with I . Increase the applied potential difference or reduce the external series resistance to obtain a larger current, within the safe heating limit of the wire. For example, in the range where the core permeability is approximately constant, doubling the current doubles the field:

$$\frac{B_2}{B_1} = \frac{I_2}{I_1}.$$

Reversing the current alone changes the field direction, not its strength.

Step 2: Use a soft-iron core Insert a suitable soft-iron core into an air-cored solenoid. The core becomes magnetised by the solenoid and its magnetisation contributes to the field. Since soft iron has a much greater permeability than air, the resulting field is stronger for the same winding and current.

If a core is already present, an appropriate higher-permeability core can strengthen the field further. This increase is limited by magnetic saturation; the proportional formula assumes operation below strong saturation.

Step 3: Increase the number of turns per unit length if the winding can be altered The general winding method is to increase $n = N/L$: wind more turns over the same length, or reduce the winding length while retaining the turns, where construction permits and the long-solenoid approximation remains suitable. At fixed current and permeability,

$$\frac{B_2}{B_1} = \frac{n_2}{n_1}.$$

Simply increasing the total turns while increasing the length in the same ratio leaves n unchanged and does not give this increase. For a given solenoid whose winding must remain unchanged, n is fixed; increasing current and using a suitable core are the directly available methods.

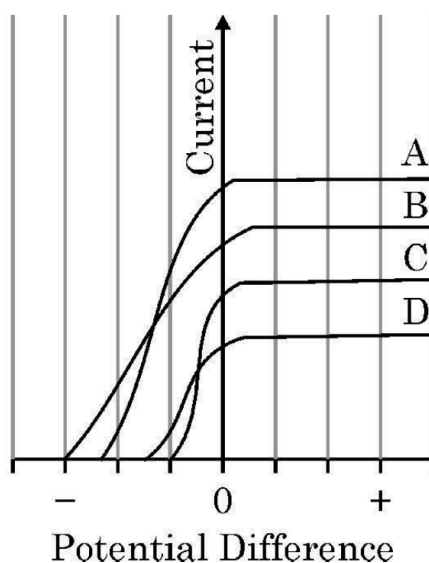
Step 4: Conclusion Strengthen the field by increasing the current and inserting a suitable high-permeability soft-iron core. If winding changes are allowed, increase the turns per unit length as well, consistent with $B = \mu nI$.

Quick Tip to Solve: Use $B = \mu nI$ as a checklist: increase permeability, current or turns per unit length. For an unchanged winding, only the first two can be adjusted.

35(a). Figure shows the variation of photoelectric current measured in a photo cell circuit as a function of the potential difference between the plates of the photo cell when light beams A, B, C and D of different wavelengths are incident on the photo cell. Examine the given figure and answer the following questions:

- Which light beam has the highest frequency and why?
- Which light beam has the longest wavelength and why?
- Which light beam ejects photoelectrons with maximum momentum and why?

[4 marks]



Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi = eV_s$, where h is Planck's constant, ν is the incident frequency, ϕ is the work function of the photocathode, e is the elementary charge and V_s is the positive magnitude of the stopping potential.
- The wavelength is $\lambda = c/\nu$, where c is the speed of light. For the same photocathode, a smaller stopping-potential magnitude corresponds to a lower frequency and hence a longer wavelength.
- The maximum photoelectron momentum is $p_{\max} = \sqrt{2m_e K_{\max}} = \sqrt{2m_e eV_s}$, where m_e is the electron mass. Thus it is determined by the negative-voltage intercept, not by the saturation current.

Step 1: Read the stopping potentials from the graph Each curve reaches zero photocurrent at a negative plate potential. Its distance from the origin along the horizontal axis gives the stopping-potential magnitude. Trace each labelled curve back from its saturation region: B meets the axis farthest to the left, followed by A, D and then C. Therefore,

$$V_{s,B} > V_{s,A} > V_{s,D} > V_{s,C}.$$

The saturation-current heights have a different order; their heights must not be used to rank photoelectron energies.

Step 2: (i) Compare the incident frequencies Since all four beams fall on the same photocathode, ϕ is constant. Rearranging Einstein's equation gives

$$\nu = \frac{eV_s + \phi}{h}.$$

Frequency increases with stopping-potential magnitude. Curve B has the most negative intercept, and hence its photons have the greatest energy. Although A produces the largest saturation current, that does not establish the greatest frequency.

Step 3: (ii) Compare the wavelengths Curve C reaches zero current at the negative potential closest to the origin, so its stopping-potential magnitude and incident frequency are the smallest. Equivalently,

$$\lambda = \frac{hc}{eV_s + \phi}.$$

With the same work function, the smallest denominator corresponds to the largest wavelength. It is the horizontal intercept of C, rather than the lowest saturation-current level of D, that identifies the longest wavelength.

Step 4: (iii) Compare the maximum photoelectron momenta The stopping field must remove the maximum kinetic energy of the emitted electrons. Using $eV_s = p_{\max}^2/(2m_e)$, the greatest stopping-potential magnitude gives the greatest maximum momentum. B has the largest value of V_s ; the common factors $2m_e e$ do not change this ordering.

Step 5: Conclusion (i) Beam B has the highest frequency, because its stopping-potential magnitude is greatest. (ii) Beam C has the longest wavelength, because its stopping-potential magnitude and

frequency are smallest. (iii) Beam B ejects photoelectrons with the maximum momentum, since $p_{\max} = \sqrt{2m_e e V_s}$.

Quick Tip to Solve: Trace each labelled curve to its negative-voltage intercept: farther left means higher frequency and maximum momentum, while nearer zero means longer wavelength.

OR

35(b). What is the effect on threshold frequency and stopping potential on increasing the frequency of incident beam of light? Justify your answer. [4 marks]

Solution:

Concept:

- The work function ϕ is the minimum energy needed to eject an electron from a given metal surface. Its threshold frequency ν_0 satisfies $\phi = h\nu_0$, where h is Planck's constant.
- For incident frequency $\nu \geq \nu_0$, Einstein's equation gives $K_{\max} = h\nu - \phi = h(\nu - \nu_0)$, where $K_{\max}$ is the maximum kinetic energy of an emitted photoelectron.
- The positive magnitude V_s of the stopping potential is defined by $eV_s = K_{\max}$, where e is the elementary charge. It measures the retarding voltage required to stop even the fastest photoelectrons.

Step 1: Determine whether the threshold frequency changes The threshold frequency is a property of the emitting material and its surface. For the same photocathode under unchanged surface conditions, the work function remains fixed. Therefore,

$$\nu_0 = \frac{\phi}{h}.$$

Increasing the frequency of the incident light changes the energy carried by each photon, but it does not change the minimum energy required to liberate an electron.

Step 2: Relate stopping potential to incident frequency An absorbed photon supplies energy $h\nu$. After an electron uses at least ϕ to escape the surface, the maximum available kinetic energy is $h\nu - \phi$. To prevent even this fastest electron from reaching the collector, the retarding field must do work eV_s . Hence,

$$V_s = \frac{h}{e}\nu - \frac{\phi}{e} = \frac{h}{e}(\nu - \nu_0).$$

This straight-line relation has positive slope h/e .

Step 3: Compare the initial and final stopping potentials If the incident frequency increases from ν_1 to ν_2 , with photoemission occurring, subtract the two energy equations:

$$\begin{aligned} e(V_{s,2} - V_{s,1}) &= h(\nu_2 - \nu_1), \\ \Delta V_s &= \frac{h}{e}\Delta\nu > 0. \end{aligned}$$

Thus the magnitude of the stopping potential rises linearly with frequency. On a current-versus-

collector-potential graph, the zero-current intercept moves farther into the negative-potential region. Below ν_0 , photoemission does not occur; this relation applies when photoelectrons are emitted.

Step 4: Conclusion Increasing the incident frequency leaves the threshold frequency unchanged for the same emitting surface, since $\nu_0 = \phi/h$. The stopping-potential magnitude increases according to $\Delta V_s = (h/e)\Delta\nu$, because the maximum kinetic energy of the photoelectrons increases. The corresponding retarding collector potential becomes more negative.

Quick Tip to Solve: Keep the material property $\nu_0 = \phi/h$ separate from the incident frequency; then use $V_s = (h/e)(\nu - \nu_0)$ to predict the change.