

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

## 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.

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

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

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

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

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

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

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

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

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

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

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

## Section A (18 marks)

1. The ratio of the magnitudes of the electric field and magnetic field of a plane electromagnetic wave is [1 mark]

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

**Correct Answer:** (C)  $c$

### Solution:

#### Concept:

- For a plane electromagnetic wave in free space, the field amplitudes satisfy  $E_0 = cB_0$ , where  $c$  is the speed of light.
- The electric and magnetic fields oscillate in phase; their magnitudes therefore have the same amplitude ratio as their instantaneous nonzero values.

**Step 1: Apply the electromagnetic-wave relation** Maxwell's wave relation gives  $E_0/B_0 = c$ . Thus the ratio has the dimensions of a speed, rather than being a dimensionless comparison of the two fields.

**Step 2: Check the alternatives** The value 1 would imply equal numerical magnitudes in SI units, which is incorrect. The reciprocal  $1/c$  corresponds to  $B_0/E_0$ ;  $1/c^2$  is also inconsistent with the field relation.

**Step 3: Conclusion**  $E_0/B_0 = c$ . Hence, the correct option is (C).

**Quick Tip to Solve:** Remember  $E_0 = cB_0$ ; check which field appears in the numerator before taking the ratio.

2. Specify the transition of electron in the wavelength of the line in the Bohr model of hydrogen atom which gives rise to the spectral line of highest wavelength. [1 mark]

- (A)  $n = 3$  to  $n = 1$
- (B)  $n = 3$  to  $n = 2$
- (C)  $n = 4$  to  $n = 1$
- (D)  $n = 4$  to  $n = 2$

**Correct Answer:** (B)  $n = 3$  to  $n = 2$

### Solution:

#### Concept:

- In hydrogen,  $E_n = -13.6/n^2$  eV, where  $n$  is the principal quantum number.
- For emission,  $hc/\lambda = 13.6(1/n_f^2 - 1/n_i^2)$  eV. The longest wavelength corresponds to the smallest positive energy difference.

**Step 1: Compare the four energy gaps** The factors multiplying 13.6 eV are  $8/9$  for  $3 \rightarrow 1$ ,  $5/36$  for  $3 \rightarrow 2$ ,  $15/16$  for  $4 \rightarrow 1$ , and  $3/16$  for  $4 \rightarrow 2$ .

**Step 2: Use the inverse energy-wavelength relation** The smallest factor is  $5/36$ . In particular,  $5/36 < 3/16$ , so even the other transition ending at  $n = 2$  emits a higher-energy photon. Both

transitions ending at  $n = 1$  have much larger energy gaps and shorter wavelengths.

**Step 3: Conclusion** The transition  $n = 3 \rightarrow n = 2$  gives the highest wavelength. Hence, the correct option is (B).

**Quick Tip to Solve:** For the longest wavelength, compare energy gaps using  $1/n_f^2 - 1/n_i^2$ , not just the change in  $n$ .

**3. 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 boundary, the frequency  $f$  of light is fixed by the source and is unchanged during reflection and refraction.
- The speed and wavelength are related by  $v = f\lambda$ ; a change of optical medium changes the speed and hence the wavelength.

**Step 1: Compare the frequencies** The reflected ray remains in air, while the refracted ray enters water. Both arise from the same monochromatic incident wave, so the oscillation frequency of each equals the incident frequency.

**Step 2: Eliminate the other quantities** The refracted ray travels more slowly in water than the reflected ray does in air; their wavelengths also differ. The incident energy is divided between reflection and transmission, and the two rays need not carry equal total energy. Equal photon energy  $hf$  does not require equal energy carried by the two rays.

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

**Quick Tip to Solve:** Across a stationary interface, keep  $f$  fixed and use  $\lambda = v/f$  to compare wavelengths.

4. 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:**

- Before equilibrium, majority carriers diffuse across a p-n junction because of their concentration gradients.
- Recombination removes mobile electrons and holes near the junction, leaving fixed ionised donor and acceptor atoms: the depletion region.

**Step 1: Trace the majority carriers** Electrons diffuse from the n-side to the p-side, while holes diffuse from the p-side to the n-side. Near the junction they recombine, reducing the concentration of mobile charge carriers.

**Step 2: Distinguish diffusion from drift** The dopant atoms remain fixed in the lattice, so their movement does not form this region. The uncovered ions establish an electric field and a potential barrier; the resulting drift opposes further diffusion. Drift of electrons alone or holes alone is therefore not the cause of initial depletion-region formation.

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

**Quick Tip to Solve:** Associate junction formation with concentration-driven diffusion; the barrier field and opposing drift arise afterwards.

5. An isolated point charge particle produces an electric field  $\vec{E}$  at a point 3 m away from it. The distance of the point at which the field is  $\frac{\vec{E}}{4}$  will be

[1 mark]

- (A) 2 m
- (B) 3 m
- (C) 4 m
- (D) 6 m

**Correct Answer:** (D) 6 m

**Solution:**

**Concept:**

- The magnitude of the electric field of an isolated point charge is  $E = k|q|/r^2$ , where  $r$  is its distance from the field point.
- For a fixed charge in the same medium,  $E_2/E_1 = r_1^2/r_2^2$ . The field direction is radial.

**Step 1: Form the field ratio** With  $r_1 = 3$  m and  $E_2 = E_1/4$ , the inverse-square law gives

$$\frac{1}{4} = \frac{(3 \text{ m})^2}{r_2^2}.$$

The new point can lie on the same radial line to preserve the stated vector direction.

**Step 2: Calculate and check the distance** Taking the positive square root gives  $r_2 = 2r_1$ . A distance of 2 m would increase the field, 3 m would leave it unchanged, and 4 m would give  $9E_1/16$ , not  $E_1/4$ .

**Step 3: Conclusion** The required distance is  $\boxed{6 \text{ m}}$ . Hence, the correct option is (D).

**Quick Tip to Solve:** To reduce a point-charge field by a factor of four, double the distance because the field varies as  $1/r^2$ .

**6. 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 into its constituent free nucleons.
- Binding energy per nucleon,  $B/A$ , is a measure of how tightly the nucleons are bound; a higher value generally indicates greater nuclear stability.

**Step 1: Interpret the local peak** A sharp peak for helium means its binding energy per nucleon is larger than for nearby nuclei on the mass-number axis. Its nucleons are therefore especially tightly bound compared with those of its neighbours.

**Step 2: Reject the instability interpretations** The peak is evidence of enhanced stability, so it does not indicate that helium is radioactive or unstable. It also does not imply easy fission: dividing such a tightly bound light nucleus into lighter constituents requires energy instead of readily releasing it.

**Step 3: Conclusion** Helium is more stable than its neighbouring nuclei. Hence, the correct option is (D).

**Quick Tip to Solve:** On a binding-energy-per-nucleon graph, a local maximum indicates extra stability relative to nearby nuclei.

7. A steady current of 8 mA flows through a wire. The number of electrons passing through a cross-section of the wire in 10 s is [1 mark]

- (A)  $4.0 \times 10^{16}$
- (B)  $5.0 \times 10^{17}$
- (C)  $1.6 \times 10^{16}$
- (D)  $1.0 \times 10^{17}$

**Correct Answer:** (B)  $5.0 \times 10^{17}$

**Solution:**

**Concept:**

- For steady current  $I$ , the magnitude of charge crossing a cross-section in time  $t$  is  $Q = It$ .
- Each electron carries charge of magnitude  $e = 1.6 \times 10^{-19}$  C, so the number crossing is  $N = Q/e$ .

**Step 1: Convert current and calculate charge** The given current is  $8 \text{ mA} = 8 \times 10^{-3} \text{ A}$ . Therefore,

$$Q = (8 \times 10^{-3})(10) = 8 \times 10^{-2} \text{ C}.$$

**Step 2: Count the electrons** Dividing the transferred charge by the charge magnitude of one electron gives

$$N = \frac{8 \times 10^{-2}}{1.6 \times 10^{-19}} = 5.0 \times 10^{17}.$$

The other proposed counts would transfer charges different from 0.08 C; the negative sign of electron charge is not used for a particle count.

**Step 3: Conclusion**  $5.0 \times 10^{17}$  electrons cross the wire. Hence, the correct option is (B).

**Quick Tip to Solve:** Convert milliamperes to amperes first, then compute  $N = It/e$ ; the electron count is always positive.

8. Which one of the following elements will require the highest energy to take out an electron from them?

Pb, Ge, C and Si

[1 mark]

- (A) Ge
- (B) C
- (C) Si
- (D) Pb

**Correct Answer:** (B) C

**Solution:**

**Concept:**

- The energy needed to remove a bound electron depends on the attraction between the nucleus and that electron.
- For the listed group-IV elements, carbon has the smallest atomic size and holds its outer electrons most strongly; it has the highest first ionisation energy among them.

**Step 1: Compare electron binding** Carbon lies above silicon, germanium and lead in the group. Its

outer electrons occupy the smaller second shell and experience strong attraction to the nucleus, so removing an electron requires more energy.

**Step 2: Compare the listed alternatives** Silicon, germanium and lead have valence electrons in more distant shells with greater shielding. None requires as much energy as carbon to remove its first electron. In the solid-state comparison used for these group-IV materials, carbon in diamond likewise has a much larger forbidden energy gap than Si or Ge, while Pb is metallic.

**Step 3: Conclusion** Carbon requires the highest energy. Hence, the correct option is (B).

**Quick Tip to Solve:** Among C, Si, Ge and Pb, identify carbon as the smallest atom with the most strongly bound valence electrons.

**9. A conductor of  $10\ \Omega$  is connected across a 6 V ideal source. The power supplied by the source to the conductor is** [1 mark]

- (A) 1.8 W
- (B) 2.4 W
- (C) 3.6 W
- (D) 7.2 W

**Correct Answer:** (C) 3.6 W

**Solution:**

**Concept:**

- Ohm's law gives  $I = V/R$ , where  $V$  is the potential difference across resistance  $R$ .
- Electrical power delivered to a resistor is  $P = VI = V^2/R$ . An ideal source has no internal voltage drop.

**Step 1: Find the current through the conductor** The entire source voltage appears across the conductor, so

$$I = \frac{6}{10} = 0.6\text{ A.}$$

**Step 2: Calculate the rate of energy supply** Multiply the source voltage by the current it supplies:

$$P = VI = 6 \times 0.6 = 3.6\text{ W.}$$

The other proposed powers, 1.8, 2.4 and 7.2 W, would require currents different from 0.6 A, and therefore violate Ohm's law for the given resistance.

**Step 3: Conclusion** The power supplied is 3.6 W. Hence, the correct option is (C).

**Quick Tip to Solve:** When voltage and resistance are given, use  $P = V^2/R$  directly; remember to square the voltage.

**10. 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, electron density  $n$  and hole density  $p$  obey the mass-action law  $np = n_i^2$ , where  $n_i$  is the intrinsic carrier density at the same temperature.
- Doping changes the individual carrier densities, but their product remains  $n_i^2$ ; the minority carrier density is found by division.

**Step 1: Isolate the electron density** Here holes are the majority carriers because  $p = 4 \times 10^{20} \text{ m}^{-3}$  is much larger than  $n_i$ . Rearranging the mass-action relation gives

$$n = \frac{n_i^2}{p}$$

**Step 2: Substitute and simplify the powers** Square both the coefficient and the power of ten:

$$n = \frac{(1.2 \times 10^{15})^2}{4 \times 10^{20}} = \frac{1.44 \times 10^{30}}{4 \times 10^{20}} = 3.6 \times 10^9 \text{ m}^{-3}.$$

Only this value reproduces  $np = 1.44 \times 10^{30} \text{ m}^{-6}$ ; none of the three other options satisfies that product.

**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 the entire intrinsic density before dividing by the majority density;  $(10^{15})^2 = 10^{30}$ .

11. 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 discharging cell obeys  $E = V + Ir$ , where  $E$  is its emf,  $V$  its terminal voltage and  $r$  its internal resistance.
- The external resistor carries the same current as the cell, so  $V = IR$ , with  $R$  the external resistance.

**Step 1: Express the internal voltage drop** The emf exceeds the terminal voltage by the drop across the internal resistance:

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

**Step 2: Eliminate current using the external resistor** Substitute  $I = V/R$  to put the result into the printed option form:

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

Option (A) incorrectly uses  $E$  where the external voltage  $V$  belongs. Option (B) has units of current. Option (C) includes an extra factor  $R$  and has units of resistance squared, so neither can represent internal resistance.

**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  $E - V = Ir$  for the internal drop and  $V = IR$  for the external resistor; do not replace its voltage by the emf.

**12. A photon of wavelength 663 nm is incident on a metal surface. The work function of the metal is 1.50 eV. The maximum kinetic energy of the emitted photoelectrons is** [1 mark]

- (A)  $3.0 \times 10^{-20}$  J
- (B)  $6.0 \times 10^{-20}$  J
- (C)  $4.5 \times 10^{-20}$  J
- (D)  $9.0 \times 10^{-20}$  J

**Correct Answer:** (B)  $6.0 \times 10^{-20}$  J

**Solution:**

**Concept:**

- Photon energy is  $E_\gamma = hc/\lambda$ , where  $h$  is Planck's constant,  $c$  is the speed of light and  $\lambda$  is the incident wavelength.
- Einstein's photoelectric equation is  $K_{\max} = E_\gamma - \phi$ , where  $\phi$  is the work function;  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ .

**Step 1: Calculate photon energy in joules** Convert the wavelength to  $663 \times 10^{-9} \text{ m}$ , then use the supplied constants:

$$E_\gamma = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{663 \times 10^{-9}} = 3.00 \times 10^{-19} \text{ J}.$$

**Step 2: Subtract the energy needed for escape** The work function is  $\phi = 1.50 \times 1.6 \times 10^{-19} = 2.40 \times 10^{-19} \text{ J}$ . Therefore,

$$K_{\max} = (3.00 - 2.40) \times 10^{-19} = 6.0 \times 10^{-20} \text{ J}.$$

Emission is possible because the photon energy exceeds the work function. The values in (A), (C) and (D) do not equal this energy difference; the whole photon energy cannot become kinetic energy.

**Step 3: Conclusion** The maximum kinetic energy is  $6.0 \times 10^{-20} \text{ J}$ . Hence, the correct option is (B).

**Quick Tip to Solve:** Convert the work function to joules before subtracting it from  $hc/\lambda$ ; energy units must match.

**13. 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 charges, so their electric interaction is attractive.
- Conventional current is opposite to electron motion and along proton motion. Thus the parallel beams carry opposite currents and their magnetic interaction is repulsive.

**Step 1: Identify both forces between the beams** Although both particle beams move in the same direction, their opposite charge signs reverse one conventional current. The magnetic force therefore

opposes the electric attraction. The question asks about the beams' interaction without restricting it to magnetic force, so both contributions must be included.

**Step 2: Compare their magnitudes** For parallel beams with charge densities per unit length of magnitudes  $\lambda_e, \lambda_p$ , separation  $d$ , and speeds  $v_e, v_p$ ,

$$\frac{F_E}{L} = \frac{\lambda_e \lambda_p}{2\pi\epsilon_0 d}, \quad \frac{F_B}{L} = \frac{\mu_0 \lambda_e \lambda_p v_e v_p}{2\pi d}.$$

Hence  $F_B/F_E = v_e v_p/c^2 < 1$ , because both massive particles have speeds below  $c$ . Electric attraction is stronger. Option (B) describes only the magnetic contribution; (C) would require equality, and (D) incorrectly allows the net force to change sign with speed.

**Step 3: Conclusion** The beams attract each other overall. Hence, the correct option is (A).

**Quick Tip to Solve:** For charged particle beams, check both electric and magnetic forces; opposite conventional currents alone determine only the magnetic part.

**14. A ray of light of wavelength 600 nm propagates from air into a medium. If its wavelength in the medium becomes 400 nm, the refractive index of the medium is** [1 mark]

- (A) 1.4
- (B) 1.5
- (C) 1.6
- (D) 1.8

**Correct Answer:** (B) 1.5

**Solution:**

**Concept:**

- The frequency  $f$  of light remains unchanged when it crosses a stationary boundary between two media.
- Since wave speed is  $v = f\lambda$ , the refractive index relative to air is  $n = v_{\text{air}}/v_{\text{medium}} = \lambda_{\text{air}}/\lambda_{\text{medium}}$ , taking the index of air as unity.

**Step 1: Relate the wavelengths to the speeds** The same frequency occurs on both sides of the boundary. Thus the wavelength decrease from 600 nm to 400 nm means that the wave speed decreases in the same ratio. Refractive index is the inverse of this speed ratio.

**Step 2: Form the wavelength ratio** Both wavelengths are given in nanometres, so the units cancel directly:

$$n = \frac{600 \text{ nm}}{400 \text{ nm}} = 1.5.$$

The other values 1.4, 1.6 and 1.8 do not reproduce the given wavelength ratio. Inverting the ratio would give an index below unity and would incorrectly imply that light speeds up despite its shorter wavelength.

**Step 3: Conclusion** The refractive index of the medium is 1.5. Hence, the correct option is (B).

**Quick Tip to Solve:** At a boundary frequency stays fixed, so divide the air wavelength by the medium wavelength to find the index.

15. 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 for a circular path of radius  $r$  around the wire gives  $B(2\pi r) = \mu_0 I_{\text{enc}}$ , where  $I_{\text{enc}}$  is the current enclosed.
- Uniform current density gives  $I_{\text{enc}} = Ir^2/a^2$  inside a wire of radius  $a$ ; outside it, the entire current  $I$  is enclosed.

**Step 1: Evaluate the field inside the wire** At  $r = a/2$ , the enclosed area is one quarter of the full cross-section, so  $I_{\text{enc}} = I/4$ . Thus

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

**Step 2: Evaluate the field outside and compare** At  $r = 2a$ , the full current is enclosed:

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

Options (A) and (C) do not match these equal values. Option (D) results from wrongly using the full current in the outside-wire formula at both distances; only a quarter of the current is enclosed at  $a/2$ .

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

**Quick Tip to Solve:** Inside a uniformly conducting wire use  $B \propto r$ ; outside use  $B \propto 1/r$ , with both matching at the surface.

**16. 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 an electrostatic field, the work done by the field in moving charge  $q$  from  $i$  to  $f$  is  $W = q(V_i - V_f)$ , where  $V$  is electric potential.
- A conservative force does path-independent work; consequently its work around any closed path is zero.

**Step 1: Evaluate the assertion** In the electrostatic setting indicated by the reason, a closed path starts and ends at the same point, so  $V_i = V_f$ . Therefore  $W = q(V_i - V_f) = 0$ , and the assertion is true in this setting. This statement is about electrostatic fields; an electric field induced by a changing magnetic flux need not have zero circulation.

**Step 2: Evaluate the reason** Electrostatic force is conservative: its work depends only on the initial and final positions, not on the route taken. Thus the reason is true.

**Step 3: Check the explanatory connection** The conservative nature is precisely why returning to the initial point gives zero net work. The reason therefore explains the assertion. Option (B) misses this direct connection, while (C) and (D) wrongly declare the reason false.

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

**Quick Tip to Solve:** For a closed electrostatic path, set the final potential equal to the initial potential in  $W = q(V_i - V_f)$ .

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

**Reason (R):** The fringe width depends upon wavelength of light ( $\lambda$ ) 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  $\lambda$  is the wavelength,  $D$  the screen distance and  $d$  the slit separation.
- Fringe width means the separation of two successive bright fringes or two successive dark fringes.

**Step 1: Evaluate the assertion** The bright fringe positions are  $y_n = n\lambda D/d$ . Therefore  $y_{n+1} - y_n = \lambda D/d$ , independent of the order  $n$ . The same spacing follows for consecutive dark fringes. Thus Assertion (A) is true within the standard Young's experiment approximation.

**Step 2: Evaluate the reason** Reason (R) correctly identifies the three quantities in  $\beta = \lambda D/d$ : the wavelength, the screen distance and the slit separation. Hence R is true.

**Step 3: Check the explanatory link** These three quantities remain fixed for a given arrangement using monochromatic light. Consequently the fringe width has no dependence on fringe order and is the same throughout the interference pattern in this approximation. Thus R explains A; option (B) wrongly denies this link, while (C) and (D) wrongly reject true statements.

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

**Quick Tip to Solve:** Write  $\beta = \lambda D/d$  and check whether it contains the fringe order; its absence gives equal fringe widths.

**18. 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:**

- Diamagnetism is a weak induced magnetic response opposite to an applied magnetic field; its susceptibility is negative,  $\chi_m < 0$ .
- In a diamagnetic atom, the electronic magnetic moments cancel in the absence of an applied field, so the permanent net magnetic dipole moment is zero.

**Step 1: Evaluate the assertion** A diamagnetic substance does exhibit magnetism when placed in an external field: it acquires a small induced magnetisation opposite to the field and is weakly repelled from stronger-field regions. Thus Assertion (A) is true. Magnetism need not be permanent to exist.

**Step 2: Evaluate the reason** Diamagnetic materials have no permanent net magnetic dipole moment because their electronic contributions cancel. Therefore Reason (R) is also true.

**Step 3: Test whether the reason explains the assertion** The absence of a permanent moment does not explain how magnetism appears. That requires the change in electronic orbital motion caused by the applied field, producing an induced opposing moment. Thus R describes the zero-field state but does not supply the mechanism for A. Option (A) incorrectly treats it as the explanation; options (C) and (D) incorrectly label 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:** Distinguish a permanent magnetic moment from an induced one; diamagnetism is an induced response opposite to the field.

**Section B (14 marks)**

**19. In a Young's double slit experiment, the separation between the two slits is  $d$  and distance of the screen from the slits is  $1000d$ . If the first minima falls at a distance  $d$  from the central maximum, obtain the relation between  $d$  and  $\lambda$ .**

[2 marks]

**Solution:**

**Concept:**

- In Young's double slit experiment, destructive interference occurs when the path difference is an odd multiple of  $\lambda/2$ , where  $\lambda$  is the wavelength.
- For slit separation  $d$ , screen distance  $D$  and transverse distance  $y$ , the small-angle path difference is  $\Delta = dy/D$ . The first minimum has  $\Delta = \lambda/2$ .

**Step 1: Express the position of the first minimum** The nearest dark fringe on either side of the central bright fringe corresponds to a half-wavelength path difference, not a full wavelength. Thus its distance  $y_1$  from the centre obeys

$$\frac{dy_1}{D} = \frac{\lambda}{2} \implies y_1 = \frac{\lambda D}{2d}.$$

This is half the usual fringe width  $\lambda D/d$ .

**Step 2: Substitute the two given distances** The question gives  $D = 1000d$  and  $y_1 = d$ . Substituting both values gives

$$d = \frac{\lambda(1000d)}{2d},$$

$$d = 500\lambda.$$

The approximation is justified because  $y_1/D = 1/1000$ , a very small ratio. Both  $d$  and  $\lambda$  have dimensions of length, as required by the result.

**Step 3: Conclusion** The required relation is  $d = 500\lambda$ , equivalently  $\lambda = d/500$ .

**Quick Tip to Solve:** For the first dark fringe use half a fringe width:  $y_1 = \lambda D/(2d)$ . A full fringe width locates the first bright fringe.

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

[2 marks]

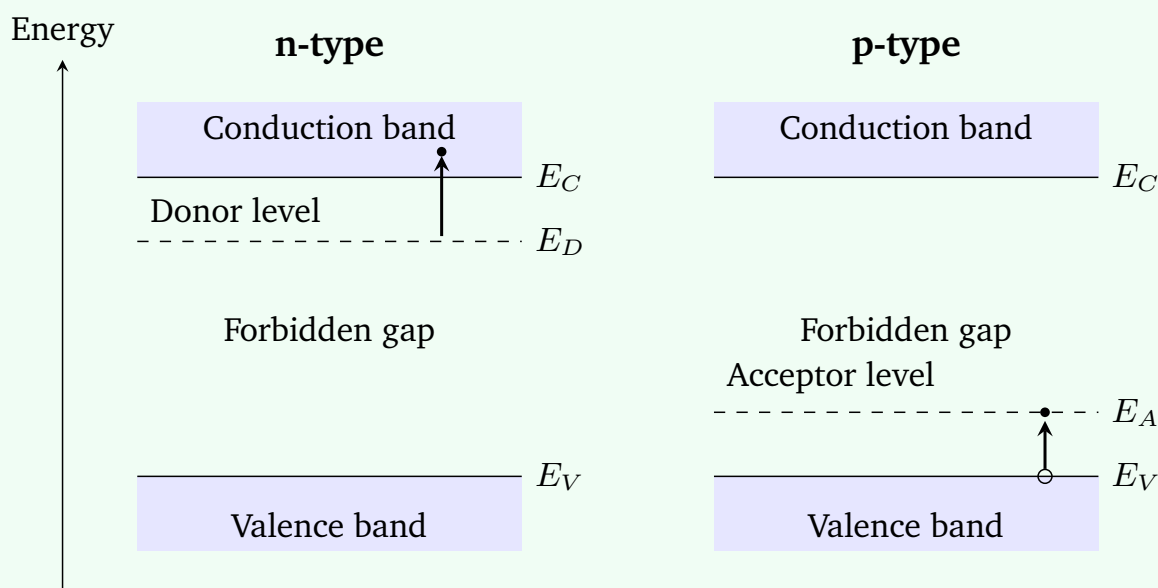
**Solution:**

**Concept:**

- The conduction-band edge  $E_C$  lies above the valence-band edge  $E_V$ ; the interval between them is the forbidden energy gap  $E_g = E_C - E_V$ .
- Donor impurities introduce a level  $E_D$  just below  $E_C$ , while acceptor impurities introduce a level  $E_A$  just above  $E_V$ . Thermal energy at  $T > 0$  K allows excitation across these small energy separations.

**Step 1: Draw the n-type energy bands** In an n-type semiconductor, a donor level lies close to and below the conduction band. A donor electron can gain thermal energy and move from  $E_D$  into the conduction band, leaving a positively ionised donor. The upward arrow in the left diagram shows this transition. Electrons are the majority carriers, while holes are minority carriers.

**Step 2: Draw the p-type energy bands** In a p-type semiconductor, the acceptor level lies close to and above the valence band. A valence electron can gain thermal energy and occupy an acceptor state at  $E_A$ , leaving a mobile hole in the valence band. The upward arrow in the right diagram represents this excitation; holes are the majority carriers. The diagrams are schematic and do not imply complete impurity ionisation at every positive temperature.



Energy bands at  $T > 0\text{ K}$ . Solid dots denote electrons and the open circle denotes a hole; upward arrows show thermal electron excitation.

**Step 3: Conclusion** The required diagrams show  $E_D$  just below the conduction band for n-type material and  $E_A$  just above the valence band for p-type material, with thermal electron transitions indicated.

**Quick Tip to Solve:** Remember: donors supply electrons to the nearby conduction band; acceptors take electrons from the nearby valence band.

**21. 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 has finite power-handling capacity. Electrical power dissipated as heat is  $P = VI$ , where  $V$  is the voltage across the diode and  $I$  its current.
- The conductivity of a semiconductor is  $\sigma = e(n\mu_e + p\mu_h)$ , where  $n, p$  are the electron and hole concentrations and  $\mu_e, \mu_h$  their mobilities. Doping controls the carrier concentrations.

**Step 1: Explain damage due to a strong current** (i) An excessive current produces too much heat in the junction and its resistive regions. If the heat is generated faster than it can be removed, the junction temperature exceeds its safe limit. This overheating can permanently damage the junction and contacts, destroying the diode's rectifying action. Thus current must be limited to the device's safe operating value; it is excessive power dissipation and the resulting temperature rise that cause the damage.

**Step 2: Explain why impurities are added** (ii) A pure or intrinsic semiconductor has relatively few thermally generated charge carriers and hence low conductivity at ordinary temperatures. Adding a small controlled amount of a suitable impurity increases the concentration of free carriers and therefore increases conductivity. Pentavalent donors produce an n-type semiconductor with electrons

as majority carriers; trivalent acceptors produce a p-type semiconductor with holes as majority carriers. This process, called doping, makes the conductivity and carrier type suitable for electronic devices.

**Step 3: Conclusion** (i) A strong current damages a diode through excessive heating. (ii) Suitable impurities are added to increase and control carrier concentration, and hence the semiconductor's conductivity.

**Quick Tip to Solve:** Link diode damage to heat and temperature rise; link doping to extra mobile electrons or holes, not to extra energy alone.

**22(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 emitted strongly by hot bodies through the vibrational motion of their atoms and molecules.
- Absorbed radiation transfers energy to matter. Infrared absorption increases molecular agitation and therefore produces a heating effect.

**Step 1: State how infrared waves are produced** Infrared waves are produced by hot bodies and by vibrating molecules. For example, a heated filament or an electric heater emits infrared radiation as part of its thermal emission. They do not require a material medium to travel.

**Step 2: Explain the name heat waves** Water molecules present in many materials readily absorb infrared radiation. The absorbed energy increases thermal motion and raises the temperature of the absorbing material; hence infrared waves are commonly called heat waves.

**Step 3: Give two uses** They are used in infrared lamps for physiotherapy, where their heating effect warms tissues. They are also used in television remote controls, which transmit coded signals using infrared radiation.

**Step 4: Conclusion** Hot bodies and vibrating molecules produce infrared waves. Their absorption causes heating; two uses are physiotherapy heat lamps and television remote controls.

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

OR

**22(b). How are X-rays produced? Give any two uses of these.** [2 marks]

**Solution:**

**Concept:**

- An accelerated or decelerated electric charge radiates electromagnetic energy. Very rapid deceleration of energetic electrons can produce X-rays.
- X-rays penetrate matter, but different materials absorb them by different amounts. Their short wavelength also makes crystal diffraction possible.

**Step 1: Describe the production of X-rays** Electrons emitted from a heated cathode are accelerated through a large potential difference towards a heavy metal target, such as tungsten. When the high-speed electrons strike the target, they are rapidly decelerated and part of their kinetic energy is emitted as X-rays. Most of the remaining energy heats the target.

**Step 2: State two applications** First, X-rays are used in medical radiography to detect bone fractures. Bones absorb them more strongly than soft tissues, so the transmitted radiation produces an image with contrast. Second, X-ray diffraction is used to determine crystal structures: the regular arrangement of atoms produces a characteristic diffraction pattern.

**Step 3: Conclusion** X-rays are produced when high-speed electrons are rapidly decelerated on striking a heavy metal target. Two uses are detecting bone fractures and determining crystal structures.

**Quick Tip to Solve:** For X-ray production, include both stages: accelerate electrons through high voltage, then rapidly stop them at a metal target.

**23. Briefly explain why and how a galvanometer is converted into an ammeter.**

[2 marks]

**Solution:**

**Concept:**

- A galvanometer is a sensitive instrument for small currents. Its resistance and limited safe current make it unsuitable for directly measuring large currents.
- Parallel branches have the same potential difference. A low shunt resistance diverts most of the current and reduces the effective resistance of the instrument.

**Step 1: Explain why conversion is needed** An ammeter must measure the required circuit current while causing very little change in it, so it must have a very low resistance. A galvanometer alone can carry only a small current; a large current may damage its coil. Its comparatively large resistance also alters the circuit current if it is connected directly in series.

**Step 2: Connect a shunt and determine its resistance** Connect a small resistance  $S$ , called a shunt, in parallel with the galvanometer. Let its coil resistance be  $G$ , its full-scale current be  $I_g$ , and the desired ammeter range be  $I$ . At full scale, the shunt carries  $I - I_g$ . Equal potential differences across the parallel branches give

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

Most of the current passes through the shunt, protecting the coil. Calibrate the scale in amperes and connect the whole combination in series with the circuit.

**Step 3: Conclusion** A galvanometer is converted into an ammeter to measure larger currents with negligible disturbance to the circuit. Connect a low resistance  $S = I_g G / (I - I_g)$  in parallel with it.

**Quick Tip to Solve:** For an ammeter, place a low shunt in parallel; equate branch voltages using coil current  $I_g$  and shunt current  $I - I_g$ .

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

[2 marks]

**Solution:**

**Concept:**

- Ionisation separates an electron completely from an isolated atom. The free electron at infinite separation and with zero kinetic energy defines the zero of energy.
- Hydrogen energy levels are  $E_n = -13.6/n^2$  eV, where  $n$  is the principal quantum number. The ground state has  $n = 1$ .

**Step 1: Define ionisation energy** Ionisation energy is the minimum energy required to remove the most loosely bound electron completely from an isolated gaseous atom in its ground state. The electron is taken to infinite separation with no remaining kinetic energy, so the atom becomes a positive ion.

**Step 2: Calculate the value for hydrogen** For a ground-state hydrogen atom,  $E_1 = -13.6$  eV. Complete removal places the electron at the ionisation limit,  $n \rightarrow \infty$ , where  $E_\infty = 0$ . The required energy is therefore

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

Using  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ , this is

$$E_{\text{ion}} = 13.6 \times 1.6 \times 10^{-19} = 2.176 \times 10^{-18} \text{ J}.$$

The positive sign indicates that energy must be supplied to overcome the electron's binding.

**Step 3: Conclusion** Ionisation energy is the minimum energy needed to remove an electron completely from an isolated gaseous ground-state atom. For hydrogen it is 13.6 eV, or  $2.176 \times 10^{-18} \text{ J}$  per atom.

**Quick Tip to Solve:** Hydrogen's ground-state energy is negative, but its ionisation energy is the positive difference  $0 - E_1$ .

OR

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

[2 marks]

**Solution:**

**Concept:**

- A bound nucleus has less mass than the sum of its separate, free protons and neutrons. This mass difference is the mass defect.
- Mass and energy are related by  $E = mc^2$ . The mass defect corresponds to nuclear binding energy; binding energy per nucleon measures the average strength of binding.

**Step 1: Define mass defect mathematically** For a nucleus with atomic number  $Z$ , mass number  $A$ , and nuclear mass  $M$ , the mass defect is

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

where  $m_p$  and  $m_n$  are the masses of a free proton and a free neutron. Thus it is the excess of the total mass of the separate constituent nucleons over the actual mass of the bound nucleus.

**Step 2: Relate the defect to nuclear stability** The energy released when the nucleons bind together is

$B = \Delta mc^2$ , where  $c$  is the speed of light. The same energy must be supplied to separate the nucleus completely into free nucleons. To compare nuclei of different sizes, use

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

A larger binding energy per nucleon generally means stronger average binding and greater nuclear stability. Total mass defect alone does not give a fair comparison between nuclei with different numbers of nucleons.

**Step 3: Conclusion** Mass defect is  $\Delta m = Zm_p + (A - Z)m_n - M$ . It gives the binding energy  $B = \Delta mc^2$ ; greater binding energy per nucleon generally indicates greater nuclear stability.

**Quick Tip to Solve:** Use nuclear mass with proton and neutron masses in the defect formula; compare stability through binding energy per nucleon, not total binding energy.

**25.** A point object in air is placed symmetrically at a distance of 60 cm in front of a concave spherical surface of refractive index 1.5. If the radius of curvature of the surface is 20 cm, find the position of the image formed. [2 marks]

**Solution:**

**Concept:**

- For paraxial refraction from a medium of index  $n_1$  into one of index  $n_2$ ,  $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$ , where all distances are measured from the pole.
- With incident light travelling to the right, distances to the left are negative. A surface concave towards the object has its centre of curvature on the object's side.

**Step 1: Apply the Cartesian sign convention** The object is in air on the incident side, and light enters the medium of refractive index 1.5. Since the surface is concave towards the object, both the object and centre of curvature lie to the left of the pole. Thus

$$n_1 = 1, \quad n_2 = 1.5, \quad u = -60 \text{ cm}, \quad R = -20 \text{ cm}.$$

**Step 2: Substitute into the refraction formula** Using centimetres consistently throughout,

$$\begin{aligned} \frac{1.5}{v} - \frac{1}{-60} &= \frac{1.5 - 1}{-20}, \\ \frac{1.5}{v} + \frac{1}{60} &= -\frac{1}{40}, \\ \frac{1.5}{v} &= -\frac{1}{40} - \frac{1}{60} = -\frac{1}{24}. \end{aligned}$$

The negative value of  $v$  means that the refracted rays diverge; their backward extensions meet on the incident side of the surface.

**Step 3: Conclusion**  $v = -36$  cm. A virtual image forms 36 cm in front of the surface, on the same side as the object.

**Quick Tip to Solve:** For a concave refracting surface facing the object, use a negative radius as well as a negative object distance before substituting.

### Section C (15 marks)

**26.** A series RL circuit with  $R = 10\ \Omega$  and  $L = \left(\frac{100}{\pi}\right)$  mH is connected to an ac source of voltage  $V = 141 \sin(100\pi t)$ , where  $V$  is in volts and  $t$  is in seconds. Calculate

- (a) impedance of the circuit  
(b) phase angle, and  
(c) voltage drop across the inductor.

[3 marks]

#### Solution:

##### Concept:

- The inductive reactance is  $X_L = \omega L$ ; the magnitude of the impedance of a series RL circuit is  $Z = \sqrt{R^2 + X_L^2}$ .
- The current lags the applied voltage by  $\phi$ , where  $\tan \phi = X_L/R$ . The resistor and inductor voltages are perpendicular phasors.
- For a sinusoidal voltage of peak value  $V_0$ ,  $V_{\text{rms}} = V_0/\sqrt{2}$ . The rms inductor voltage is  $V_{L,\text{rms}} = I_{\text{rms}}X_L$ .

**Step 1: Convert the inductance and identify angular frequency** Comparing the source with  $V = V_0 \sin \omega t$  gives  $V_0 = 141\text{ V}$  and  $\omega = 100\pi\text{ rad s}^{-1}$ . Convert millihenries to henries before calculating reactance:

$$L = \frac{100}{\pi} \times 10^{-3} = \frac{0.1}{\pi}\text{ H}, \quad X_L = (100\pi) \frac{0.1}{\pi} = 10\ \Omega.$$

**Step 2: Calculate impedance and phase angle** (a) The resistance and reactance contribute in quadrature, so

$$Z = \sqrt{10^2 + 10^2} = 10\sqrt{2}\ \Omega \simeq 14.14\ \Omega.$$

(b) Since the inductive reactance equals the resistance,

$$\tan \phi = \frac{X_L}{R} = 1, \quad \phi = 45^\circ = \frac{\pi}{4}.$$

This is an inductive circuit: the current lags the source voltage by this angle, while the source voltage leads the current.

**Step 3: Calculate the inductor voltage** (c) The given coefficient 141 is a peak voltage, so the rms current and inductor voltage are

$$I_{\text{rms}} = \frac{141/\sqrt{2}}{10\sqrt{2}} = 7.05\text{ A},$$
$$V_{L,\text{rms}} = 7.05 \times 10 = 70.5\text{ V}.$$

For completeness, its peak voltage is  $V_{L,0} = 70.5\sqrt{2} \simeq 99.70\text{ V}$ . Since the inductor voltage leads the

current by  $\pi/2$ , its instantaneous voltage is

$$v_L(t) = \frac{141}{\sqrt{2}} \sin \left( 100\pi t + \frac{\pi}{4} \right) \text{ V.}$$

**Step 4: Conclusion** (a)  $Z = 10\sqrt{2} \Omega$ . (b) Current lags the supply by  $45^\circ$ . (c) The inductor voltage is 70.5 V rms, or 99.70 V peak.

**Quick Tip to Solve:** When  $X_L = R$ , the phase lag is  $45^\circ$  and each component's rms voltage is the supply rms voltage divided by  $\sqrt{2}$ .

**27. A ray of light is incident on a glass prism of refractive index  $\mu$  and refracting angle  $A$ . If it just suffers total internal reflection at the other face, obtain a relation between the angle of incidence, angle of prism and critical angle.** [3 marks]

**Solution:**

**Concept:**

- If  $r_1$  and  $r_2$  are the internal angles of the ray with the normals at the two faces of a prism, its geometry gives  $r_1 + r_2 = A$ , where  $A$  is the prism angle.
- At the air-to-glass face, Snell's law gives  $\sin i = \mu \sin r_1$ , where  $i$  is the external incidence angle and  $\mu$  is the refractive index of glass relative to air.
- At a glass-to-air boundary, the critical angle  $C$  satisfies  $\mu \sin C = 1$ . Total internal reflection occurs for internal incidence greater than  $C$ .

**Step 1: Apply the limiting condition at the second face** The phrase “just suffers total internal reflection” refers to the threshold of total internal reflection. At this limiting condition the angle of incidence at the second face equals the critical angle:

$$r_2 = C.$$

Strictly at equality the refracted ray grazes the surface; an infinitesimal increase in  $r_2$  produces total internal reflection. This is why the equality, rather than a strict inequality, is used to obtain the requested limiting relation.

**Step 2: Use prism geometry and Snell's law** The internal angles satisfy  $r_1 + r_2 = A$ . Substituting the critical condition gives

$$r_1 = A - C.$$

Applying Snell's law at the first face then gives

$$\sin i = \mu \sin(A - C).$$

All these angles are measured from the respective surface normals. Angles measured from the faces themselves must not be inserted into Snell's law.

**Step 3: Eliminate the refractive index** For the same glass and air at the second face, Snell's law at

grazing emergence gives

$$\mu \sin C = \sin 90^\circ = 1, \quad \mu = \frac{1}{\sin C}.$$

Inserting this value removes the material parameter and leaves a relation involving only the incidence angle, prism angle and critical angle.

**Step 4: Conclusion** The required limiting relation is

$$\sin i = \frac{\sin(A - C)}{\sin C}, \quad \text{or} \quad \sin i \sin C = \sin(A - C).$$

**Quick Tip to Solve:** Start from the second face: put its internal incidence equal to  $C$ , use  $r_1 = A - C$ , and only then apply Snell's law at entry.

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

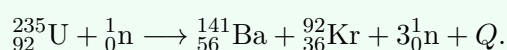
**(ii) Explain the release of energy in nuclear fission and fusion on the basis of binding energy per nucleon curve.** [3 marks]

**Solution:**

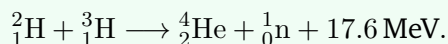
**Concept:**

- Binding energy  $B$  is the energy needed to separate a nucleus into its nucleons. Larger binding energy per nucleon  $B/A$  generally indicates a more tightly bound, stable nucleus.
- Energy released in a nuclear reaction is  $Q = (m_{\text{initial}} - m_{\text{final}})c^2$ , equivalently the increase in total binding energy of the products over the reactants.
- The binding energy per nucleon curve rises steeply for light nuclei, reaches its maximum near iron and nickel ( $A \simeq 56-62$ ), and decreases slowly towards very heavy nuclei.

**Step 1: Distinguish the processes and give examples** (i) In **nuclear fission**, a heavy nucleus splits into two medium-mass nuclei, usually releasing neutrons and energy. A neutron-induced example is



In **nuclear fusion**, two light nuclei combine to form a heavier nucleus, with energy release. An example is



Both equations conserve nucleon number and electric charge. Fission can be initiated by absorption of a neutron; ordinary thermonuclear fusion requires very high temperature so that light nuclei can approach closely despite their electrostatic repulsion.

**Step 2: Explain fission using the binding energy curve** (ii) Heavy nuclei such as uranium lie on the slowly descending side of the curve, with binding energy per nucleon near 7.6 MeV. Their medium-mass fission products lie closer to the peak and typically have about 8.4 MeV per nucleon. The products therefore have greater total binding energy and a smaller total rest mass. This increase in binding accounts for the released energy, mainly carried initially as kinetic energy of the fragments and emitted neutrons.

**Step 3: Explain fusion using the binding energy curve** Light nuclei lie on the rising left-hand portion of the curve. When suitable light nuclei fuse, the product nucleus has a larger binding energy per

nucleon. For example, helium is more tightly bound per nucleon than deuterium or tritium. The final total binding energy is greater, so the final rest mass is smaller; the mass difference appears as kinetic energy of the reaction products. Thus both reactions move the nuclear system towards more tightly bound configurations, although one splits nuclei and the other combines them.

**Step 4: Conclusion** Fission splits heavy nuclei; fusion joins light nuclei. Both release energy when the products have greater total binding energy than the reactants:  $Q = \Delta B = \Delta mc^2 > 0$ .

**Quick Tip to Solve:** Locate the reactants on the binding energy per nucleon curve: heavy nuclei release energy by splitting towards its peak, while light nuclei can release energy by combining towards it.

OR

**28(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 sizes are determined from scattering experiments: energetic probe particles resolve the very small region occupied by the nucleus.
- The empirical radius law is  $R = R_0 A^{1/3}$ , where  $A$  is the mass number and  $R_0 \simeq 1.2 \times 10^{-15} \text{ m}$ .
- Nuclear density is mass divided by volume. Approximate the nuclear mass by  $M = Am_N$ , where  $m_N \simeq 1.67 \times 10^{-27} \text{ kg}$  is the mass of one nucleon.

**Step 1: (i) Describe the experimental method** Nuclear size is found by studying the scattering of energetic particles by nuclei, for example high-energy electrons. The measured angular distribution depends on the nuclear charge distribution; analysis of the scattering determines its spatial extent and hence the nuclear radius. Alpha-particle scattering also probes the nucleus and gives an estimate or bound on its size through the distance of closest approach.

**Step 2: State the measured radius relation** Measurements for different nuclei give the approximate empirical relation

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

Thus nuclear volume is proportional to mass number, although the radius increases only as the cube root of mass number.

**Step 3: (ii) Substitute the mass and volume into density** Treating the nucleus as approximately spherical, its volume and density are

$$\begin{aligned} V &= \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A, \\ \rho &= \frac{Am_N}{(4/3)\pi R_0^3 A} = \frac{3m_N}{4\pi R_0^3}. \end{aligned}$$

The factor  $A$  cancels because both nuclear mass and nuclear volume increase in direct proportion to the number of nucleons. Substituting the stated constants gives  $\rho \simeq 2.3 \times 10^{17} \text{ kg m}^{-3}$ ; small differences due to binding energies are neglected in this model.

**Step 4: Conclusion** Nuclear scattering experiments give  $R = R_0 A^{1/3}$ . Hence  $\rho = 3m_N/(4\pi R_0^3)$ , so

nuclear density is approximately independent of mass number.

**Quick Tip to Solve:** Cube the radius law before calculating density: the resulting factor of  $A$  cancels the factor of  $A$  in nuclear mass.

**29. Two cells of emf  $E_1$  and  $E_2$  and internal resistances  $r_1$  and  $r_2$  are connected in parallel, with their terminals of the same polarity connected together. Obtain an expression for the equivalent emf of the combination.** [3 marks]

**Solution:**

**Concept:**

- Parallel branches have the same terminal potential difference  $V$ . For a cell delivering signed current  $I_j$ , its terminal voltage is  $V = E_j - I_j r_j$ .
- The equivalent emf is the open-circuit terminal voltage. For an equivalent cell,  $V = E_{\text{eq}} - I r_{\text{eq}}$ , where  $I$  is the total current supplied externally.

**Step 1: Express the branch currents** Let  $I_1$  and  $I_2$  be positive when the respective cells supply current out of their common positive terminal. Since terminals of the same polarity are joined, both branches have terminal voltage  $V$ . Applying the terminal-voltage relation separately gives

$$I_1 = \frac{E_1 - V}{r_1}, \quad I_2 = \frac{E_2 - V}{r_2}.$$

A negative branch current simply means that the other cell drives current into that cell; it does not invalidate these signed equations.

**Step 2: Apply the junction rule and rearrange** The current delivered to an external circuit is  $I = I_1 + I_2$ . Therefore

$$I = \frac{E_1}{r_1} + \frac{E_2}{r_2} - V \left( \frac{1}{r_1} + \frac{1}{r_2} \right),$$
$$V = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} - I \frac{r_1 r_2}{r_1 + r_2}.$$

Comparing with  $V = E_{\text{eq}} - I r_{\text{eq}}$  identifies the constant term as the emf and the coefficient of  $I$  as the equivalent internal resistance.

**Step 3: Check the open-circuit interpretation** With no external load,  $I = 0$ , so the equivalent emf equals the terminal voltage found above. If  $E_1 \neq E_2$ , an internal circulating current can still flow between the cells, even though no current is supplied outside. When  $r_1 = r_2$ , the expression becomes  $(E_1 + E_2)/2$ ; when both emfs are equal to  $E$ , it gives  $E$ , as expected.

**Step 4: Conclusion** The equivalent emf for like terminals connected in parallel is

$$E_{\text{eq}} = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} = \frac{E_1/r_1 + E_2/r_2}{1/r_1 + 1/r_2}.$$

The corresponding internal resistance is  $r_{\text{eq}} = r_1 r_2 / (r_1 + r_2)$ .

**Quick Tip to Solve:** Weight each emf by its conductance  $1/r$ ; a cell with smaller internal resistance has more influence on the parallel combination's emf.

**30(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 wire attain the same electrostatic potential: otherwise a potential difference would continue to drive charge through the wire.
- For a spherical conductor of radius  $R$  carrying charge  $Q$ ,  $V = kQ/R$  and the field immediately outside the surface is  $E = kQ/R^2$ , where  $k = 1/(4\pi\epsilon_0)$ .

**Step 1: Apply equality of potentials** Let the final charges on the spheres of radii  $a$  and  $b$  be  $Q_a$  and  $Q_b$ . Use the standard spherical-conductor approximation: the spheres are sufficiently far apart that mutual distortion of their surface-charge distributions and the wire's contribution can be neglected. At electrostatic equilibrium their potentials are equal, so

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

Cancelling the common electrostatic constant gives  $Q_a/Q_b = a/b$ . The larger sphere therefore receives a proportionately larger charge, rather than both spheres necessarily receiving equal charge.

**Step 2: Divide the surface-field expressions** The electric fields are evaluated immediately outside the spherical surfaces; the field inside either conductor is zero. Their magnitudes are

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

Dividing and using the ratio of the final charges yields

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

Equivalently, eliminating charge gives  $E = |V|/R$ : equal potential produces a greater surface field on the smaller sphere.

**Step 3: Conclusion** The surface-field ratio in the order of radii  $a$  and  $b$  is

$$E_a : E_b = b : a.$$

This ratio assumes a nonzero common potential; if the combined charge is zero in the stated approximation, both final fields vanish.

**Quick Tip to Solve:** After joining spherical conductors, equate their potentials first; then use  $E = |V|/R$  to get the inverse-radius field ratio directly.

**30(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.
- Once the battery is removed, charge on each isolated connected group of plates is conserved. Capacitors connected in parallel eventually share a common voltage.

**Step 1: Find the initial charge and energy** Initially capacitor A carries charge at voltage  $V$ , while B is uncharged. The initial plate-charge magnitude and stored energy are

$$Q_0 = CV, \quad U_i = \frac{1}{2}CV^2.$$

The disconnected battery cannot maintain the original voltage during redistribution.

**Step 2: (i) Determine the common voltage and final charges** Write the common final voltage as  $V_f$ . The total parallel capacitance is  $C + 2C = 3C$ . Conservation of charge on the connected positive plates gives

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

The magnitudes of the final charges on the two capacitors are therefore

$$Q_A = CV_f = \frac{CV}{3}, \quad Q_B = 2CV_f = \frac{2CV}{3}.$$

Hence  $Q_A/Q_B = 1/2$ . These are plate-charge magnitudes; opposite plates carry opposite signs.

**Step 3: (ii) Calculate the final total energy** Add the energies of the capacitors at their common final voltage:

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

Electrostatic energy is not conserved during charge sharing: the difference  $U_i - U_f = CV^2/3$  leaves the electric field, being dissipated in the connecting circuit and possibly radiated during the transient.

**Step 4: Conclusion** The required ratios are  $Q_A : Q_B = 1 : 2$  and  $U_f : U_i = 1 : 3$ , with common final voltage  $V_f = V/3$ .

**Quick Tip to Solve:** After removing the battery, conserve charge first. Use the new total capacitance to find the reduced voltage before calculating either charge or energy.

## Section D (15 marks)

**31(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.

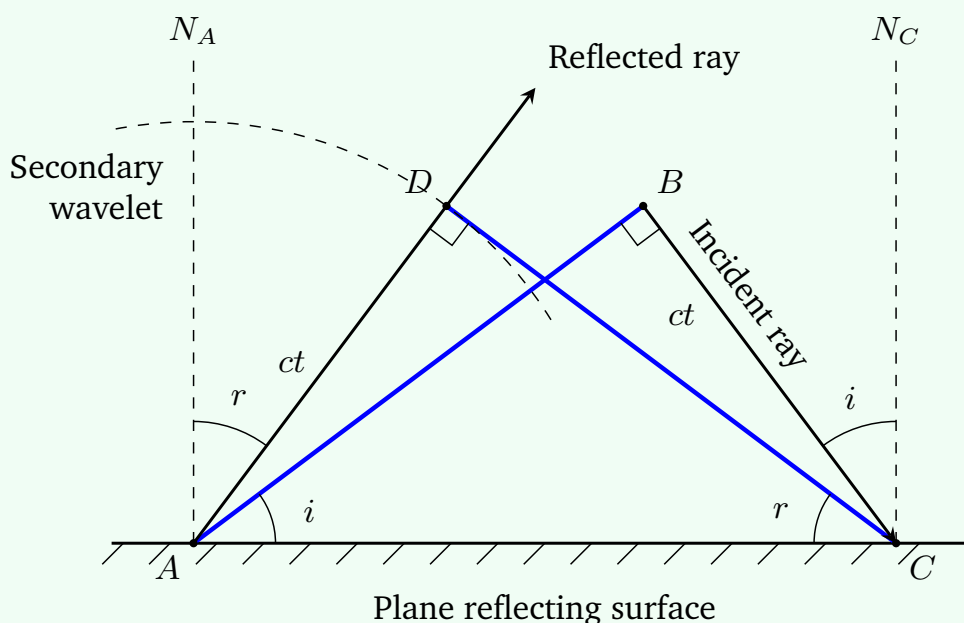
(ii) A concave mirror of focal length 12 cm forms a three times magnified virtual image of an object. Find the distance of the object from the mirror. [5 marks]

**Solution:**

**Concept:**

- Huygens' principle: each point of a wavefront acts as a source of secondary wavelets, which spread with the wave speed in the medium. The forward envelope of these wavelets at a later instant gives the new wavefront.
- A ray is normal to its wavefront. During reflection the incident and reflected waves travel in the same medium, so their speeds are equal.
- For a spherical mirror,  $1/f = 1/v + 1/u$  and transverse magnification  $m = -v/u$ , where  $u$ ,  $v$  and  $f$  are signed object distance, image distance and focal length.

**Step 1: (i) Construct the reflected wavefront** Let  $AB$  be a plane incident wavefront meeting a plane reflecting surface  $AC$  first at  $A$ . The incident ray from  $B$  reaches  $C$  after time  $t$ . If the wave speed is  $c$ , then  $BC = ct$ . In the same time the secondary reflected wavelet from  $A$  grows to radius  $AD = ct$ . Draw the tangent  $CD$  from  $C$  to this wavelet. It is the common envelope of the reflected secondary wavelets from the surface and therefore represents the reflected plane wavefront. The reflected ray  $AD$  is perpendicular to  $CD$ .



*Huygens construction:  $AB$  is incident,  $CD$  is reflected, and  $BC = AD = ct$ .*

**Step 2: Verify the law of reflection geometrically** Since rays are perpendicular to their wavefronts,  $AB \perp BC$  and  $AD \perp DC$ . Thus  $ABC$  and  $ADC$  are right triangles with the same hypotenuse  $AC$  and equal sides  $BC = AD = ct$ . If  $i$  and  $r$  are the angles of the incident and reflected rays with the normal, they also equal the angles of the corresponding wavefronts with the reflecting surface. Consequently,

$$\sin i = \frac{BC}{AC} = \frac{ct}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{ct}{AC}.$$

Equality of these sines for angles between  $0^\circ$  and  $90^\circ$  establishes equality of the two angles. The construction is in the plane containing the incident ray and the surface normal; the reflected ray is in this same plane. Thus both laws of reflection follow.

**Step 3: (ii) Apply the magnification and mirror formulae** Choose the Cartesian sign convention with incident light travelling towards the mirror. A concave mirror has  $f = -12$  cm. Its virtual image is erect, so the given threefold magnification is  $m = +3$ . Therefore,

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

Substitute this relation in 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, placing the virtual image behind the mirror. The object lies between the pole and focus, as required for an erect magnified virtual image in a concave mirror.

**Step 4: Conclusion** The 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:** In the wavefront proof, compare equal distances travelled in the same time. For a virtual mirror image, use positive magnification before substituting into the mirror formula.

OR

**31(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]

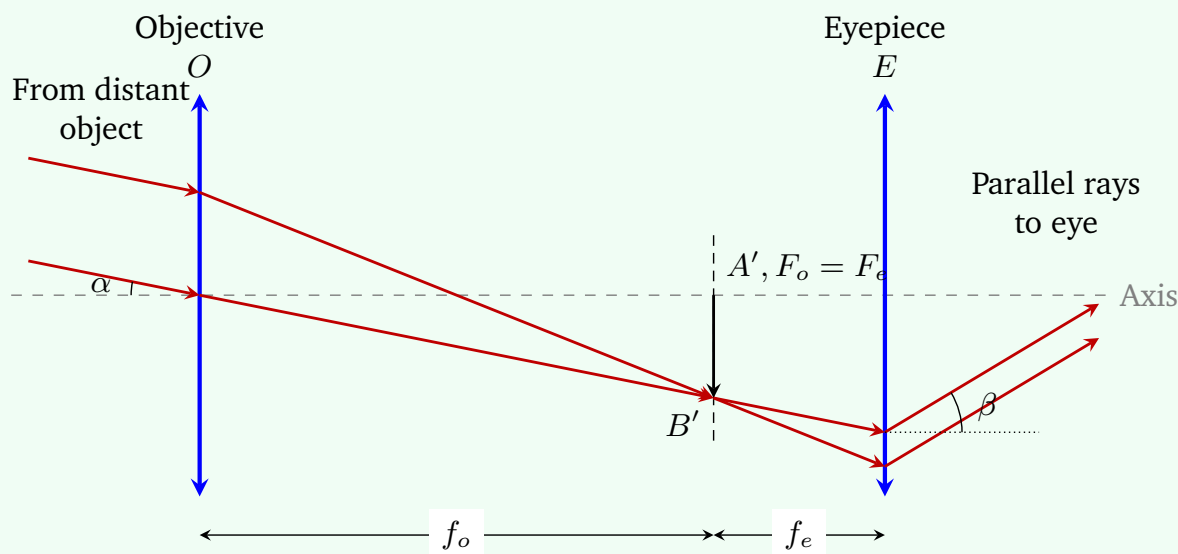
**Solution:**

**Concept:**

- A refracting astronomical telescope has a large-aperture objective of focal length  $f_o$  and a short-focal-length eyepiece of focal length  $f_e$ . In normal adjustment their focal planes coincide and the final image is at infinity.
- Angular magnifying power is  $M = \beta/\alpha$ , where  $\beta$  is the angle subtended at the eye by the final image and  $\alpha$  is the angle subtended by the distant object at the unaided eye. For a telescope in normal adjustment,  $M = -f_o/f_e$ .
- For a compound microscope in normal adjustment, the standard tube-length approximation gives  $|M| \simeq (L/f_o)(D/f_e)$ , where  $L$  is the effective tube length and  $D = 25$  cm is the least distance of distinct vision.

**Step 1: (i) Trace the rays through the telescope** Choose normal adjustment. Parallel rays from a distant off-axis object enter the objective and converge to a real, inverted and diminished intermediate image  $A'B'$  in its focal plane. Place the eyepiece so that this same plane is its first focal plane:  $F_o = F_e$ . The eyepiece receives rays diverging from  $B'$  and makes them parallel again. Thus the eye sees an

enlarged angular image at infinity, inverted relative to the object. The objective-eyepiece separation is  $f_o + f_e$ . In the ray diagram, both incoming rays are parallel to one another and both emerging rays are parallel to one another.



*Refracting telescope in normal adjustment; the objective forms  $A'B'$  in the common focal plane and the eyepiece gives parallel emergent rays.*

**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 at the unaided eye. If the intermediate image has height  $h$ , the small-angle approximation gives

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

The signed magnifying power is  $M = -f_o/f_e$ ; the negative sign expresses inversion. A long-focal-length objective and a short-focal-length eyepiece therefore provide large angular magnification.

**Step 3: (i) State two limitations relative to a reflecting telescope** First, a refracting objective suffers from chromatic aberration: different wavelengths have different focal lengths, giving coloured fringes and imperfect focus. A reflecting objective focuses by reflection, whose law is independent of wavelength, and therefore does not produce chromatic aberration.

Second, making and supporting a very large objective lens is difficult. A lens must transmit light and can be supported mainly at its rim; a large lens is heavy and may sag. A reflecting telescope's primary mirror can be supported from behind, making a much larger aperture practical. Such an aperture collects more light and gives better resolving power.

**Step 4: (ii) Substitute the microscope data** The problem does not specify the final-image position. Using the usual normal-adjustment convention and the standard microscope tube-length approximation, take  $f_o = 1.0$  cm,  $f_e = 2.5$  cm,  $|M| = 300$  and  $D = 25$  cm. The eyepiece magnification is  $D/f_e = 25/2.5 = 10$ ; the objective must therefore supply magnification  $300/10 = 30$ . Rearranging the microscope formula gives

$$\begin{aligned} L &\simeq \frac{|M|f_of_e}{D} \\ &= \frac{300 \times (1.0 \text{ cm}) \times (2.5 \text{ cm})}{25 \text{ cm}}. \end{aligned}$$

This formula refers to the effective tube length used in the standard CBSE approximation. If instead

the final image were explicitly required at the near point, the eyepiece factor would be  $1 + D/f_e = 11$ , giving  $L \simeq 300/11 \text{ cm} \simeq 27.3 \text{ cm}$ . The viewing condition must therefore accompany a numerical tube length.

**Step 5: Conclusion** The refracting telescope in normal adjustment has signed magnifying power  $M = -f_o/f_e$  and forms an inverted final image at infinity. Its limitations include chromatic aberration and the difficulty of constructing a large objective lens. For the microscope, assuming normal adjustment, the required effective tube length is  $L \simeq 30 \text{ cm}$ .

**Quick Tip to Solve:** Keep the two instruments separate: telescope magnification is  $f_o/f_e$ , whereas microscope magnification is objective magnification multiplied by the eyepiece factor. State infinity or near point before selecting that factor.

**32(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  $\lambda$ .

(ii) An infinitely long positively charged straight wire has a linear charge density  $\lambda$ . 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  $\lambda$  on the wire.

(iii) Draw a graph of kinetic energy as a function of linear charge density  $\lambda$ .

[5 marks]

**Solution:**

**Concept:**

- Gauss' law states that  $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$ , where  $Q_{\text{enc}}$  is the enclosed charge and  $\epsilon_0$  is the permittivity of free space.
- An infinite uniformly charged wire has cylindrical symmetry: the electric field is radial, and its magnitude depends only on the perpendicular distance  $r$  from the wire. The linear charge density is charge per unit length,  $\lambda = Q/\ell$ .
- The electric attraction on an electron of charge magnitude  $e$  supplies the centripetal force  $m_e v^2/r$ . Its kinetic energy is  $K = \frac{1}{2} m_e v^2$ .

**Step 1: (i) Choose a cylindrical Gaussian surface** Take a closed cylinder of radius  $r$  and length  $\ell$ , coaxial with the infinitely long straight wire. The magnitude  $E(r)$  is constant on its curved surface. Here the radial field is parallel to the outward area vector for a positive wire, so its flux is  $E(r) 2\pi r \ell$ . On each circular end cap, the area vector is parallel to the wire while the field is perpendicular to it. Thus  $\vec{E} \cdot d\vec{A} = 0$  on the caps. Only the curved surface contributes to the net flux.

**Step 2: (i) Apply Gauss' law to obtain the field** The length of charged wire enclosed by the cylinder is  $\ell$ , so  $Q_{\text{enc}} = \lambda \ell$ . Taking  $\lambda > 0$  initially, Gauss' law gives

$$E(r) 2\pi r \ell = \frac{\lambda \ell}{\epsilon_0}, \quad E(r) = \frac{\lambda}{2\pi \epsilon_0 r}.$$

In vector form,  $\vec{E} = \lambda \hat{r}/(2\pi \epsilon_0 r)$ , where  $\hat{r}$  points radially away from the wire. This form also applies to

a negative signed  $\lambda$ : the field then points towards the wire. The field magnitude is  $|\lambda|/(2\pi\epsilon_0 r)$ , falling inversely with distance, and is independent of the arbitrary Gaussian length  $\ell$ .

**Step 3: (ii) Relate electric attraction to circular motion** In this part the wire is positively charged, so  $\lambda$  is positive. Let the electron's orbital radius be  $r$ , its mass be  $m_e$ , and its charge be  $-e$ , with  $e = |q_e|$ . The outward field of the wire exerts an inward force on the electron, directed towards the centre of its circular orbit. Equating its magnitude to the required centripetal force,

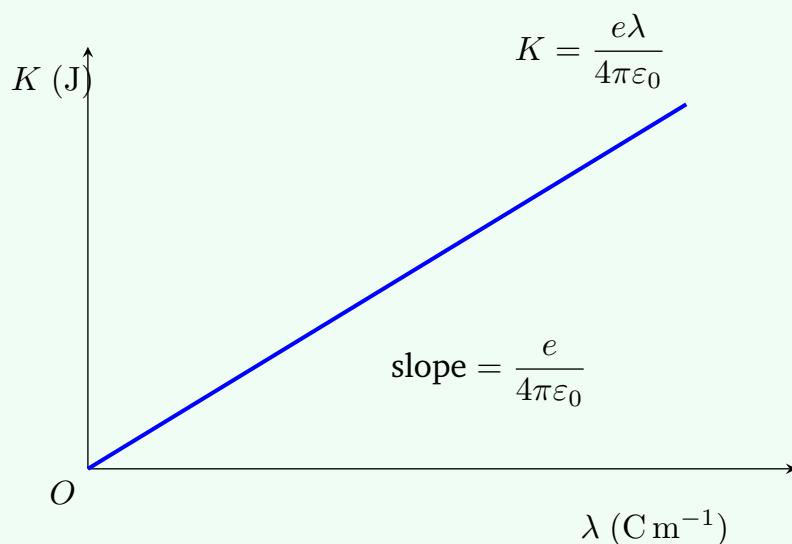
$$\begin{aligned} eE &= \frac{m_e v^2}{r}, \\ \frac{e\lambda}{2\pi\epsilon_0 r} &= \frac{m_e v^2}{r}, \\ m_e v^2 &= \frac{e\lambda}{2\pi\epsilon_0}, \\ K = \frac{1}{2}m_e v^2 &= \frac{e\lambda}{4\pi\epsilon_0}. \end{aligned}$$

The radius cancels because both the electrostatic force and the required centripetal force vary as  $1/r$  at fixed speed. Thus the kinetic energy depends on the charge magnitude and wire density, but not on the orbital radius or electron mass. Since the force is perpendicular to the instantaneous velocity, it changes the direction of motion without changing the speed.

**Step 4: (iii) Plot kinetic energy against linear charge density** Write the result as  $K = (e/4\pi\epsilon_0)\lambda$ . Therefore  $K$  is directly proportional to  $\lambda$ , with positive constant slope

$$\frac{dK}{d\lambda} = \frac{e}{4\pi\epsilon_0}.$$

The graph is a straight line through the origin in the first quadrant. The vertical axis represents kinetic energy in joules, and the horizontal axis represents positive linear charge density in coulombs per metre. The origin is the limiting value as  $\lambda$  tends to zero; a nonzero-speed bound circular orbit requires a positive charge density.



*Kinetic energy increases linearly with positive linear charge density.*

**Step 5: Conclusion** (i)  $\vec{E} = \frac{\lambda}{2\pi\epsilon_0 r} \hat{r}$ , radially outward for a positive wire. (ii) The electron has kinetic energy  $K = \frac{e\lambda}{4\pi\epsilon_0}$ , where  $e = |q_e|$ . (iii) The  $K$ -versus- $\lambda$  graph is a straight line through the origin with slope  $e/(4\pi\epsilon_0)$ .

**Quick Tip to Solve:** For a charged-wire orbit, equate  $eE$  to  $m_e v^2 / r$  before calculating energy: the radius cancels immediately, and dividing the resulting  $m_e v^2$  by two gives  $K$ .

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

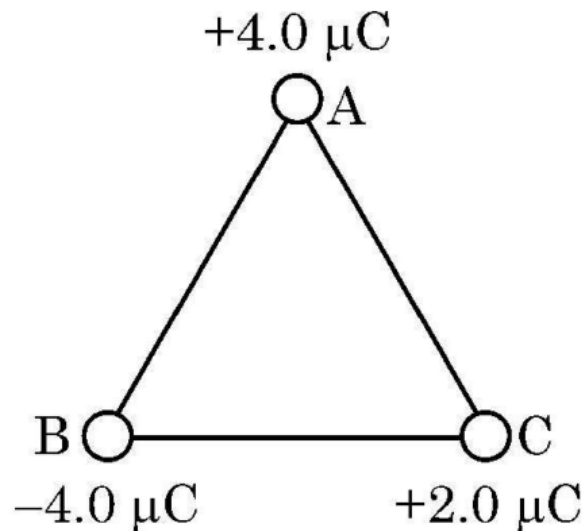
(1) Is there a point on the line joining them at which the electric field is zero?

(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 is a vector and obeys superposition. For a point charge  $q$ , its magnitude is  $k|q|/r^2$ , where  $k = 1/(4\pi\epsilon_0)$  and  $r$  is the distance from the charge.
- Potential is a scalar:  $V = \sum_i kq_i/r_i$ , with its zero chosen at infinity. Equal signed contributions to potential add even when the corresponding field vectors cancel.
- The potential energy of distinct point charges is the sum over pairs,  $U = \sum_{i < j} kq_iq_j/r_{ij}$ , taking the energy of infinitely separated charges to be zero.

**Step 1: (i)(1) Locate the point where the fields cancel** Write each identical nonzero charge as  $q$ , and let a point between them have coordinates  $(x, 0)$ , where  $0 < x < a$ . The two field vectors there have opposite directions. Their magnitudes are equal when

$$\frac{k|q|}{x^2} = \frac{k|q|}{(a-x)^2} \Rightarrow x = a - x = \frac{a}{2}.$$

Thus the midpoint  $(a/2, 0)$  has zero net field. This holds for either sign of the identical charges. Outside the segment joining them the two fields point in the same direction, so they cannot cancel at any finite point. The field at either charge itself is undefined.

**Step 2: (i)(2) Examine the potential along the line** At a finite point  $(x, 0)$  different from the charge positions, the potential is

$$V(x) = kq \left( \frac{1}{|x|} + \frac{1}{|x-a|} \right).$$

Both distances are positive, and both contributions have the same sign as  $q$ . Therefore there is no finite point on the line at which the potential is zero. In particular, the zero-field midpoint has  $V = 4kq/a$ , which is nonzero. With the usual reference, potential tends to zero only at infinity; a zero electric field does not imply a zero potential.

**Step 3: (ii) Interpret a negative potential energy** Negative electrostatic potential energy means that the configuration has lower energy than the state in which all the charges are infinitely separated. A net amount of energy  $-U$  must be supplied by an external agent to separate the charges quasistatically to infinity. Equivalently, the electric field does positive net work during assembly from infinity, and the external work during assembly is negative. This is the energetic sense in which the configuration is bound relative to separated charges; it does not by itself establish mechanical equilibrium of freely moving charges.

**Step 4: (ii) Add the three pair energies of the triangle** From the figure,  $q_A = +4.0 \mu\text{C}$ ,  $q_B = -4.0 \mu\text{C}$  and  $q_C = +2.0 \mu\text{C}$ . Every pair is separated by  $r = 2.0 \text{ m}$ . Count each pair once, retaining the signs of the charges:

$$\begin{aligned} U &= \frac{k}{r}(q_A q_B + q_B q_C + q_C q_A) \\ &= \frac{9 \times 10^9}{2.0} [(-16) - 8 + 8] \times 10^{-12} \text{ J} \\ &= -7.2 \times 10^{-2} \text{ J}. \end{aligned}$$

The  $BC$  attractive pair contributes  $-0.036 \text{ J}$ , while the  $CA$  repulsive pair contributes  $+0.036 \text{ J}$ ; these cancel. The remaining  $AB$  contribution is  $-0.072 \text{ J}$ .

**Step 5: Conclusion** The electric field vanishes at  $(a/2, 0)$ , while the potential has no finite zero on the line. Negative potential energy means external energy is required for complete separation to infinity. The triangular system has  $U = -7.2 \times 10^{-2} \text{ J}$ ; its separation requires  $0.072 \text{ J}$  of net external work.

**Quick Tip to Solve:** For identical charges, cancel field vectors but add potentials. In the triangle, list only the three distinct pairs and retain the sign of every charge product.

**33(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  $\left(\frac{200}{\pi}\right) \text{ Hz}$  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:**

- Self-inductance  $L$  relates the magnetic flux linkage of a coil to its current:  $N\Phi = LI$ . Faraday's law then gives the self-induced emf  $\varepsilon = -L dI/dt$  for constant  $L$ .

- For a long air-core solenoid,  $B = \mu_0 n I$ , where  $n = N/l$  is the number of turns per unit length. The approximately uniform internal field links each turn of area  $A$ .
- A real coil has resistance  $R$  and inductive reactance  $X_L = \omega L$ . Its AC impedance is  $Z = \sqrt{R^2 + X_L^2}$ , while under steady DC the inductive emf vanishes.

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

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

Equivalently, it is numerically equal to the magnitude of the emf induced when the current changes at unit rate, because  $\varepsilon = -L dI/dt$ . The negative sign expresses Lenz's law: the induced emf opposes the change in current. Its SI unit is the henry: a coil has inductance 1 H if a current changing at 1 A s<sup>-1</sup> induces an emf of magnitude 1 V.

**Step 2: (i) Derive the self-inductance of the solenoid** Assume an air or vacuum core and a solenoid sufficiently long that edge effects are negligible. Its internal magnetic field is directed along the axis and is approximately uniform:

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

The field is normal to the plane of each turn. Thus the flux through one turn is  $\Phi = BA$ , and the total flux linkage is

$$\begin{aligned} N\Phi &= NBA = \frac{\mu_0 N^2 AI}{l}, \\ L &= \frac{N\Phi}{I} = \frac{\mu_0 N^2 A}{l}. \end{aligned}$$

For a homogeneous linear material of relative permeability  $\mu_r$  filling the core, replace  $\mu_0$  by  $\mu_0 \mu_r$ . This derivation assumes essentially all the internal flux links all the turns.

**Step 3: (ii) Determine the coil resistance from DC data** After the DC current reaches its steady value,  $dI/dt = 0$ , so the inductive emf is zero. The terminal voltage then determines only the resistance:

$$R = \frac{V_{DC}}{I_{DC}} = \frac{4.0}{1.0} = 4.0 \Omega.$$

The remaining two readings give  $6.0/1.5 = 4.0 \Omega$  and  $8.0/2.0 = 4.0 \Omega$ , confirming the same value of  $R$ .

**Step 4: (ii) Find impedance and inductive reactance from AC data** For the sinusoidal AC readings, use the ratio of rms voltage to rms current:

$$Z = \frac{V_{AC}}{I_{AC}} = \frac{3.0}{0.5} = 6.0 \Omega.$$

The other readings give  $6.0/1.0 = 6.0 \Omega$  and  $9.0/1.5 = 6.0 \Omega$ . Resistive and inductive voltages differ in phase by 90°, so their contributions combine in quadrature:

$$X_L = \sqrt{Z^2 - R^2} = \sqrt{6^2 - 4^2} = \sqrt{20} \Omega.$$

**Step 5: (ii) Calculate the inductance using the frequency** Convert the supplied frequency to angular

frequency before using  $X_L = \omega L$ :

$$\begin{aligned}\omega &= 2\pi f = 2\pi \left( \frac{200}{\pi} \right) = 400 \text{ rad s}^{-1}, \\ L &= \frac{X_L}{\omega} = \frac{\sqrt{20}}{400} \text{ H} \\ &= 1.118 \times 10^{-2} \text{ H} \approx 11.2 \text{ mH}.\end{aligned}$$

The increased opposition to AC compared with DC is thus accounted for by the coil's inductive reactance, as well as its resistance.

**Step 6: Conclusion** The coefficient of self-induction is  $L = N\Phi/I$ , measured in henry. A long air-core solenoid has  $L = \mu_0 N^2 A/l$ . The given coil has  $R = 4.0 \Omega$ ,  $Z = 6.0 \Omega$ , and  $L \approx 1.12 \times 10^{-2} \text{ H} = 11.2 \text{ mH}$ .

**Quick Tip to Solve:** Obtain resistance from steady DC and impedance from AC; then use  $L = \sqrt{Z^2 - R^2}/(2\pi f)$ . Do not subtract resistance directly from impedance.

OR

**33(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.

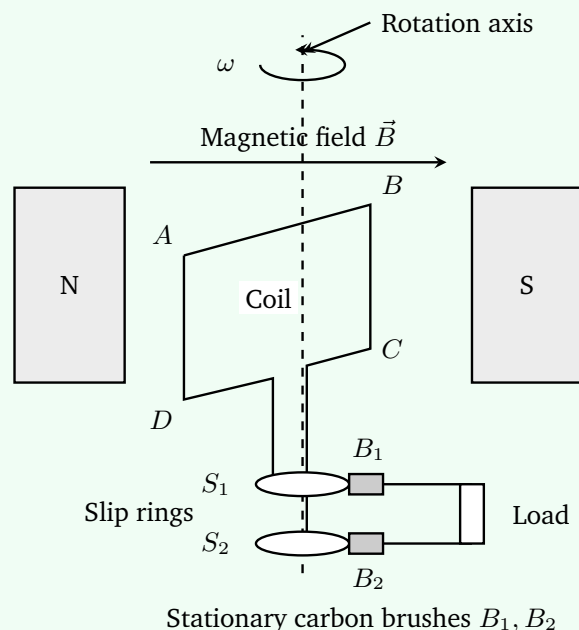
**(ii)** The coil of an ac generator consists of 100 turns of wire, each of area  $0.5 \text{ m}^2$ . The resistance of the wire is  $100 \Omega$ . The coil is rotating in a magnetic field of  $0.8 \text{ T}$  perpendicular to its axis of rotation, at a constant angular speed of  $60 \text{ radian per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

**Solution:**

**Concept:**

- An ac generator converts mechanical energy into electrical energy by electromagnetic induction. Faraday's law gives the induced emf as  $e = -d(N\Phi)/dt$ , where  $N\Phi$  is the flux linkage of the rotating coil.
- For a coil of area  $A$ , with its normal making angle  $\theta$  with a uniform magnetic field  $B$ , the flux through each turn is  $\Phi = BA \cos \theta$ .
- For a sinusoidal emf across a purely resistive closed circuit of resistance  $R$ ,  $E_{\text{rms}} = E_0/\sqrt{2}$  and average power is  $P_{\text{av}} = E_{\text{rms}}^2/R$ .

**Step 1: (i) Describe the construction and principle** A rectangular armature coil  $ABCD$ , having  $N$  turns, rotates between the north and south poles of a magnet. Its rotation axis lies in the plane of the coil and is perpendicular to the magnetic field. The two coil ends connect to separate, continuous slip rings  $S_1$  and  $S_2$ , insulated from each other and the shaft. Stationary carbon brushes  $B_1$  and  $B_2$  press against these rings and connect the coil to the external circuit. The labelled schematic below shows the connections. An external mechanical source turns the shaft; the changing magnetic flux through the coil induces an emf according to Faraday's law.



AC generator: rotating coil, separate slip rings and stationary brushes (schematic).

**Step 2: Explain how alternating emf is produced** As the coil rotates, its orientation relative to the magnetic field changes continuously, so the magnetic flux linkage changes. The induced current direction, when the circuit is closed, follows Fleming's right-hand rule. After each half-revolution, the motion of each active side relative to the field reverses, reversing the induced emf. The continuous slip rings maintain the connection of each coil end to the same brush, so the output changes polarity every half-cycle. Thus the output is alternating, with one complete cycle per revolution. Mechanical work supplied against the electromagnetic opposing torque provides the electrical energy.

**Step 3: Derive the instantaneous emf** Choose  $t = 0$  when the coil normal is parallel to the field. At constant angular speed  $\omega$ , the angle between the normal and the field is  $\theta = \omega t$ . Therefore,

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

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 coil normal is parallel to the field, since the flux is instantaneously stationary. Its magnitude is greatest when the normal is perpendicular to the field, when the flux changes most rapidly. A different choice of the initial orientation changes only the phase of the sinusoid.

**Step 4: (ii) Calculate the maximum generated emf** Here  $N = 100$ ,  $A = 0.5 \text{ m}^2$ ,  $B = 0.8 \text{ T}$ , and  $\omega = 60 \text{ rad s}^{-1}$ . Since the given speed is already angular speed, no factor of  $2\pi$  is needed:

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

With the same initial orientation, the instantaneous emf is  $e(t) = 2400 \sin(60t) \text{ V}$ , with  $t$  in seconds.

**Step 5: Calculate the power dissipated in the coil** Taking the coil as a closed purely resistive circuit of

resistance  $R = 100 \Omega$ , as intended in this numerical, its instantaneous current is  $i = e/R$ . Thus the instantaneous Joule heating is

$$p(t) = \frac{e^2(t)}{R} = 57600 \sin^2(60t) \text{ W}.$$

Since  $\langle \sin^2 \omega t \rangle = 1/2$ , the power dissipated averaged over a complete cycle is

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

The peak instantaneous power is 57.6 kW; the usual ac power rating and the requested dissipated power refer to the average value. An open coil has an emf but no Joule heating from a circuit current.

**Step 6: Conclusion** The ac generator works by electromagnetic induction and produces  $e(t) = NBA\omega \sin \omega t$ . For the given coil, the maximum emf is  $2400 \text{ V}$  and the average power dissipated is  $28.8 \text{ kW}$ , under the closed resistive-circuit assumption.

**Quick Tip to Solve:** Use  $E_0 = NBA\omega$  directly for angular speed in radian per second; use  $E_0^2/(2R)$ , not  $E_0^2/R$ , for average ac heating.

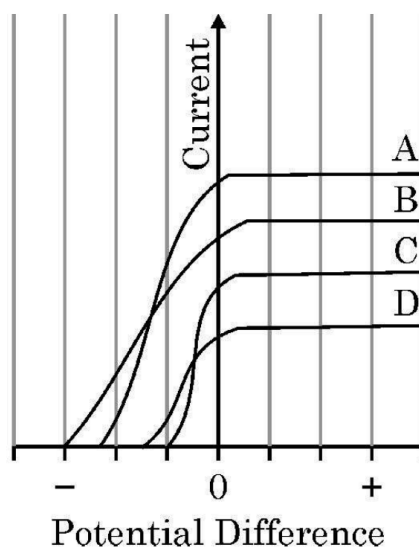
### Section E (8 marks)

**Note :** Questions number 34 and 35 are case study based questions. Read the following paragraph and answer the questions.

**34(a).** 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:

- (i) Which light beam has the highest frequency and why?
- (ii) Which light beam has the longest wavelength and why?
- (iii) 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  $\nu$  is the incident frequency,  $\phi$  is the photocathode work function,  $e$  is the magnitude of the electron charge and  $V_s$  is the positive magnitude of the stopping potential.
- The stopping potential is read from the negative-voltage intercept where the photocurrent becomes zero. For the same photocathode, a larger  $V_s$  means a larger frequency. Wavelength is related to frequency by  $\lambda = c/\nu$ .
- The maximum photoelectron momentum is  $p_{\max} = \sqrt{2m_e K_{\max}} = \sqrt{2m_e eV_s}$ , where  $m_e$  is the electron mass.

**Step 1: Read the stopping-potential intercepts** Trace each labelled curve from its saturation plateau back to the point at which it meets the potential-difference axis. The intercept for B lies farthest to the left, whereas the intercept for C lies nearest the origin. Thus B has the greatest stopping-potential magnitude and C has the least. These intercepts must be followed carefully because the curves cross. The heights of the plateaus indicate saturation currents, not the maximum kinetic energies of the emitted electrons.

**Step 2: Identify the highest-frequency beam in part (i)** Rearrange Einstein's equation for the same

photocathode:

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

Since  $\phi$  is common to all four measurements, frequency increases with stopping-potential magnitude. Beam B has the most negative zero-current intercept and therefore has the highest frequency. Beam A's larger saturation current does not establish a higher frequency.

**Step 3: Identify the longest-wavelength beam in part (ii)** Beam C has the smallest stopping-potential magnitude and hence the lowest incident frequency among the beams shown. Consequently, using

$$\lambda = \frac{c}{\nu} = \frac{hc}{\phi + eV_s},$$

C has the longest wavelength. This comparison uses the same metal throughout, so its work function cannot change from one curve to another.

**Step 4: Compare maximum photoelectron momenta in part (iii)** At the stopping potential, even the fastest photoelectrons are prevented from reaching the collector. Their maximum kinetic energy is  $eV_s$ . Therefore,

$$\frac{p_{\max}^2}{2m_e} = eV_s \Rightarrow p_{\max} = \sqrt{2m_e eV_s}.$$

The electron mass and charge are common constants. The largest  $V_s$ , belonging to beam B, therefore gives the largest maximum momentum. A larger saturation current only means more electrons are collected per unit time; it does not mean each electron is more energetic.

**Step 5: Conclusion** (i) Beam B has the highest frequency. (ii) Beam C has the longest wavelength. (iii) Beam B ejects photoelectrons with the greatest maximum momentum. The deciding feature is the magnitude of the negative-voltage intercept, not the saturation-current height.

**Quick Tip to Solve:** Follow each labelled plateau back through any crossing to its zero-current intercept: farthest left gives the highest frequency and momentum; nearest zero gives the longest wavelength.

OR

**34(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 threshold frequency  $\nu_0$  is the minimum incident frequency required for photoemission from a given metal. It obeys  $h\nu_0 = \phi$ , where  $\phi$  is the work function and  $h$  is Planck's constant.
- Einstein's equation gives  $K_{\max} = h\nu - \phi = h(\nu - \nu_0)$ , where  $\nu$  is the incident frequency and  $K_{\max}$  is the maximum photoelectron kinetic energy.
- The stopping-potential magnitude  $V_s$  satisfies  $eV_s = K_{\max}$ . Here  $e$  is the positive magnitude of the electron charge; the actual stopping voltage of the collector relative to the emitter is negative.

**Step 1: Determine the effect on threshold frequency** Threshold frequency is fixed by the minimum energy needed to remove an electron from the metal surface:

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

Increasing the incident frequency raises the energy of each incident photon, but does not change the work function of the unchanged photocathode. Since both  $\phi$  and  $h$  remain fixed, the threshold frequency remains unchanged. It is a property of the emitting surface, rather than a frequency selected by the incident beam.

**Step 2: Determine the effect on stopping potential** For photoemission, the photon supplies energy  $h\nu$ . The amount  $\phi$  is required for escape, and the excess appears as the maximum kinetic energy. A retarding voltage must remove all this kinetic energy to stop the fastest electrons. Hence,

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

If the incident frequency is increased from  $\nu_1$  to  $\nu_2$ , with both above threshold, subtracting the two equations gives

$$V_{s2} - V_{s1} = \frac{h}{e}(\nu_2 - \nu_1) > 0.$$

Thus the stopping-potential magnitude increases linearly with incident frequency, with slope  $h/e$ . Physically, the more energetic emitted electrons require a stronger retarding electric field to stop them. On a photocurrent-versus-voltage graph, the zero-current intercept consequently moves farther into the negative-voltage region.

**Step 3: State the photoemission condition** These stopping-potential comparisons concern light that produces photoelectrons. If the incident frequency is below  $\nu_0$ , photoemission does not occur and there is no photoelectric stopping-potential measurement. At the ideal threshold the maximum kinetic energy, and hence the stopping-potential magnitude, is zero. Raising the frequency above threshold starts emission without altering the threshold itself.

**Step 4: Conclusion** The threshold frequency remains unchanged for the same emitting surface. The stopping-potential magnitude increases with incident frequency according to  $\Delta V_s = (h/e)\Delta\nu$ ; the collector must be made more negative to stop the photoelectrons.

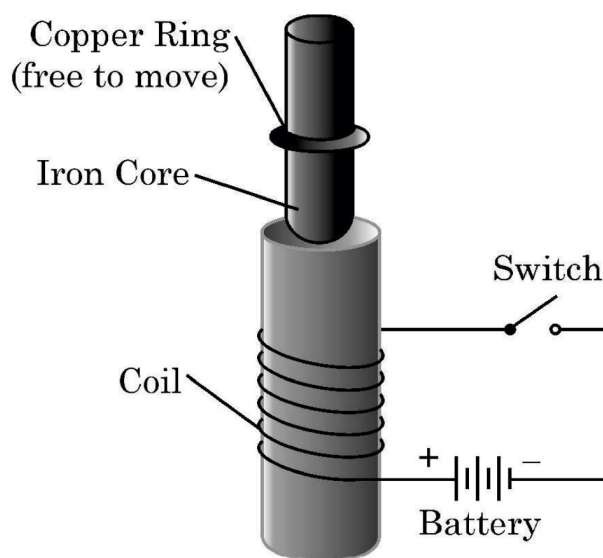
**Quick Tip to Solve:** Separate the material property  $\nu_0 = \phi/h$  from the beam-dependent quantity  $V_s = (h/e)(\nu - \nu_0)$ . A higher frequency changes the latter while the same surface keeps the former fixed.

**35(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:

- (i) Explain the reason of jumping of the ring when the switch is closed in the circuit.
- (ii) What will happen if the terminals of the battery are reversed and the switch is closed? Explain.
- (iii) Explain the two laws that help us understand this phenomenon.

[4 marks]



### Solution:

#### Concept:

- Faraday's law relates induced emf to changing magnetic flux:  $\mathcal{E} = -N d\Phi_B/dt$ , where  $N$  is the number of turns and  $\Phi_B$  is flux through each turn.
- Lenz's law states that the induced current flows in a direction that opposes the change in magnetic flux producing it. The negative sign in Faraday's law expresses this opposition.

**Step 1: (i) Follow the flux change when the switch closes** Immediately after the switch is closed, the solenoid current grows from zero, so the magnetic field in its iron core and the flux through the conducting ring increase. Faraday's law therefore gives an induced emf in the ring. Because the ring is a closed conducting path, a transient induced current flows through it; being non-magnetic does not prevent electrical conduction or electromagnetic induction.

**Step 2: (i) Determine the resulting force on the ring** By Lenz's law, the ring current produces a magnetic field opposing the increase of the solenoid's flux. Its current circulates oppositely to the solenoid current as viewed from the same end. The adjacent faces of the ring and solenoid therefore behave as like magnetic poles and repel. The upward magnetic force in the non-uniform field near the core's end throws the ring off when sufficiently large. With a battery, this is a switching transient: after the solenoid current becomes steady, a stationary ring has no continuing induced emf from the solenoid.

**Step 3: (ii) Reverse the battery and compare the interaction** Reversing the battery reverses the solenoid current and its magnetic field. On closing the switch, the changing flux now has the opposite direction, so the induced current in the ring also reverses. The ring still opposes the increasing flux. Both magnetic polarities reverse together, leaving like poles facing each other; hence the interaction is

again repulsive and the ring jumps upward.

**Step 4: (iii) State the two governing laws** Faraday's law states that a changing magnetic flux linked with a circuit induces an emf whose magnitude equals the rate of change of flux linkage. For this single-turn ring,

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

Lenz's law supplies the direction: the induced current opposes the change causing it, so an increasing solenoid flux produces an opposing ring field and repulsion. It is the change in flux, rather than the mere presence of flux, that induces current; this opposition is consistent with conservation of energy.

**Step 5: Conclusion** The ring jumps because a transient induced current produces magnetic repulsion. Reversing the battery reverses both currents, so the ring still jumps. Faraday's law explains the induction and Lenz's law its direction.

**Quick Tip to Solve:** On reversing the battery, reverse both the solenoid field and the induced ring current; their repulsive relationship is unchanged.

OR

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

**Solution:**

**Concept:**

- For a long solenoid, the magnetic field inside is approximately  $B = \mu_0 \mu_r n I$ , where  $I$  is current,  $n = N/\ell$  is turns per unit length, and  $\mu_r$  is the relative permeability of the core.
- The magnetic fields of successive turns reinforce each other inside the solenoid. A ferromagnetic core becomes magnetised and adds to the field produced by the winding.

**Step 1: Increase the current through the winding** For a given winding and core,  $n$  and approximately  $\mu_r$  are fixed, so

$$B \propto I.$$

Increasing the applied voltage or reducing a series rheostat's resistance increases the current and strengthens the magnetic field. For example, doubling the current approximately doubles the field if the core remains in its linear response range. The current must remain within the winding's thermal limit because Joule heating also increases.

**Step 2: Insert a suitable magnetic core** Place a soft-iron core inside the solenoid in place of air. Air has  $\mu_r$  close to unity, whereas soft iron has a much larger permeability. Its magnetic domains align with the winding's field, adding a strong magnetisation field. Thus the same current and winding produce a much stronger magnetic field. Soft iron is suitable because it magnetises readily; the increase eventually becomes limited by magnetic saturation.

**Step 3: Increase turns per unit length if the winding can be adjusted** The winding dependence is

$$B \propto n = \frac{N}{\ell}.$$

Adding turns over the same length, for example by rewinding in additional layers, increases  $n$ . If the construction permits, bringing existing turns closer together also increases the number of turns

per unit length. Compare these changes at the same current, since additional wire can increase resistance and reduce the current from a fixed-voltage source. Simply making a longer solenoid with proportionally more turns leaves  $n$  unchanged. For a strictly unchanged given winding, use the first two methods; changing  $n$  requires a physical adjustment of the winding.

**Step 4: Conclusion** Strengthen the field by increasing the current and inserting a high-permeability soft-iron core. If altering the winding is permitted, increasing turns per unit length also strengthens the field, as expressed by  $B \approx \mu_0 \mu_r n I$ .

**Quick Tip to Solve:** Use the three factors in  $B = \mu_0 \mu_r n I$ : current, core permeability and turns per unit length. For an unchanged winding,  $n$  is fixed.