

CBSE Class 12 Physics Question Paper 2023 with Solution PDF-Set 55/4/3



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

Use the following values of physical constants, if required :

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

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

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

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

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

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

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

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

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

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

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

Section A (18 marks)

1. In a Young's double-slit experiment, the fringe width is found to be β . If the entire apparatus is immersed in a liquid of refractive index μ , the new fringe width will be: [1 mark]

- (A) β
- (B) $\mu\beta$
- (C) $\frac{\beta}{\mu}$
- (D) $\frac{\beta}{\mu^2}$

Correct Answer: (C) $\frac{\beta}{\mu}$

Solution:

Concept:

- For slit separation d , screen distance D and wavelength λ , the fringe width is $\beta = \lambda D/d$.
- In a medium of refractive index μ , the frequency stays unchanged while the wavelength becomes λ/μ .

Step 1: Identify what changes Immersing the entire apparatus changes the speed of light to c/μ . Since its frequency does not change at the interface, the wavelength decreases by the same factor. The slit separation and screen distance remain fixed.

Step 2: Compare fringe widths Substituting the wavelength in the medium gives

$$\beta' = \frac{(\lambda/\mu)D}{d} = \frac{\beta}{\mu}.$$

Option (A) ignores the change in wavelength, (B) predicts an increase instead of a decrease, and (D) incorrectly introduces a second factor of μ .

Step 3: Conclusion The new fringe width is β/μ . Hence, the correct option is (C).

Quick Tip to Solve: For complete immersion in YDSE, keep D/d fixed and divide the wavelength, hence the fringe width, by μ .

2. A light of frequency ν is incident on a metal surface whose work function is W_0 . The kinetic energy of emitted electron is K . If the frequency of the incident light is doubled then the kinetic energy of emitted electron will be: [1 mark]

- (A) $2K$
- (B) more than $2K$
- (C) between K and $2K$
- (D) less than K

Correct Answer: (B) more than $2K$

Solution:

Concept:

- Einstein's photoelectric equation is $K = h\nu - W_0$, where K is maximum kinetic energy and W_0 is the work function.
- The work function is a property of the metal and is unchanged when the light frequency changes.

Step 1: Express the new kinetic energy At twice the incident frequency, each photon has energy $2h\nu$. The same work function is subtracted only once:

$$K' = 2h\nu - W_0.$$

Step 2: Compare with twice the original energy From the original equation, $h\nu = K + W_0$. Therefore

$$K' = 2(K + W_0) - W_0 = 2K + W_0.$$

Since $W_0 > 0$, the new energy exceeds $2K$. Thus (A) overlooks the work-function term; (C) and (D) underestimate the increase.

Step 3: Conclusion The emitted electron has kinetic energy greater than $2K$. Hence, the correct option is (B).

Quick Tip to Solve: Double the photon energy first, then subtract the unchanged work function once; do not simply double the initial kinetic energy.

3. Which of the following statements is not true for nuclear forces? [1 mark]

- (A) They are stronger than Coulomb forces.
- (B) They have about the same magnitude for different pairs of nucleons.
- (C) They are always attractive.
- (D) They saturate as the separation between two nucleons increases.

Correct Answer: (C) They are always attractive.

Solution:

Concept:

- The nuclear force binds nucleons and is very strong over nuclear distances, but it has a very short range.
- It is attractive at typical nucleon separations and becomes strongly repulsive at extremely small separations.

Step 1: Test the claim of universal attraction The word “always in option (C) is decisive. A short-range repulsive core prevents nucleons from collapsing into one another. Thus attraction is not maintained at every possible separation.

Step 2: Check the other stated properties At nuclear distances, nuclear forces dominate the Coulomb repulsion between protons, supporting (A). Their approximate charge independence supports (B). Nuclear-force saturation means a nucleon effectively interacts with only nearby nucleons, owing to the short range. Option (D) is an imprecise statement of this saturation property; it should not be read as a nonzero force persisting at large separation.

Step 3: Conclusion Nuclear forces are not always attractive because they have a repulsive core. Hence, the correct option is (C).

Quick Tip to Solve: For nuclear-force questions, separate the attractive binding range from the repulsive core; an unqualified “always attractive is false.

4. A particle of mass m and charge $-q$ is moving with a uniform speed v in a circle of radius r , with another charge q at the centre of the circle. The value of r is: [1 mark]

- (A) $\frac{1}{4\pi\epsilon_0 m} \left(\frac{q}{v}\right)$
(B) $\frac{1}{4\pi\epsilon_0 m} \left(\frac{q}{v}\right)^2$
(C) $\frac{m}{4\pi\epsilon_0} \left(\frac{q}{v}\right)$
(D) $\frac{m}{4\pi\epsilon_0} \left(\frac{q}{v}\right)^2$

Correct Answer: (B) $\frac{1}{4\pi\epsilon_0 m} \left(\frac{q}{v}\right)^2$

Solution:

Concept:

- The attractive Coulomb force between charges $+q$ and $-q$ has magnitude $F = q^2/(4\pi\epsilon_0 r^2)$.
- Uniform circular motion requires an inward centripetal force mv^2/r , with m the orbiting mass and v its speed.

Step 1: Equate inward forces The opposite central charge attracts the moving particle towards the centre. This electric force supplies the required centripetal force:

$$\frac{q^2}{4\pi\epsilon_0 r^2} = \frac{mv^2}{r}.$$

Step 2: Isolate the orbital radius Multiply by r^2 and divide by mv^2 :

$$r = \frac{q^2}{4\pi\epsilon_0 mv^2} = \frac{1}{4\pi\epsilon_0 m} \left(\frac{q}{v}\right)^2.$$

Options (A) and (C) lack the required square of q/v ; (D) places m in the numerator instead of the denominator.

Step 3: Conclusion $r = \frac{1}{4\pi\epsilon_0 m} \left(\frac{q}{v}\right)^2$. Hence, the correct option is (B).

Quick Tip to Solve: Equate Coulomb force to mv^2/r ; cancelling one power of r immediately gives the radius proportional to $q^2/(mv^2)$.

5. Photons of energy 3.2 eV are incident on a photosensitive surface. If the stopping potential for the emitted electrons is 1.5 V, the work function for the surface is : [1 mark]

- (A) 1.5 eV
- (B) 1.7 eV
- (C) 3.2 eV
- (D) 4.7 eV

Correct Answer: (B) 1.7 eV

Solution:

Concept:

- Photoelectric energy conservation gives $E_\gamma = W_0 + K_{\max}$, where W_0 is the work function.
- The stopping potential V_s satisfies $K_{\max} = eV_s$; a stopping potential of 1 V corresponds to 1 eV of electron kinetic energy.

Step 1: Find maximum kinetic energy The stopping potential is 1.5 V, so the fastest emitted electrons have kinetic energy

$$K_{\max} = 1.5 \text{ eV}.$$

Keep all energies in electron-volts to avoid an unnecessary conversion to joules.

Step 2: Subtract the kinetic energy The photon supplies both the escape energy and the final kinetic energy. Therefore

$$W_0 = 3.2 - 1.5 = 1.7 \text{ eV}.$$

Option (A) is the kinetic energy, (C) is the photon energy, and (D) incorrectly adds the two given numerical values.

Step 3: Conclusion The work function is 1.7 eV. Hence, the correct option is (B).

Quick Tip to Solve: When photon energy is in eV and stopping potential in V, subtract their numerical values to obtain the work function in eV.

6. Which one of the following has relative magnetic permeability between 0 and 1? [1 mark]

- (A) Aluminium
- (B) Alnico
- (C) Water
- (D) Sodium

Correct Answer: (C) Water

Solution:

Concept:

- Relative permeability and magnetic susceptibility are related by $\mu_r = 1 + \chi_m$.
- Diamagnetic substances have a small negative susceptibility, so their relative permeability is slightly less than unity.

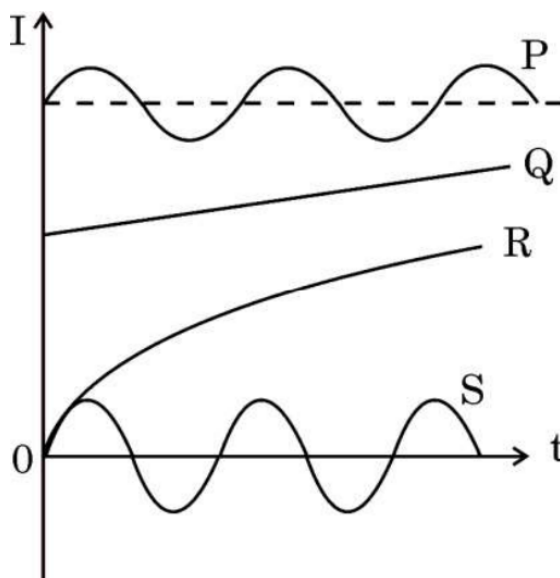
Step 1: Identify the magnetic response The interval $0 < \mu_r < 1$ implies $\chi_m < 0$. Such a material develops a weak induced magnetisation opposite to the applied magnetic field; this is the characteristic response of a diamagnetic substance.

Step 2: Classify the listed materials Water is diamagnetic and consequently has relative permeability slightly below one. Aluminium and sodium are paramagnetic, with small positive susceptibility and $\mu_r > 1$. Alnico is a ferromagnetic alloy used for permanent magnets, so it does not represent the weak diamagnetic response sought here.

Step 3: Conclusion Water has relative magnetic permeability between zero and one. Hence, the correct option is (C).

Quick Tip to Solve: Use $\mu_r - 1 = \chi_m$: a permeability below one identifies diamagnetism, and water is the diamagnetic choice in this list.

7. The figure shows variation of current (I) with time (t) in four devices P, Q, R and S. The device in which an alternating current flows is: [1 mark]



- (A) P
- (B) Q
- (C) R
- (D) S

Correct Answer: (D) S

Solution:**Concept:**

- An alternating current reverses its direction periodically; its graph takes both positive and negative values relative to $I = 0$.
- A current can vary in magnitude while retaining one direction, so time variation alone does not establish alternating current.

Step 1: Locate the zero-current axis The horizontal axis through the marked origin represents $I = 0$. The dashed horizontal line through the waveform P is above this axis; it is not the zero-current reference. The whole P waveform remains positive.

Step 2: Compare the four devices P oscillates in magnitude without reversing direction. Q rises linearly and R rises nonlinearly, but both stay on the positive side of the time axis. S repeatedly crosses the zero-current axis and has successive positive and negative portions, showing periodic reversal of current direction.

Step 3: Conclusion Alternating current flows in device S. Hence, the correct option is (D).

Quick Tip to Solve: Check whether the current crosses the actual $I = 0$ axis; an oscillating trace above zero, such as P, does not reverse direction.

8. Name the electromagnetic waves also known as ‘heat waves’.

[1 mark]

- (A) Radio waves
- (B) Microwaves
- (C) X-rays
- (D) Infrared waves

Correct Answer: (D) Infrared waves

Solution:**Concept:**

- Infrared radiation is strongly associated with thermal emission from warm bodies and is conventionally called heat radiation.
- All electromagnetic waves can transfer energy, but the name “heat waves specifically refers to the infrared region in this context.

Step 1: Connect thermal radiation with the spectrum Infrared waves lie beyond the red end of the visible spectrum. Their absorption by matter commonly increases molecular vibrational and rotational energy and produces heating, explaining the name used in the question.

Step 2: Distinguish the alternatives Radio waves are principally associated with radio communication. Microwaves can certainly heat food, but this application does not make them the spectral band conventionally named heat waves. X-rays are high-energy radiation commonly used for imaging. The standard name asked here identifies infrared radiation.

Step 3: Conclusion Infrared waves are also known as heat waves. Hence, the correct option is (D).

Quick Tip to Solve: Distinguish the conventional spectrum name from a heating application: “heat waves means infrared, even though microwaves can also heat matter.

9. A plane wavefront is incident on a concave mirror of radius of curvature R . The radius of the refracted wavefront will be:

[1 mark]

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

Correct Answer: (C) $\frac{R}{2}$

Solution:

Concept:

- A wavefront is a surface of constant phase; rays are normal to it. A plane incident wavefront corresponds to parallel incident rays.
- A concave spherical mirror brings paraxial rays parallel to its principal axis to its focus, at focal distance $f = R/2$, where R is the mirror radius.

Step 1: Identify the outgoing wavefront The paper uses the word “refracted, but a mirror reflects light. The intended outgoing wavefront is therefore the reflected wavefront. Parallel incident rays converge towards the principal focus, so their wavefront is a converging spherical surface centred at that focus.

Step 2: Relate the radius to the focal distance Immediately after reflection, the radius of the spherical wavefront near the mirror is the distance to the focus:

$$r = f = \frac{R}{2}.$$

The value R is the mirror surface radius, not this wavefront radius; $2R$ and $R/4$ do not follow from the focal-length relation.

Step 3: Conclusion The radius of the outgoing reflected wavefront at the mirror is $R/2$. Hence, the correct option is (C).

Quick Tip to Solve: For a plane wavefront incident on a concave mirror, locate the focus first; the initial reflected wavefront radius is the focal length.

10. A proton and an alpha particle have the same kinetic energy. The ratio of de Broglie wavelengths associated with the proton to that with the alpha particle is:

[1 mark]

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

Correct Answer: (B) 2

Solution:

Concept:

- The de Broglie wavelength is $\lambda = h/p$, where h is Planck's constant and p is momentum.

- For non-relativistic motion, $K = p^2/(2m)$; hence $\lambda = h/\sqrt{2mK}$. An alpha particle has approximately four times the mass of a proton.

Step 1: Compare at equal kinetic energy Because both particles have the same kinetic energy K , their wavelengths vary inversely as the square root of mass:

$$\frac{\lambda_p}{\lambda_\alpha} = \sqrt{\frac{m_\alpha}{m_p}}.$$

Their charges do not enter this relation, since equal kinetic energies are already specified.

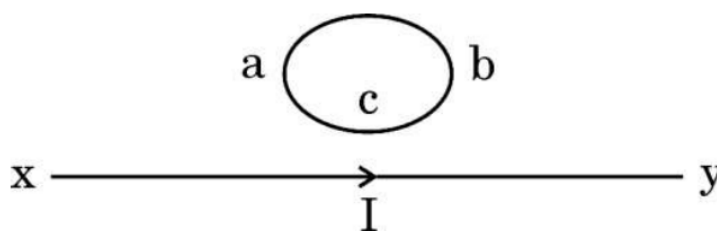
Step 2: Substitute the mass ratio Using $m_\alpha \simeq 4m_p$, the ratio becomes $\sqrt{4} = 2$. Equal wavelengths would require equal momenta, not merely equal kinetic energies. The value $1/2$ reverses the requested ratio, and $2\sqrt{2}$ incorrectly introduces an extra factor associated with charge.

Step 3: Conclusion $\lambda_p/\lambda_\alpha = 2$. Hence, the correct option is (B).

Quick Tip to Solve: At equal kinetic energy use the inverse square root of mass; charge matters only if an accelerating potential must first determine the energy.

11. The direction of induced current in the loop abc is :

[1 mark]



- (A) along abc if I decreases
- (B) along acb if I increases
- (C) along abc if I is constant
- (D) along abc if I increases

Correct Answer: (D) along abc if I increases

Solution:

Concept:

- The right-hand thumb rule gives the direction of the magnetic field around a straight current-carrying wire.
- Faraday's law requires changing magnetic flux for an induced emf. Lenz's law makes the induced magnetic field oppose the change in flux.

Step 1: Determine the applied magnetic field The wire current is from x to y , towards the right. At the loop above the wire, the right-hand rule gives a magnetic field out of the page. Increasing I therefore increases the outward flux through the loop.

Step 2: Apply Lenz's law to the labelled loop To oppose increasing outward flux, the induced current must produce a field into the page. This requires a clockwise current, which follows $a \rightarrow b \rightarrow c \rightarrow a$ in the figure. A decreasing I instead produces anticlockwise current along acb ; a constant I induces no current. Thus (A), (B) and (C) each describe the wrong condition or direction.

Step 3: Conclusion The induced current is along abc when I increases. Hence, the correct option is (D).

Quick Tip to Solve: First find the wire field at the loop, then oppose its change; only afterwards translate clockwise or anticlockwise into the printed letter order.

12. An ac voltage $v = v_0 \sin \omega t$ is applied to a series combination of a resistor R and an element X . The instantaneous current in the circuit is $I = I_0 \sin \left(\omega t + \frac{\pi}{4} \right)$. Then which of the following is correct? [1 mark]

- (A) X is a capacitor and $X_C = \sqrt{2}R$
- (B) X is an inductor and $X_L = R$
- (C) X is an inductor and $X_L = \sqrt{2}R$
- (D) X is a capacitor and $X_C = R$

Correct Answer: (D) X is a capacitor and $X_C = R$

Solution:

Concept:

- In a series resistor-capacitor circuit, current leads the applied voltage; in a series resistor-inductor circuit, current lags it.
- For a series RC circuit, the lead angle obeys $\tan \phi = X_C/R$, where $X_C = 1/(\omega C)$ is the positive magnitude of capacitive reactance.

Step 1: Identify the phase relation The voltage phase is ωt , while the current phase is $\omega t + \pi/4$. The positive phase shift means that current leads voltage by $\pi/4$. Therefore the element X is a capacitor; both inductive options (B) and (C) would make current lag.

Step 2: Use the magnitude of the phase angle Substituting the measured lead into the RC phase relation gives

$$\frac{X_C}{R} = \tan \frac{\pi}{4} = 1.$$

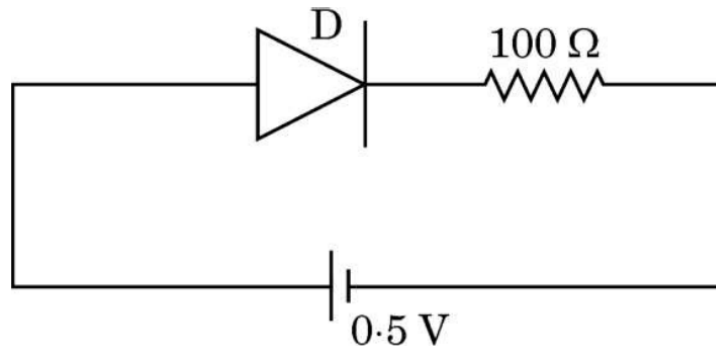
Thus $X_C = R$. Option (A) would give $\tan \phi = \sqrt{2}$, which is incompatible with the specified phase. The factor $\sqrt{2}$ here belongs to the impedance magnitude $Z = \sqrt{R^2 + X_C^2}$, not the reactance.

Step 3: Conclusion X is a capacitor and $X_C = R$. Hence, the correct option is (D).

Quick Tip to Solve: Read lead or lag from the sign inside the current sine, then use the tangent of the phase angle to compare reactance with resistance.

13. The threshold voltage for a p-n junction diode used in the circuit is 0.7 V. The type of biasing and current in the circuit are:

[1 mark]



- (A) Forward biasing, 0 A
- (B) Reverse biasing, 0 A
- (C) Forward biasing, 5 mA
- (D) Reverse biasing, 2 mA

Correct Answer: (A) Forward biasing, 0 A

Solution:

Concept:

- A diode is forward biased when its anode (p-side) is connected to the positive battery terminal and its cathode (n-side) to the negative terminal.
- In the threshold model, appreciable forward current flows only when the applied forward voltage reaches the cut-in voltage. Below threshold, the diode is treated as non-conducting.

Step 1: Check the battery and diode polarities The longer battery plate is on the left, so the left wire is positive. It connects to the diode anode, while the cathode bar on the right connects through the $100\ \Omega$ resistor to the negative terminal. The connection is therefore forward bias, irrespective of whether appreciable current flows.

Step 2: Compare the supply with the threshold The supply is only 0.5 V, less than the stated 0.7 V threshold. In the stated diode model, $I = 0\text{ A}$. Computing $0.5/100 = 5\text{ mA}$ would wrongly treat the diode as a conducting short circuit. The reverse-bias options fail the polarity test.

Step 3: Conclusion The diode is forward biased and the current is 0 A in the threshold approximation. Hence, the correct option is (A).

Quick Tip to Solve: Classify bias from terminal polarity first; then compare the available forward voltage with the threshold before applying Ohm's law.

14. The potential energy of an electron in the second excited state in hydrogen atom is: [1 mark]

- (A) -3.4 eV
- (B) -3.02 eV
- (C) -1.51 eV
- (D) -6.8 eV

Correct Answer: (B) -3.02 eV

Solution:

Concept:

- The hydrogen energy levels are $E_n = -13.6/n^2$ eV, where n is the principal quantum number.
- For an electron bound by the Coulomb force, its potential energy is $U_n = 2E_n = -27.2/n^2$ eV.

Step 1: Identify the second excited state The ground state is $n = 1$, the first excited state is $n = 2$, and the second excited state is $n = 3$. The phrase “second excited must therefore not be interpreted as $n = 2$.

Step 2: Calculate potential energy rather than total energy For $n = 3$,

$$U_3 = -\frac{27.2}{3^2} \text{ eV} = -3.02 \text{ eV (approximately).}$$

The value -1.51 eV is the total energy at $n = 3$, not the potential energy. The values -3.4 eV and -6.8 eV are the total and potential energies, respectively, at $n = 2$.

Step 3: Conclusion The potential energy is approximately -3.02 eV. Hence, the correct option is (B).

Quick Tip to Solve: Convert the excited-state number to n first, and double the total Bohr energy when the question asks for potential energy.

15. The difference in mass of 7X nucleus and total mass of its constituent nucleons is 21.00 u. The binding energy per nucleon for this nucleus is equal to the energy equivalent of: [1 mark]

- (A) 3 u
- (B) 3.5 u
- (C) 7 u
- (D) 21 u

Correct Answer: (A) 3 u

Solution:

Concept:

- Binding energy is the energy equivalent of the mass defect: $B = \Delta mc^2$, where Δm is the constituent-nucleon mass minus the bound-nucleus mass.
- Binding energy per nucleon is B/A , where the mass number A is the total number of protons and neutrons.

Step 1: Identify the quantities as printed The superscript in 7X gives $A = 7$ nucleons. The paper explicitly supplies a mass difference of 21.00 u; using that printed datum gives a total binding-energy equivalent of $21.00 \text{ u } c^2$.

Step 2: Divide the total energy by the nucleon count The requested average is

$$\frac{B}{A} = \frac{21.00 \text{ u } c^2}{7} = 3.00 \text{ u } c^2.$$

Thus the required mass equivalent is 3 u. The value 21 u is the total defect, 7 is the nucleon count, and 3.5 u would result from dividing by six instead of seven. The supplied defect is physically unrealistic for such a light nucleus, but the requested arithmetic follows directly from the printed values.

Step 3: Conclusion Using the stated data, the binding energy per nucleon equals the energy equivalent of 3 u. Hence, the correct option is (A).

Quick Tip to Solve: When options are mass equivalents, divide the printed mass defect by the mass number directly; conversion to MeV is unnecessary.

16. Assertion (A): In 'n' type semiconductor, number density of electrons is greater than the number density of holes but the crystal maintains an overall charge neutrality.

Reason (R): The charge of electrons donated by donor atoms is just equal and opposite to that of the ionised donor. [1 mark]

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

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

Solution:

Concept:

- Doping a semiconductor with pentavalent donors creates an n-type material in which electrons are majority carriers and holes are minority carriers.
- Ionising a neutral donor releases a mobile electron and leaves an immobile positively charged donor ion; the two charges are equal and opposite.

Step 1: Evaluate the assertion In an n-type semiconductor, the electron number density n exceeds the hole number density p . The crystal nevertheless remains electrically neutral because total charge includes the ionised dopants as well as mobile carriers. The assertion is true.

Step 2: Evaluate the reason Each singly ionised donor contributes one electron of charge $-e$ and leaves a donor ion of charge $+e$. Their charges cancel. The stated equality and opposite signs of donated-electron and ionised-donor charge are therefore correct, so the reason is true.

Step 3: Check whether the reason explains the assertion The extra conduction electrons are balanced by positive donor ions rather than by an equal number of holes. For uncompensated n-type material, charge neutrality can be expressed as $n = p + N_D^+$, where N_D^+ is the ionised-donor number density. This explains how $n > p$ coexists with overall neutrality. Thus the reason explains the assertion; (B) wrongly denies that link, and (C) and (D) wrongly classify a true statement as false.

Step 4: Conclusion Both statements are true, and the reason correctly explains the assertion. Hence,

the correct option is (A).

Quick Tip to Solve: For semiconductor neutrality, count fixed dopant-ion charge as well as mobile electron and hole charge; equal carrier densities are not required.

17. Assertion (A): When three electric bulbs of power 200 W, 100 W and 50 W are connected in series to a source, the power consumed by the 50 W bulb is maximum.

Reason (R): In a series circuit, current is the same through each bulb, but the potential difference across each bulb is different. [1 mark]

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

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

Solution:

Concept:

- For bulbs rated at the same voltage V_0 , resistance is $R = V_0^2/P_0$, where P_0 is the rated power.
- Series elements carry the same current I ; their voltage drops and actual powers are $V = IR$ and $P = I^2R$.

Step 1: Judge the assertion Using the usual common rated-voltage assumption for the bulbs, their resistances satisfy

$$R_{200} : R_{100} : R_{50} = \frac{1}{200} : \frac{1}{100} : \frac{1}{50} = 1 : 2 : 4.$$

The 50 W bulb has the largest resistance. Since the series current is common, its actual power I^2R is largest. Thus Assertion (A) is true. The printed wattages are ratings, not the actual powers in this series connection.

Step 2: Judge the reason A series circuit has only one current path, so the same current flows through every bulb. Their resistances differ, hence their potential differences IR differ. Reason (R) is true.

Step 3: Test the explanatory connection The common current makes the power proportional to the voltage drop, $P = IV$, or equivalently to resistance, $P = I^2R$. The 50 W bulb has the largest drop and consumes the most power. The reason therefore explains the assertion. Option (B) misses this connection; (C) and (D) wrongly declare a true statement false.

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

Quick Tip to Solve: For bulbs of the same rated voltage in series, invert the rated powers to compare their resistances and actual powers.

18. Assertion (A): A current carrying square loop made of a wire of length L is placed in a magnetic field. It experiences a torque which is greater than the torque on a circular loop made of the same wire carrying the same current in the same magnetic field.

Reason (R): A square loop occupies more area than a circular loop, both made of wire of the same length. [1 mark]

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

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

Solution:

Concept:

- A single current loop in a uniform magnetic field experiences torque $\tau = IAB \sin \alpha$, where A is its area and α is the angle between its area vector and the field.
- For equal wire length, compare the enclosed areas; the circle encloses more area than the square.

Step 1: Judge the assertion For wire length L , the square has side $L/4$, whereas the circle has radius $L/(2\pi)$. Therefore

$$A_s = \frac{L^2}{16}, \quad A_c = \frac{L^2}{4\pi}.$$

At the same orientation, for nonzero torque,

$$\frac{\tau_s}{\tau_c} = \frac{A_s}{A_c} = \frac{\pi}{4} < 1.$$

The square's torque is smaller, not greater; the same comparison holds for maximum torques. Assertion (A) is false.

Step 2: Judge the reason Since $4\pi < 16$, we have $L^2/(4\pi) > L^2/16$. Thus the circular loop encloses the greater area for the same wire length. Reason (R) states the opposite and is false.

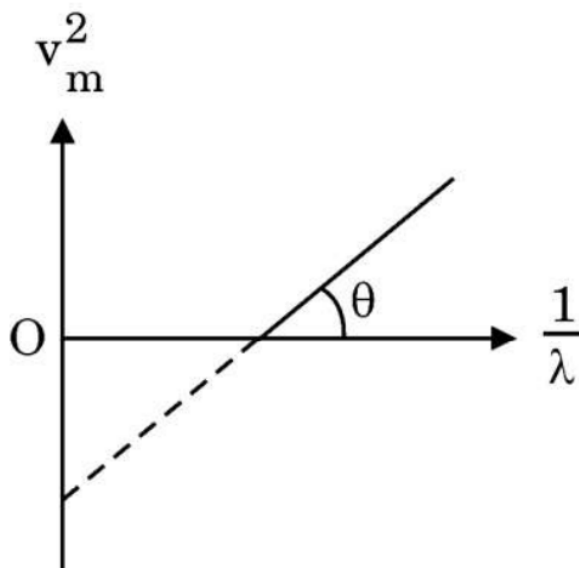
Step 3: Test the explanatory connection A false area comparison cannot explain the assertion. Under the standard comparison at equal orientation, both statements are false; if both area vectors lie along the field, both torques are zero. Options (A), (B) and (C) all require a true assertion and therefore fail.

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

Quick Tip to Solve: For loops made from equal wire lengths, calculate area from perimeter before comparing magnetic moments or torques.

Section B (14 marks)

19. The figure shows v_m^2 versus $\frac{1}{\lambda}$ graph for photoelectrons emitted from a surface where v_m is the maximum speed of electrons and λ is the wavelength of incident radiation. Using this graph and Einstein's photoelectric equation, obtain the expression for Planck's constant and work function of the surface. [2 marks]



Solution:

Concept:

- Einstein's photoelectric equation is $\frac{1}{2}m_e v_m^2 = hc/\lambda - \phi$, where m_e is electron mass, c is the speed of light and ϕ is the work function.
- For a straight line $y = Sx + b$, S is the slope and b is the signed intercept on the vertical axis.

Step 1: Put Einstein's equation in graph form Take the horizontal variable as $x = 1/\lambda$ and the vertical variable as $y = v_m^2$. Multiplying Einstein's equation by $2/m_e$ gives

$$v_m^2 = \frac{2hc}{m_e} \left(\frac{1}{\lambda} \right) - \frac{2\phi}{m_e}.$$

Thus the observed straight line has positive slope and its backward extension cuts the vertical axis below the origin.

Step 2: Obtain Planck's constant from the slope If $S = \Delta v_m^2 / \Delta(1/\lambda)$, comparison with the linear equation gives

$$S = \frac{2hc}{m_e}, \quad h = \frac{m_e S}{2c}.$$

With the graph's indicated angle θ , the slope is conventionally written $S = \tan \theta$, taking the axis scales into account. Therefore $h = m_e \tan \theta / (2c)$ in that graph notation.

Step 3: Obtain the work function from an intercept Let $b < 0$ denote the signed vertical intercept of the dashed extension. Then $b = -2\phi/m_e$. If $a = |b|$ is its magnitude,

$$\phi = -\frac{m_e b}{2} = \frac{m_e a}{2}.$$

Equivalently, the horizontal intercept is $x_0 = 1/\lambda_0$, where the maximum kinetic energy becomes zero, so $\phi = hc x_0 = hc/\lambda_0$. No numerical intercept is supplied, so the answers remain expressions in the graph quantities.

Step 4: Conclusion Planck's constant is $h = m_e S/(2c)$, with $S = \tan \theta$ in the stated graph notation. The work function is $\phi = m_e |b|/2 = hc/\lambda_0$, where b is the vertical intercept and $1/\lambda_0$ is the horizontal intercept.

Quick Tip to Solve: Rearrange the equation for the quantity on the vertical axis first; use the slope for h and the negative intercept's magnitude for ϕ .

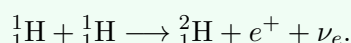
20. Briefly describe the multi-step process involved in the generation of energy in the Sun. [2 marks]

Solution:

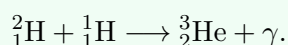
Concept:

- The Sun releases energy mainly through the proton-proton fusion chain: hydrogen nuclei ultimately form helium nuclei.
- The products have lower total rest mass; the mass defect Δm releases energy $Q = \Delta mc^2$, where c is the speed of light.

Step 1: Form deuterium and helium-3 The very high core temperature and pressure allow hydrogen nuclei to undergo fusion. First two protons form a deuterium nucleus, a positron and an electron neutrino:

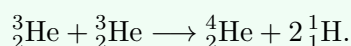


Deuterium then captures another proton and emits a gamma photon:



These two reactions occur twice to supply two helium-3 nuclei. The emitted particles and photons carry the released energy.

Step 2: Form helium-4 and identify the net energy release Two helium-3 nuclei fuse and return two protons to the plasma:



After cancelling the intermediate nuclei and the returned protons, four protons have become one helium-4 nucleus, two positrons and two neutrinos. The positrons annihilate with electrons in the plasma. Including this annihilation, each completed chain releases about 26.7 MeV; neutrinos carry a small share away, while the remaining energy heats the Sun and eventually emerges as radiation.

Step 3: Conclusion Solar energy is generated by the multi-step proton-proton fusion chain, whose net effect is to convert four hydrogen nuclei into one helium-4 nucleus. The mass defect supplies approximately 26.7 MeV per completed chain, including positron annihilation.

Quick Tip to Solve: Write the first two reactions twice, then cancel deuterium, helium-3 and the two returned protons to check that four protons are consumed.

21. Use Gauss's law to obtain the expression for electric field due to a thin infinitely long straight uniformly charged wire. [2 marks]

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the enclosed charge and ϵ_0 is vacuum permittivity.
- An infinite uniformly charged straight wire has cylindrical symmetry: its field is radial and its magnitude depends only on the perpendicular distance r from the wire.

Step 1: Choose a cylindrical Gaussian surface Let the wire have uniform linear charge density λ . Choose a closed cylinder of radius r and length ℓ , coaxial with the wire. Its enclosed charge is $Q_{\text{enc}} = \lambda\ell$. On the curved surface the field magnitude is constant by symmetry and the radial field is parallel to the outward area vector for positive charge.

Step 2: Evaluate the flux and apply Gauss's law On both flat ends the area vectors point along the wire, whereas the electric field is perpendicular to the wire. Thus the end-cap fluxes vanish. Only the curved surface of area $2\pi r\ell$ contributes. For positive λ ,

$$E(2\pi r\ell) + 0 + 0 = \frac{\lambda\ell}{\epsilon_0}.$$

Cancelling the arbitrary cylinder length gives

$$E = \frac{\lambda}{2\pi\epsilon_0 r}.$$

A negative line charge reverses the radial direction; the magnitude uses $|\lambda|$. The inverse-distance dependence follows because the cylindrical area increases in proportion to r .

Step 3: Conclusion At perpendicular distance r , the field is $\vec{E} = \frac{\lambda}{2\pi\epsilon_0 r} \hat{r}$, where $\hat{r}$ points radially away from the wire. Its magnitude is $|\lambda|/(2\pi\epsilon_0 r)$, outward for a positive wire and inward for a negative wire.

Quick Tip to Solve: Use a coaxial cylinder for an infinite wire; both flat ends give zero flux, leaving only the curved area $2\pi r\ell$.

22. A cell of emf E and internal resistance r is connected to a variable resistance R . Draw plots showing the variation of (a) terminal voltage V with R , and (b) V with current I , in the circuit. [2 marks]

Solution:

Concept:

- For a cell of emf E and internal resistance r supplying an external resistance R , the current is $I = E/(R + r)$.
- The terminal voltage is the potential difference across the external resistance: $V = IR = E - Ir$. Here Ir is the voltage drop inside the cell.

Step 1: (a) Express terminal voltage in terms of resistance Substituting the circuit current in $V = IR$,

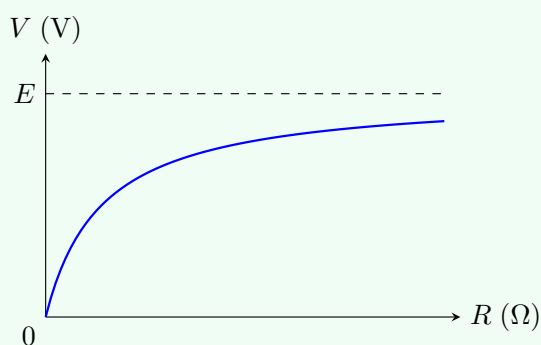
$$V = \frac{ER}{R+r}.$$

For a short circuit, $R = 0$, so $V = 0$. As R increases, the voltage rises, but the rate of increase becomes smaller. For $R \gg r$, V approaches E from below. Thus the graph is an increasing curve, concave down, with horizontal asymptote $V = E$.

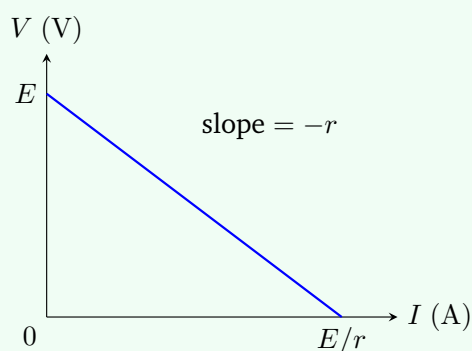
Step 2: (b) Express terminal voltage in terms of current Kirchhoff's loop law gives

$$E = V + Ir \Rightarrow V = E - rI.$$

Hence the V -versus- I plot is a straight line of slope $-r$. Its voltage intercept is E , corresponding to an open circuit, and its current intercept is E/r , corresponding to a short circuit. For a passive variable resistance, the plotted operating range is $0 \leq I \leq E/r$.



(a) V against R



(b) V against I

Terminal-voltage plots for a cell with finite internal resistance.

Step 3: Conclusion The required plots are an increasing saturating curve $V = ER/(R+r)$ against R , and a descending straight line $V = E - rI$ against I , as shown.

Quick Tip to Solve: Fix the endpoints first: an open circuit has $V = E$, while a short circuit has $V = 0$.

23. A particle of charge q and mass m starts moving with uniform velocity $v_0\hat{i}$. Specify the direction of magnetic field which should be set up in the region so that the particle moves (a) straight undeviated, and (b) in a circle. Justify your answers. [2 marks]

Solution:

Concept:

- The magnetic force on a charge moving with velocity $\vec{v}$ is $\vec{F} = q(\vec{v} \times \vec{B})$, whose magnitude is $|q|vB \sin \theta$.
- A magnetic field does no work because the force is perpendicular to the velocity. A uniform field perpendicular to the entire velocity produces circular motion at constant speed.

Step 1: (a) Set the force equal to zero The initial velocity $v_0\hat{i}$ is along the positive x -axis. Choose the field parallel or antiparallel to this axis, that is, $\vec{B} = B\hat{i}$ or $\vec{B} = -B\hat{i}$. The angle between velocity and field is then 0° or 180° , so

$$\vec{F} = q(v_0\hat{i} \times \vec{B}) = \vec{0}.$$

With no magnetic force the velocity remains unchanged, so the particle continues straight without deviation.

Step 2: (b) Choose a uniform transverse field Set up a nonzero uniform magnetic field perpendicular to $\hat{i}$, for example $\vec{B} = B\hat{k}$, along the positive z -axis. The initial force is then $-qv_0B\hat{j}$. Throughout the motion, the force remains perpendicular to the velocity and acts as the centripetal force in the xy -plane:

$$|q|v_0B = \frac{mv_0^2}{\rho}, \quad \rho = \frac{mv_0}{|q|B}.$$

The speed stays constant and the trajectory is circular. Changing the sign of the charge reverses the sense of rotation but not the required perpendicular orientation of the field. A field with both parallel and perpendicular components would generally produce a helix instead.

Step 3: Conclusion (a) Choose $\vec{B}$ along either direction of the x -axis for undeviated motion. (b) Choose a uniform $\vec{B}$ perpendicular to the x -axis, such as $B\hat{k}$, for circular motion.

Quick Tip to Solve: Use $\sin \theta$: parallel velocity gives zero force; wholly perpendicular velocity gives a circle.

24(a). Obtain an expression for electrostatic potential energy of a system of three charges q , $2q$ and $-3q$ placed at the vertices of an equilateral triangle of side a . [2 marks]

Solution:

Concept:

- Taking the potential energy of infinitely separated charges as zero, the energy of two point charges q_i, q_j a distance d apart is $U_{ij} = kq_iq_j/d$, with $k = 1/(4\pi\epsilon_0)$.
- The total electrostatic potential energy of a system is the sum over distinct pairs. For three charges, there are three pairs; each pair must be counted only once.

Step 1: Identify the three pair interactions Let the charges at the three vertices be $q_1 = q$, $q_2 = 2q$ and $q_3 = -3q$. Since the triangle is equilateral, the separation in every pair is a . The like-charge pair contributes positive energy, while each pair containing the negative charge contributes negative energy:

$$U_{12} = \frac{2kq^2}{a}, \quad U_{23} = -\frac{6kq^2}{a}, \quad U_{31} = -\frac{3kq^2}{a}.$$

Step 2: Add the energies with their signs By superposition, the energy required to assemble the system from infinity is

$$\begin{aligned} U &= U_{12} + U_{23} + U_{31} \\ &= \frac{k}{a} [q(2q) + (2q)(-3q) + (-3q)q] \\ &= \frac{kq^2}{a} (2 - 6 - 3). \end{aligned}$$

No additional factor of one-half is needed because the three distinct pairs have already been counted just once. The negative sum means that the net electrostatic interaction releases energy during a

quasistatic assembly from infinite separation.

Step 3: Conclusion The electrostatic potential energy is $U = -\frac{7q^2}{4\pi\epsilon_0 a}$, in joules when q and a are in SI units, with zero energy at infinite separation.

Quick Tip to Solve: For three charges, list all three products once and retain the signs before adding them.

OR

24(b). Two small conducting balls A and B of radius r_1 and r_2 have charges q_1 and q_2 respectively. They are connected by a wire. Obtain the expression for charges on A and B, in equilibrium. [2 marks]

Solution:

Concept:

- Charge flows through a connecting wire until the connected conductors are at the same potential. Their charges need not be equal.
- For a small spherical conductor, $V = kQ/r$, where Q is its charge and r its radius. The usual model here neglects mutual influence between well-separated balls and charge held by the thin wire.

Step 1: Apply equality of potential Let the final charges on balls A and B be Q_A and Q_B , respectively. While their potentials differ, charge flows along the wire. At electrostatic equilibrium,

$$V_A = V_B \Rightarrow \frac{kQ_A}{r_1} = \frac{kQ_B}{r_2}.$$

Therefore,

$$\frac{Q_A}{r_1} = \frac{Q_B}{r_2} = \lambda,$$

where λ is their common charge-to-radius ratio. Thus the final charges divide in the ratio $r_1 : r_2$, rather than necessarily in equal amounts.

Step 2: Conserve the total charge The two balls and wire form an isolated system, so their total charge remains $q_1 + q_2$. Neglecting the wire's charge and inserting $Q_A = \lambda r_1$, $Q_B = \lambda r_2$, we obtain

$$\begin{aligned} Q_A + Q_B &= q_1 + q_2, \\ \lambda(r_1 + r_2) &= q_1 + q_2, \\ \lambda &= \frac{q_1 + q_2}{r_1 + r_2}. \end{aligned}$$

The initial charges are added algebraically, including their signs. If the total charge is zero, the final charge on each ball is zero in this model.

Step 3: Conclusion The equilibrium charges are $Q_A = \frac{r_1(q_1 + q_2)}{r_1 + r_2}$ and $Q_B = \frac{r_2(q_1 + q_2)}{r_1 + r_2}$. Their potentials are equal and their total charge is conserved.

Quick Tip to Solve: First add the initial charges algebraically, then divide the total in the radius ratio $r_1 : r_2$.

25(a). What is a displacement current? How is it different from a conduction current?

[2 marks]

Solution:

Concept:

- A changing electric flux produces a magnetic field and is represented by Maxwell's displacement current.
- In vacuum, $I_d = \varepsilon_0 \frac{d\Phi_E}{dt}$, where $\Phi_E = \int \mathbf{E} \cdot d\mathbf{A}$ is electric flux and ε_0 is the permittivity of free space.

Step 1: Define displacement current Displacement current is the current associated with a time-varying electric field or electric flux. It need not involve the actual transport of free charge across the region. For example, the changing field between the plates of a charging capacitor gives a displacement current even though free charges do not cross the vacuum gap.

Step 2: Compare it with conduction current Conduction current is produced by the actual directed motion of free charge carriers, such as electrons in a metallic wire; its magnitude is $I_c = dq/dt$. Displacement current instead arises from $d\Phi_E/dt$, and can exist in a vacuum or dielectric without free-charge transport across it. Both act as sources of magnetic field. During capacitor charging, the displacement current through the gap equals the conduction current in the connecting wire.

Step 3: Conclusion Displacement current is $I_d = \varepsilon_0 d\Phi_E/dt$ in vacuum; it represents changing electric flux, whereas conduction current represents the flow of free charges.

Quick Tip to Solve: Use a charging capacitor to distinguish current in its wire from displacement current across its gap.

OR

25(b). Write any two characteristics of an electromagnetic wave. Why are microwaves used in radar systems?

[2 marks]

Solution:

Concept:

- An electromagnetic wave consists of time-varying electric and magnetic fields that sustain each other's propagation.
- Microwaves have short wavelengths, enabling a directional beam with a suitably sized transmitting antenna.

Step 1: State two characteristics First, electromagnetic waves are transverse: the electric field $\mathbf{E}$, magnetic field $\mathbf{B}$, and propagation direction are mutually perpendicular. The two fields oscillate in phase. Second, they require no material medium and travel in vacuum at speed $c = 1/\sqrt{\mu_0\varepsilon_0} \simeq 3.0 \times 10^8 \text{ m s}^{-1}$, where μ_0 and ε_0 are the permeability and permittivity of free space.

Step 2: Explain their use in radar Owing to their short wavelengths, microwaves can be sent as narrow, highly directional beams using practical antennas, with relatively little diffraction. This allows radar to locate a target accurately in direction. They also reflect from objects such as aircraft and ships, so the returning echo can be detected. Measuring the round-trip travel time t gives the target's distance as $d = ct/2$; the narrow beam makes the echo's direction identifiable.

Step 3: Conclusion Electromagnetic waves are transverse and propagate through vacuum at speed c .

Microwaves are useful in radar because their short wavelengths permit narrow directional beams and detectable reflections from targets.

Quick Tip to Solve: Link the short microwave wavelength to reduced diffraction and a narrow radar beam, then mention the reflected echo.

Section C (15 marks)

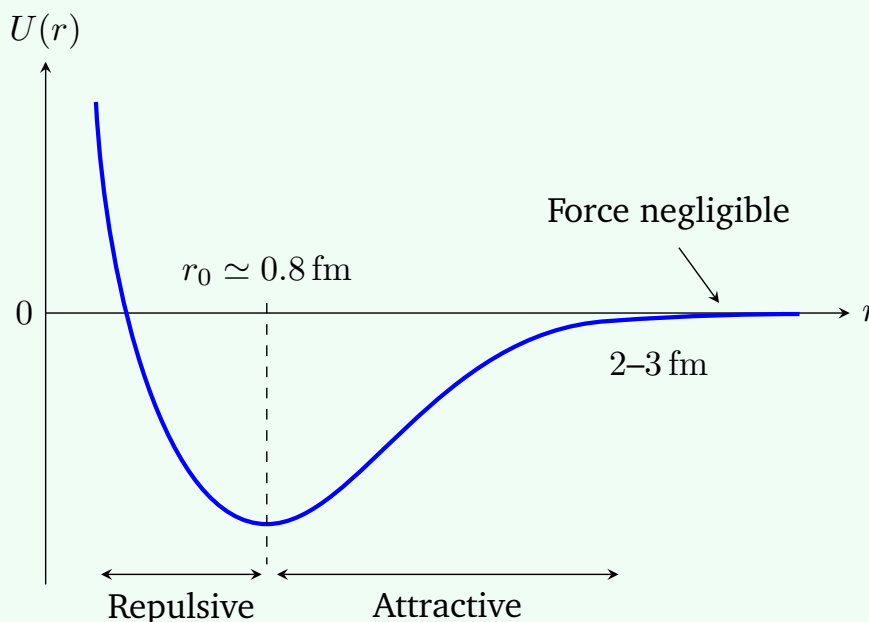
26. Draw a plot showing the variation of potential energy of two nucleons as a function of distance between them. Identify the regions in which the force between the nucleons is (i) attractive, and (ii) repulsive. Justify your answers. [3 marks]

Solution:

Concept:

- The nuclear interaction has a strongly repulsive core at very small nucleon separation and an attractive region at somewhat larger separation. It becomes negligible beyond a few femtometres.
- The radial force follows $F_r = -dU/dr$, where $U(r)$ is the interaction potential energy and increasing r is the positive radial direction. Also, $1 \text{ fm} = 10^{-15} \text{ m}$.

Step 1: Sketch the potential-energy curve Take the potential energy to be zero at very large separation. At very small r , the potential rises steeply to positive values. As r increases, it falls through zero to a negative minimum at a separation r_0 of about 0.8 fm. It then rises towards zero, becoming practically negligible beyond about 2–3 fm. The graph is schematic; its essential features are the repulsive core, the negative well and the short range.



Schematic nucleon potential: the slope changes sign at the minimum r_0 .

Step 2: Identify the attractive region To the right of the minimum, within the nuclear-force range, the curve rises with increasing separation: $dU/dr > 0$. Hence $F_r < 0$; the force acts towards decreasing separation and pulls the nucleons together. This is the attractive region, approximately $r_0 < r \lesssim 2\text{--}3 \text{ fm}$. Farther away, the nearly horizontal curve implies negligible force.

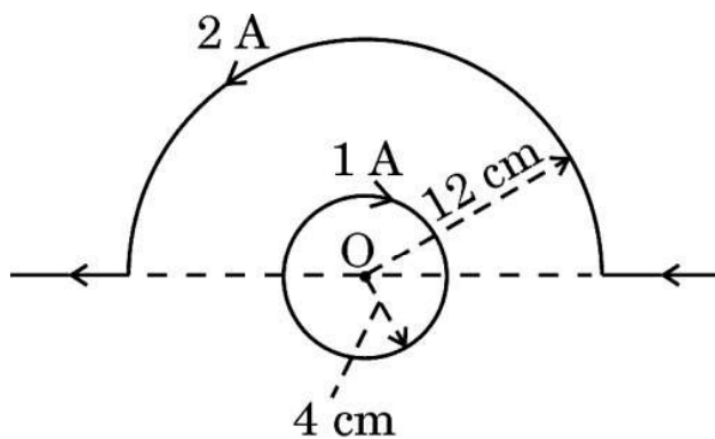
Step 3: Identify the repulsive region To the left of the minimum, $dU/dr < 0$, so $F_r > 0$. The force

therefore acts towards increasing separation, pushing the nucleons apart: the interaction is repulsive for $r < r_0$. At the minimum itself, $dU/dr = 0$, so the force vanishes. The sign of the potential alone does not determine attraction or repulsion; the slope of the potential does.

Step 4: Conclusion Using $F_r = -dU/dr$, the force is attractive on the rising side of the well and repulsive on its falling, small-separation side; it is negligible outside the short nuclear range.

Quick Tip to Solve: Read the slope, not the sign of potential energy: rising U means attraction, while falling U means repulsion.

27. A current carrying circular loop and a straight wire bent partly in the form of a semicircle are placed as shown in the figure. Find the magnitude and direction of net magnetic field at point O. [3 marks]



Solution:

Concept:

- At the centre of a circular current arc of radius R and angle θ radians, $B = \mu_0 I \theta / (4\pi R)$. Thus a complete circle gives $\mu_0 I / (2R)$, while a semicircle gives $\mu_0 I / (4R)$.
- The right-hand rule determines the field direction. In the Biot-Savart law, a straight element contributes zero at a point on its own line because $d\ell \times \hat{r} = 0$.

Step 1: Read the figure and eliminate straight portions The inner loop carries 1 A clockwise and has radius $r = 4 \text{ cm} = 0.04 \text{ m}$. The semicircle carries 2 A anticlockwise from its right end to its left end, and has radius $R = 12 \text{ cm} = 0.12 \text{ m}$. O lies on the line of both straight portions, so their elements have zero cross product with the displacement towards O: these portions give no field.

Step 2: Calculate the circular-loop field With $\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$, the full circular loop produces

$$B_{\text{loop}} = \frac{\mu_0(1)}{2(0.04)} = 5\pi \times 10^{-6} \text{ T}.$$

The clockwise current gives a field directed into the plane of the paper.

Step 3: Combine the opposing fields The anticlockwise semicircle produces a field directed out of the plane:

$$B_{\text{semi}} = \frac{\mu_0(2)}{4(0.12)} = \frac{5\pi}{3} \times 10^{-6} \text{ T}.$$

These fields oppose each other, so subtract their magnitudes. The circular-loop field is larger, giving

$$B_{\text{net}} = \left(5\pi - \frac{5\pi}{3}\right) 10^{-6} = \frac{10\pi}{3} \times 10^{-6} \text{ T}.$$

Step 4: Conclusion The net magnetic field at O is $B_{\text{net}} \simeq 1.05 \times 10^{-5} \text{ T}$, directed into the plane of the paper.

Quick Tip to Solve: First eliminate the radial straight portions, then assign each arc a field direction before adding or subtracting.

28(a). (i) In diffraction due to a single slit, the phase difference between light waves reaching a point on the screen is 5π . Explain whether a bright or a dark fringe will be formed at the point.

(ii) What should the width (a) of each slit be to obtain eight maxima of two double-slit patterns (slit separation d) within the central maximum of the single slit pattern?

(iii) Draw the plot of intensity distribution in a diffraction pattern due to a single slit. [3 marks]

Solution:

Concept:

- For a slit of width a , the extreme-ray phase difference is $\phi = 2\pi a \sin \theta / \lambda$. With $u = \phi/2$, the intensity is $I = I_0 (\sin u / u)^2$, where I_0 is the central intensity.
- On a distant screen at distance D , the central diffraction width is $W = 2\lambda D / a$, while the double-slit fringe width for slit separation d is $\beta = \lambda D / d$.

Step 1: (i) Decide whether cancellation is complete The printed phase difference is 5π , so the extreme-ray path difference is $5\lambda/2$. Divide the slit into five equal zones: rays from successive zones differ in path by $\lambda/2$. Four zones cancel in pairs, leaving an uncompensated zone. Thus the point lies in a weak bright fringe, rather than a diffraction minimum. Quantitatively,

$$I = I_0 \left[\frac{\sin(5\pi/2)}{5\pi/2} \right]^2 = \frac{4I_0}{25\pi^2} > 0.$$

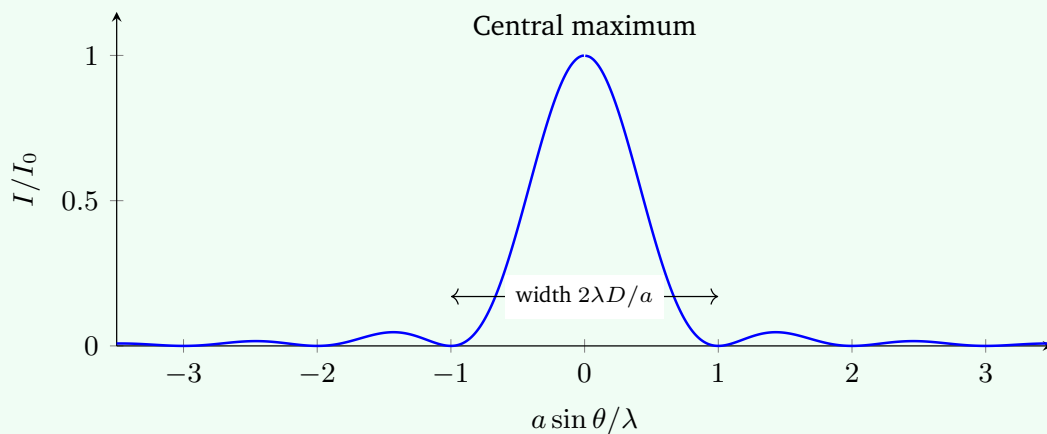
This is the usual secondary-bright-fringe condition in the elementary approximation; it does not place the point at the exact peak of that secondary lobe.

Step 2: (ii) Compare the two pattern widths The standard fringe-count relation used here is the central-envelope width divided by the interference fringe spacing. Hence,

$$\frac{W}{\beta} = \frac{2\lambda D / a}{\lambda D / d} = \frac{2d}{a} = 8.$$

Rearranging gives $8a = 2d$. Both the wavelength and screen distance cancel because they scale the two pattern widths equally.

Step 3: (iii) Plot the single-slit intensity distribution The graph uses $x = a \sin \theta / \lambda$ as its horizontal coordinate, so the diffraction minima occur at $x = \pm 1, \pm 2, \dots$. The central maximum extends from -1 to $+1$; it is twice as wide as a secondary lobe. The weaker side maxima decrease rapidly in height and appear symmetrically on both sides. The value at $x = 0$ is the limiting value $I/I_0 = 1$.



Single-slit intensity: minima at nonzero integral values of $a \sin \theta / \lambda$.

Step 4: Conclusion (i) A weak bright fringe is formed. (ii) The required slit width is $a = d/4$, using the standard width-to-fringe-spacing count. (iii) The plot shows a broad central maximum and successively weaker secondary maxima.

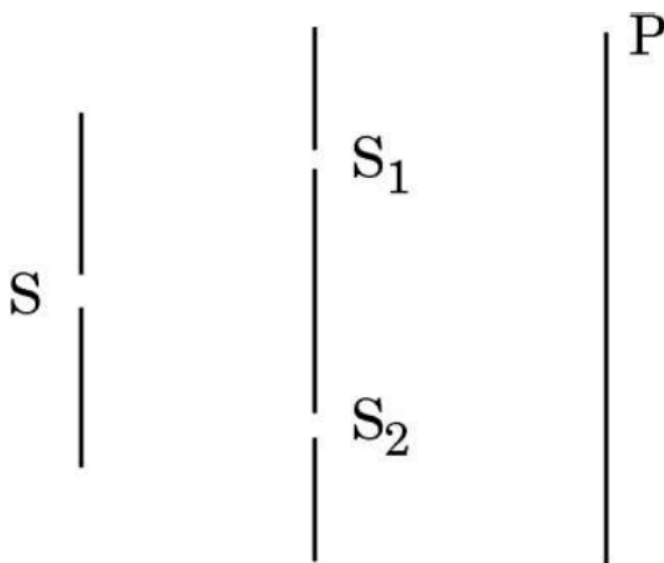
Quick Tip to Solve: For a combined double-slit and diffraction pattern, divide the central diffraction width by the interference fringe width before substituting numbers.

OR

28(b). (i) In a Young's double-slit experiment $SS_2 - SS_1 = \frac{\lambda}{4}$, where S_1 and S_2 are the two slits as shown in the figure. Find the path difference ($S_2P - S_1P$) for constructive and destructive interference at P.

(ii) What is the effect on the interference fringes in a Young's double-slit experiment, if the monochromatic source S is replaced by a source of white light?

[3 marks]



Solution:

Concept:

- The phase difference at the screen depends on the complete paths from the common source to the observation point, including the paths before the two slits.
- Constructive interference requires total path difference $n\lambda$, while destructive interference requires $(n + \frac{1}{2})\lambda$, with n any integer. For each wavelength, the fringe spacing is $\beta = \lambda D/d$.

Step 1: (i) Include the initial path difference Let the requested signed path difference be $\delta = S_2P - S_1P$. The total path difference, taking the second path minus the first consistently, is

$$\begin{aligned}\Delta &= (SS_2 + S_2P) - (SS_1 + S_1P) \\ &= \frac{\lambda}{4} + \delta.\end{aligned}$$

It would be incorrect to apply the interference conditions to δ alone, since the incident waves already have a phase difference at the slits.

Step 2: Apply the bright and dark conditions For constructive interference, $\Delta = n\lambda$, giving

$$\delta = n\lambda - \frac{\lambda}{4} = \frac{(4n - 1)\lambda}{4}.$$

For destructive interference, $\Delta = (n + \frac{1}{2})\lambda$, giving

$$\delta = \left(n + \frac{1}{2}\right)\lambda - \frac{\lambda}{4} = \frac{(4n + 1)\lambda}{4}.$$

For example, $\delta = -\lambda/4$ gives zero total path difference and hence a bright fringe; $\delta = \lambda/4$ gives total path difference $\lambda/2$ and a dark fringe.

Step 3: (ii) Replace monochromatic light by white light White light contains many wavelengths. At the position where the total optical path difference is zero, all wavelengths interfere constructively, producing a white central fringe. The incident-path offset in this arrangement shifts that position from the equal-screen-path point. On either side, different wavelengths have maxima at different positions: violet fringes lie nearer the white fringe and red fringes farther away. A few coloured fringes are visible close to the centre. Farther out, the patterns for different wavelengths overlap, wash out the contrast, and merge into nearly uniform illumination rather than a long sequence of distinct fringes.

Step 4: Conclusion Constructive interference requires $S_2P - S_1P = (4n - 1)\lambda/4$; destructive interference requires $S_2P - S_1P = (4n + 1)\lambda/4$, with $n \in \mathbb{Z}$. White light produces a white zero-path-difference fringe with a few coloured fringes on each side.

Quick Tip to Solve: Write both complete source-to-screen paths in the same subtraction order before applying the bright or dark fringe condition.

29(a). A resistor of $30\ \Omega$ and a capacitor of $\frac{250}{\pi}\ \mu\text{F}$ are connected in series to a 200 V, 50 Hz ac source. Calculate (i) the current in the circuit, and (ii) voltage drops across the resistor and the capacitor. (iii) Is the algebraic sum of these voltages more than the source voltage? If yes, solve the paradox. [3 marks]

Solution:

Concept:

- A capacitor has reactance $X_C = 1/(2\pi fC)$, where f is the supply frequency and C is the capacitance in farads. A series RC circuit has impedance magnitude $Z = \sqrt{R^2 + X_C^2}$.
- The same rms current I flows through both components: $I = V/Z$, $V_R = IR$ and $V_C = IX_C$. The resistor voltage is in phase with current; the capacitor voltage lags current by 90° .

Step 1: (i) Calculate reactance and circuit current The official question gives $R = 30\ \Omega$, $C = (250/\pi)\ \mu\text{F}$, $f = 50\ \text{Hz}$ and source voltage $V = 200\ \text{V}$. The specified ac voltage is taken as its rms value. Converting capacitance to farads,

$$X_C = \frac{1}{2\pi(50)(250/\pi) \times 10^{-6}} = 40\ \Omega,$$

$$Z = \sqrt{30^2 + 40^2} = 50\ \Omega,$$

$$I = \frac{200}{50} = 4\ \text{A}.$$

The reactance and resistance enter in quadrature because their voltages have different phases; adding 30 and 40 directly would not give the impedance.

Step 2: (ii) Calculate the component voltage drops Both series components carry the same rms current. Thus,

$$V_R = IR = (4)(30) = 120\ \text{V},$$

$$V_C = IX_C = (4)(40) = 160\ \text{V}.$$

These are the rms readings a voltmeter would measure across the resistor and capacitor separately; their maxima occur at different times.

Step 3: (iii) Resolve the apparent voltage paradox The algebraic sum of the rms magnitudes is $120 + 160 = 280\ \text{V}$, which exceeds the source rms voltage. However, these two voltages differ in phase by 90° , so their phasors add at right angles:

$$V = \sqrt{V_R^2 + V_C^2} = \sqrt{120^2 + 160^2} = 200\ \text{V}.$$

Kirchhoff's voltage law still holds at each instant: $v(t) = v_R(t) + v_C(t)$. The false paradox arises only when rms magnitudes are added as if the corresponding alternating voltages were in phase.

Step 4: Conclusion $I = 4\ \text{A}$, $V_R = 120\ \text{V}$, $V_C = 160\ \text{V}$, all rms values. Their magnitude sum is 280 V, but their phasor sum has magnitude 200 V, exactly the source voltage.

Quick Tip to Solve: Recognise the 30-40-50 impedance triangle; then use the same 3:4:5 ratio for the resistor, capacitor and source rms voltages.

29(b). A series LCR circuit with $R = 20\ \Omega$, $L = 2\ \text{H}$ and $C = 50\ \mu\text{F}$ is connected to a 200 volts ac source of variable frequency. What is (i) the amplitude of the current, and (ii) the average power transferred to the circuit in one complete cycle, at resonance? (iii) Calculate the potential drop across the capacitor. [3 marks]

Solution:

Concept:

- At resonance in a series LCR circuit, the inductive and capacitive reactances are equal: $\omega_0 L = 1/(\omega_0 C)$. The impedance then equals the resistance, $Z = R$.
- The stated ac source voltage is its rms value. Peak current is $I_0 = \sqrt{2}I_{\text{rms}}$, and average power is $P = V_{\text{rms}}I_{\text{rms}}\cos\phi$.
- The rms capacitor voltage is $V_{C,\text{rms}} = I_{\text{rms}}X_C$, where $X_C = 1/(\omega_0 C)$.

Step 1: (i) Find the current amplitude At resonance the net reactance vanishes, so the source voltage and circuit current are in phase. With $V_{\text{rms}} = 200\ \text{V}$ and $R = 20\ \Omega$,

$$I_{\text{rms}} = \frac{200}{20} = 10\ \text{A}, \quad I_0 = \sqrt{2} \times 10 = 10\sqrt{2}\ \text{A}.$$

The amplitude is the peak value, so it must not be confused with the rms current of 10 A.

Step 2: (ii) Evaluate the average power Since $\phi = 0$, the power factor is unity. The inductor and capacitor store and return energy, while the resistor dissipates energy. Thus the power averaged over a complete cycle is

$$P_{\text{av}} = I_{\text{rms}}^2 R = (10)^2(20) = 2000\ \text{W}.$$

Equivalently, using peak quantities gives $P_{\text{av}} = I_0^2 R/2$, with the same result.

Step 3: (iii) Calculate the capacitor voltage First determine the resonant angular frequency and then the capacitive reactance:

$$\begin{aligned} \omega_0 &= \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{2 \times 50 \times 10^{-6}}} = 100\ \text{rad s}^{-1}, \\ X_C &= \frac{1}{100 \times 50 \times 10^{-6}} = 200\ \Omega, \\ V_{C,\text{rms}} &= 10 \times 200 = 2000\ \text{V}. \end{aligned}$$

The capacitor voltage can exceed the source voltage: the equal inductor and capacitor voltages have opposite phases and cancel in the phasor sum. If a peak capacitor voltage is required, it is $V_{C,0} = 2000\sqrt{2}\ \text{V}$.

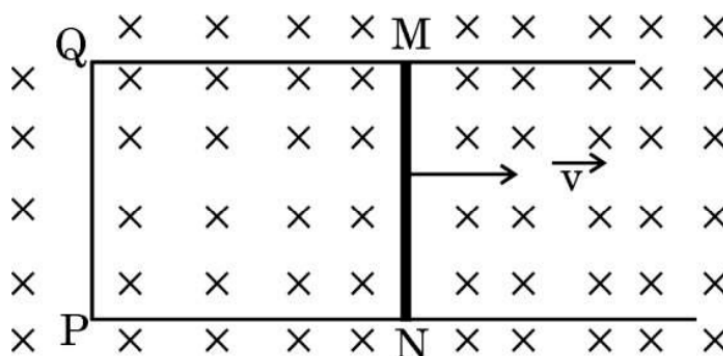
Step 4: Conclusion $I_0 = 10\sqrt{2}\ \text{A} \approx 14.1\ \text{A}$, $P_{\text{av}} = 2000\ \text{W}$, and $V_{C,\text{rms}} = 2000\ \text{V}$.

Quick Tip to Solve: Use rms voltage for average power, but multiply the rms current by $\sqrt{2}$ when the question asks for amplitude.

30. A rectangular conductor MNPQ with a movable arm MN (resistance r) is kept in a uniform magnetic field as shown in the figure. Resistance of arms MQ, QP and PN are negligible. Obtain the expression for the:

- (a) current induced in the loop specifying its direction, and
 (b) power required to move the arm.

[3 marks]



Solution:

Concept:

- A rod of length ℓ , moving at speed v perpendicular to a uniform magnetic field B , develops a motional emf of magnitude $\varepsilon = B\ell v$.
- Lenz's law fixes the current direction so that its magnetic effect opposes the change in flux. With total circuit resistance r , the induced current has magnitude $I = \varepsilon/r$.

Step 1: (a) Derive the induced current and determine its direction Let $\ell = MN$ be the separation of the parallel rails, and let x be the distance of MN from QP. As MN moves right with speed v , the loop area $A = \ell x$ grows at rate $dA/dt = \ell v$. Therefore,

$$|\varepsilon| = \left| \frac{d\Phi_B}{dt} \right| = B\ell v, \quad I = \frac{B\ell v}{r}.$$

The crosses show a magnetic field into the paper, so the inward flux increases. The induced current must produce an outward magnetic field and is consequently anticlockwise: $N \rightarrow M \rightarrow Q \rightarrow P \rightarrow N$. In MN it flows from N to M, making M the positive end.

Step 2: (b) Obtain the force and mechanical power The upward current in MN and inward magnetic field give a leftward magnetic force, opposing motion:

$$F_B = BI\ell = \frac{B^2\ell^2 v}{r}.$$

A balancing rightward external force maintains constant speed. Its power is

$$P_{\text{ext}} = F_{\text{ext}}v = \frac{B^2\ell^2 v^2}{r}.$$

As a check, $I^2 r = (B\ell v/r)^2 r = P_{\text{ext}}$: mechanical work becomes Joule heat in MN.

Step 3: Conclusion $I = B\ell v/r$, anticlockwise, and $P = B^2\ell^2 v^2/r$, where $\ell = MN$.

Quick Tip to Solve: For the expanding loop, first oppose the increasing inward flux; then use $P = I^2 r$ to check the mechanical-power result.

Section D (15 marks)

31(a). (i) A germanium crystal is doped with antimony. With the help of energy-band diagram, explain how the conductivity of the doped crystal is affected.

(ii) Briefly explain the two processes involved in the formation of a p-n junction.

(iii) What will the effect of (1) forward biasing, and (2) reverse biasing be on the width of depletion layer in a p-n junction diode?

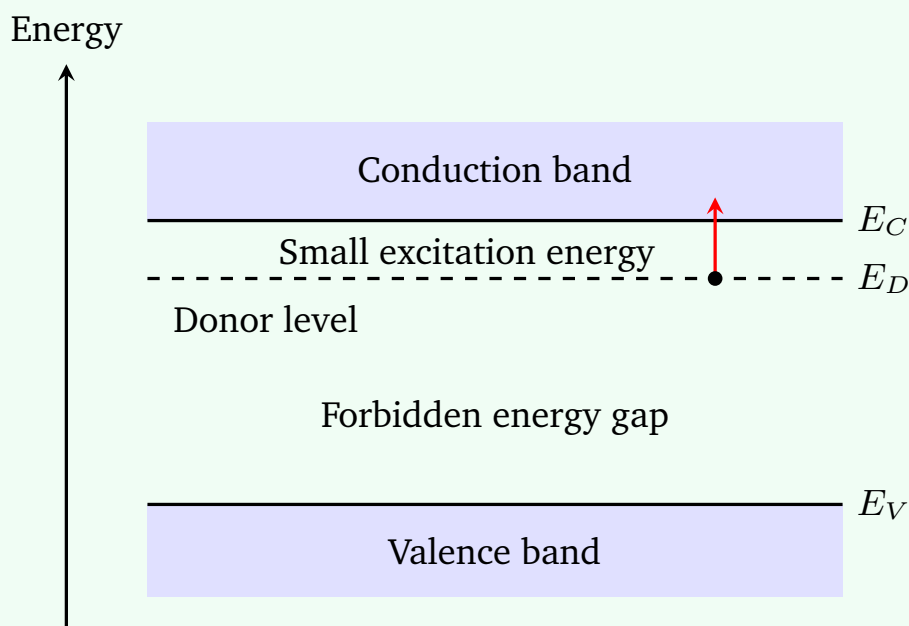
[5 marks]

Solution:

Concept:

- Germanium is tetravalent, whereas antimony is pentavalent. A pentavalent dopant supplies donor electrons and produces an n-type semiconductor.
- Conductivity is $\sigma = e(n\mu_e + p\mu_h)$, where n, p are electron and hole concentrations and μ_e, μ_h their mobilities.
- Diffusion is carrier motion caused by a concentration gradient; drift is carrier motion caused by an electric field. Both occur during p-n junction formation.

Step 1: (i) Explain donor doping using the energy bands An antimony atom replacing a germanium atom uses four of its five valence electrons to form covalent bonds with neighbouring Ge atoms. The fifth electron is weakly bound. The donor impurity introduces an energy level E_D in the forbidden gap, just below the conduction-band edge E_C , as shown below. Very little thermal energy is therefore needed to excite this electron into the conduction band, leaving an immobile positive donor ion. At ordinary temperatures, donor electrons greatly increase the concentration of free conduction electrons. The crystal becomes n-type: electrons are majority carriers and holes are minority carriers. Consequently its conductivity increases and its resistivity decreases compared with pure germanium. Doping does not make the crystal negatively charged overall; positive donor ions balance the extra mobile electrons.



Energy bands of antimony-doped germanium; the donor level lies just below the conduction band (not to scale).

Step 2: (ii) Describe diffusion during junction formation On forming a p-n junction within a semiconductor crystal, electrons diffuse from the electron-rich n-side to the p-side, and holes diffuse

from the hole-rich p-side to the n-side. They recombine near the junction. Loss of mobile electrons exposes fixed positive donor ions on the n-side; loss of mobile holes exposes fixed negative acceptor ions on the p-side. This region is depleted of mobile carriers and is called the depletion layer.

Step 3: (ii) Describe drift and the equilibrium barrier The uncovered ions establish an electric field directed from the positive n-side toward the negative p-side. This field opposes further majority-carrier diffusion and creates a potential barrier. It also drives holes toward the p-side and electrons toward the n-side, producing drift current opposite to diffusion current. At thermal equilibrium, without an external bias, drift and diffusion currents are equal in magnitude, so the net junction current is zero.

Step 4: (iii) Explain the effects of bias on depletion width In forward bias, the p-side is connected to the positive terminal and the n-side to the negative terminal of the battery. The applied voltage opposes the junction barrier. Majority carriers are pushed toward the junction, the barrier is reduced and the depletion layer becomes narrower. In reverse bias, the p-side is connected to the negative terminal and the n-side to the positive terminal. The applied voltage reinforces the barrier and pulls majority carriers away from the junction. More fixed ions are uncovered, so the depletion layer becomes wider.

Step 5: Conclusion Antimony produces n-type germanium with increased conductivity through donor electrons. Junction formation involves diffusion and opposing drift. Forward bias decreases depletion-layer width; reverse bias increases it.

Quick Tip to Solve: Place the donor level just below the conduction band; remember that forward bias lowers the barrier and narrows the depletion region.

OR

31(b). (i) With the help of a circuit diagram, briefly explain the working of a full-wave rectifier using p-n junction diodes.

(ii) Draw V-I characteristics of a p-n junction diode. Explain how these characteristics make a diode suitable for rectification.

(iii) Carbon and silicon have the same lattice structure. Then why is carbon an insulator but silicon a semiconductor?

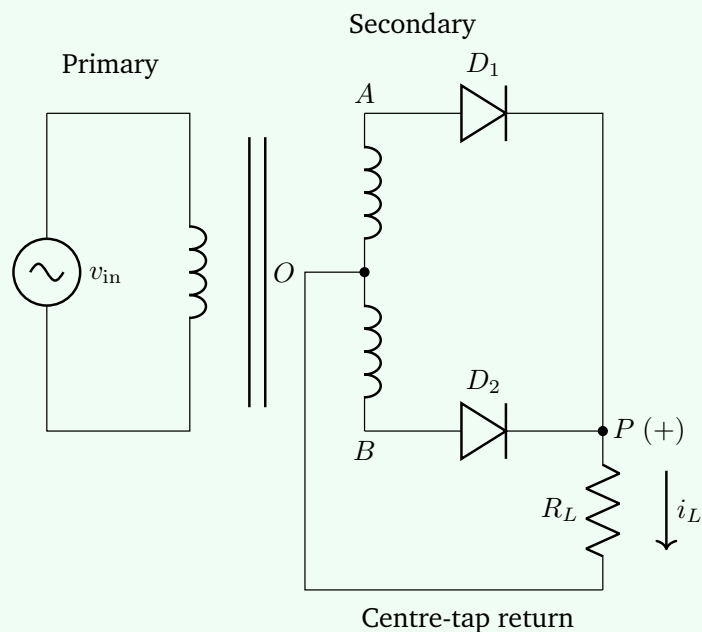
[5 marks]

Solution:

Concept:

- A p-n junction diode conducts readily in forward bias and offers very high resistance in reverse bias, before breakdown. This unequal conduction in the two directions allows rectification.
- In a centre-tapped full-wave rectifier, two diodes conduct alternately while the load current retains the same direction during both half-cycles of the input.
- The forbidden energy gap E_g separates the valence and conduction bands. A smaller gap allows more electrons to become mobile charge carriers at room temperature.

Step 1: (i) Connect the full-wave rectifier Connect the ends A and B of a centre-tapped transformer secondary to the anodes of diodes D_1 and D_2 . Join their cathodes at P , the positive output terminal. Connect the load resistance R_L between P and the centre tap O . The primary is connected to the alternating supply. The voltages of A and B , measured relative to O , have equal magnitudes and opposite signs at any instant.



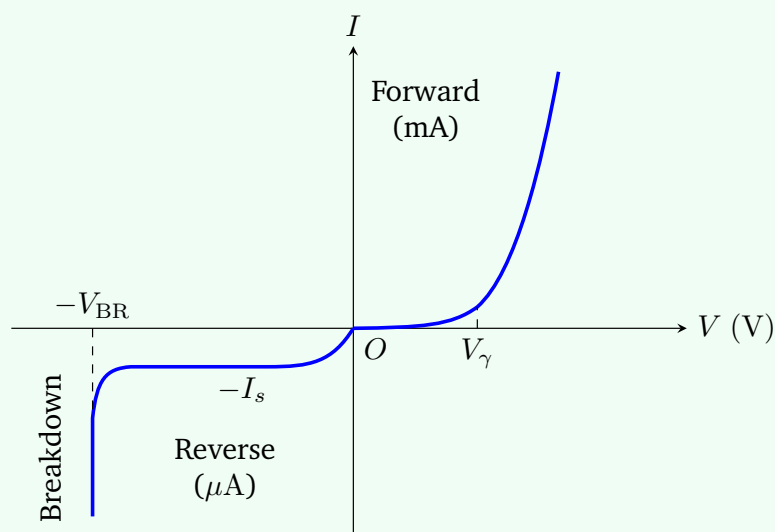
Centre-tapped full-wave rectifier; both diode cathodes meet at P.

Step 2: (i) Follow the current during each half-cycle When A is positive and B is negative relative to O, D_1 is forward biased and D_2 is reverse biased. Conventional current follows $A \rightarrow D_1 \rightarrow P \rightarrow R_L \rightarrow O$, returning through the upper half of the secondary. During the next half-cycle, B is positive and A is negative relative to O. Now D_2 conducts and D_1 blocks. Current follows $B \rightarrow D_2 \rightarrow P \rightarrow R_L \rightarrow O$, returning through the lower half of the secondary. Thus current flows from P towards O through the load in both half-cycles. For ideal diodes, if either half-secondary has peak voltage V_m ,

$$v_L = V_m |\sin \omega t|, \quad i_L = \frac{v_L}{R_L}.$$

Both halves of the input are used, so the output is unidirectional but pulsating, with ripple frequency $2f$ for input frequency f . A filter would be required to smooth this pulsating output.

Step 3: (ii) Interpret the diode characteristics In forward bias, the current is small initially and then rises steeply beyond the knee voltage V_γ . Typical knee voltages are about 0.7 V for silicon and 0.3 V for germanium. The diode therefore has low resistance in its conducting region. In reverse bias, only a very small reverse saturation current I_s , due to minority carriers, flows until the breakdown voltage V_{BR} is reached. Beyond breakdown, the reverse-current magnitude increases sharply. A rectifier is operated below reverse breakdown. Hence a diode passes the intended forward current while nearly blocking the reverse current. In the two-diode circuit, this property selects one diode on each half-cycle and prevents reversal of current through R_L . The qualitative graph uses different forward- and reverse-current scales to make the small leakage visible.



Qualitative diode V-I characteristics; forward current in mA, reverse leakage in μA . Scales are schematic.

Step 4: (iii) Compare the energy gaps of carbon and silicon Here carbon means diamond, the form having a crystal structure analogous to silicon. Although both have four valence electrons and form covalent bonds, their energy gaps are very different. Diamond has a large forbidden gap, about 5.4 eV, whereas silicon has a much smaller gap, about 1.1 eV. At room temperature, thermal energy cannot promote an appreciable number of electrons across diamond's large gap. Its valence electrons remain bound and it behaves as an insulator. In silicon, thermal excitation across the smaller gap produces a useful population of conduction-band electrons and valence-band holes, so it behaves as a semiconductor. Similar lattice geometry alone does not imply similar electrical conductivity.

Step 5: Conclusion The two diodes conduct alternately and produce load current in the same direction during both half-cycles. A diode's low forward resistance and high reverse resistance enable rectification. Diamond is insulating because of its large energy gap; silicon is semiconducting because its gap is much smaller.

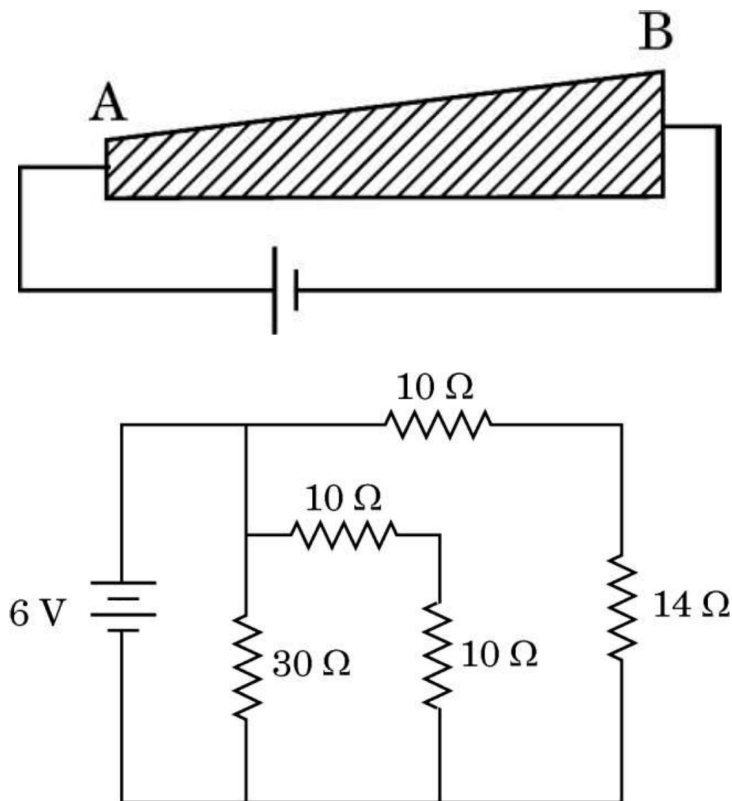
Quick Tip to Solve: Trace each conducting path from a secondary end through its diode and the load back to the centre tap: both paths must cross the load in the same direction. Compare band gaps, not just lattice structure, for the carbon-silicon explanation.

32(a). (i) Define mobility of electrons. Give its SI units.

(ii) A steady current flows through a wire AB, as shown in the figure. What happens to the electric field and the drift velocity along the wire? Justify your answer.

(iii) Consider the circuit shown in the figure. Find the effective resistance of the circuit and the current drawn from the battery.

[5 marks]



Solution:

Concept:

- Electron mobility is $\mu = v_d/E = e\tau/m$, where v_d is the magnitude of drift velocity, E is electric-field magnitude and τ is the mean relaxation time.
- Steady-current continuity gives $I = neAv_d$, where n is free-electron number density and A is local cross-sectional area. For a uniform material, $J = \sigma E$ and $J = I/A$.
- Series resistances add; parallel branches share the same potential difference and obey $1/R_{eq} = \sum 1/R_i$. The battery current is $I = V/R_{eq}$.

Step 1: (i) Define electron mobility and its unit Mobility is the magnitude of the drift velocity acquired by an electron per unit applied electric field. Thus

$$\mu = \frac{v_d}{E}, \quad [\mu] = \frac{\text{m s}^{-1}}{\text{V m}^{-1}} = \text{m}^2 \text{V}^{-1} \text{s}^{-1}.$$

The mobility is positive; the electron drift velocity vector is opposite to the field, so $\vec{v}_d = -\mu\vec{E}$.

Step 2: (ii) Apply current continuity to the tapering wire The wire widens from A to B. In steady state charge does not accumulate within the wire, so the same current crosses every cross-section. Taking the material and temperature to be uniform, n and conductivity σ remain constant. Consequently,

$$v_d = \frac{I}{neA}, \quad E = \frac{J}{\sigma} = \frac{I}{\sigma A}.$$

As the area increases from A to B, both the drift speed and the electric-field magnitude decrease. The battery's positive terminal is connected to A, so the field and conventional current point towards B, while electrons drift towards A. The statement about decrease refers to the magnitudes at successive positions from A to B, not to the direction of electron motion.

Step 3: (iii) Identify the three parallel branches The entire upper-left connecting wire is one node and the bottom wire is the other node. Between these same two nodes there are three branches: the single $30\ \Omega$ resistor; the two inner $10\ \Omega$ resistors in series; and the outer $10\ \Omega$ and $14\ \Omega$ resistors in series. Their resistances are therefore

$$R_1 = 30\ \Omega, \quad R_2 = 10 + 10 = 20\ \Omega, \quad R_3 = 10 + 14 = 24\ \Omega.$$

The two inner resistors have no branching at their common junction, which is why they are in series, even though they are drawn at right angles.

Step 4: (iii) Combine the branches and calculate battery current Since all three branches are across the $6\ \text{V}$ battery,

$$\frac{1}{R_{\text{eq}}} = \frac{1}{30} + \frac{1}{20} + \frac{1}{24} = \frac{4 + 6 + 5}{120} = \frac{1}{8}\ \Omega^{-1}.$$

Thus $R_{\text{eq}} = 8\ \Omega$. Applying Ohm's law gives

$$I = \frac{6}{8} = 0.75\ \text{A}.$$

As a check, the branch currents are $6/30 = 0.20\ \text{A}$, $6/20 = 0.30\ \text{A}$ and $6/24 = 0.25\ \text{A}$; their sum equals the battery current.

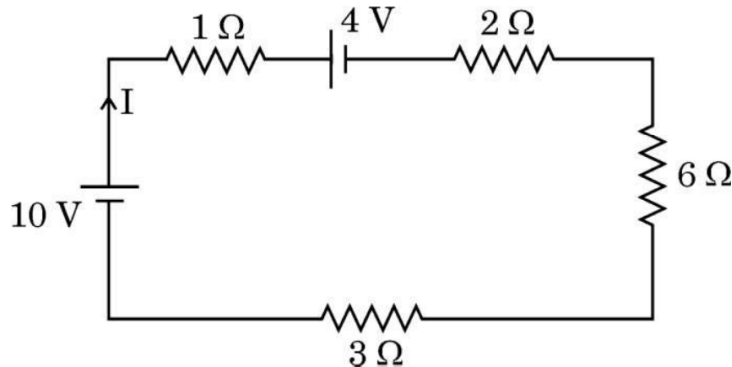
Step 5: Conclusion (i) $\mu = v_d/E$, with SI unit $\text{m}^2\text{V}^{-1}\text{s}^{-1}$. (ii) Both E and drift-speed magnitude decrease from A to B. (iii) $R_{\text{eq}} = 8\ \Omega, \quad I = 0.75\ \text{A}$.

Quick Tip to Solve: Mark the two battery nodes first: this exposes the $30\ \Omega$, $20\ \Omega$ and $24\ \Omega$ parallel branches. In the tapering wire, keep current fixed and use the local area.

32(b). (i) Define electrical conductivity of a wire. Give its SI unit.

(ii) High current is to be drawn safely from (1) a low-voltage battery, and (2) a high-voltage battery. What can you say about the internal resistance of the two batteries?

(iii) Calculate the total energy supplied by the batteries to the circuit shown in the figure, in one minute. [5 marks]



Solution:

Concept:

- Electrical conductivity σ is the reciprocal of resistivity ρ ; it relates current density and electric field by $J = \sigma E$.
- For a cell of emf $\mathcal{E}$, internal resistance r and external resistance R , the current is $I = \mathcal{E}/(R + r)$. The limiting short-circuit current is $\mathcal{E}/r$.
- Kirchhoff's loop law uses signed emfs. A source supplies energy $\mathcal{E}It$ when current leaves its positive terminal; it absorbs that energy when current enters its positive terminal.

Step 1: (i) Define conductivity and state its SI unit Conductivity measures how readily a material conducts electric current. It is the reciprocal of the material's resistivity, or equivalently the current density produced per unit electric field:

$$\sigma = \frac{1}{\rho} = \frac{J}{E}.$$

Since resistivity has unit $\Omega \text{ m}$, the SI unit of conductivity is $\Omega^{-1} \text{ m}^{-1}$, also written S m^{-1} . For a uniform wire of length l , area A and resistance R , $\sigma = l/(RA)$.

Step 2: (ii) Compare the required internal resistances For the low-voltage battery, the internal resistance should be very small. Otherwise a substantial fraction of its small emf is lost internally and a high external current cannot be obtained. This follows directly from $I = \mathcal{E}/(R + r)$. For the high-voltage battery, a comparatively larger internal resistance is required for safe operation: its large emf can still drive a high current, while the internal resistance limits an excessively large current if the external resistance becomes very small. In particular, $I_{\text{sc}} = \mathcal{E}/r$; hence a higher emf requires a higher current-limiting resistance for the same safe limiting current. This is a qualitative comparison; no numerical resistance can be fixed without the permissible current and load.

Step 3: (iii) Determine the signs of the emfs and the loop current Follow the indicated clockwise current. The 10 V battery is crossed from its negative to positive terminal, producing a rise of 10 V. The 4 V battery is crossed from its positive to negative terminal, producing a drop of 4 V. The batteries

therefore oppose each other; their emfs must not be added. All four resistors are in series:

$$R_{\text{total}} = 1 + 2 + 6 + 3 = 12 \Omega.$$

Kirchhoff's loop law gives

$$10 - 4 - 12I = 0, \quad I = \frac{6}{12} = 0.50 \text{ A}.$$

The positive value confirms the indicated current direction.

Step 4: (iii) Calculate the net energy supplied in one minute The elapsed time is $t = 60 \text{ s}$, so the charge passing is $Q = It = 0.50 \times 60 = 30 \text{ C}$. The 10 V battery delivers energy

$$W_{10} = 10Q = 300 \text{ J}.$$

Current enters the positive terminal of the 4 V battery, so that battery is being charged and absorbs $W_4 = 4Q = 120 \text{ J}$. Thus the net energy supplied by the two batteries to the resistive circuit is

$$W_{\text{net}} = (10 - 4)It = 6 \times 0.50 \times 60 = 180 \text{ J}.$$

Energy conservation confirms this: the heat in the resistors is $I^2 R_{\text{total}} t = (0.50)^2 \times 12 \times 60 = 180 \text{ J}$. The 300 J delivered by the larger battery divides into 120 J stored in the smaller battery and 180 J dissipated in the resistors.

Step 5: Conclusion (i) $\sigma = 1/\rho$, with SI unit S m^{-1} . (ii) The low-voltage battery should have very small internal resistance; the high-voltage battery should have comparatively larger internal resistance to limit excessive current. (iii) $I = 0.50 \text{ A}$ and the net energy supplied to the resistive circuit in one minute is 180 J.

Quick Tip to Solve: Trace current through each battery before adding emfs: here the 4 V battery is charged. Subtract its absorbed energy from the 10 V battery's output, then check with $I^2 R t$.

33(a). (i) Draw a ray diagram to show how the final image is formed at infinity in an astronomical refracting telescope. Obtain an expression for its magnifying power.

(ii) Two thin lenses L_1 and L_2 , L_1 being a convex lens of focal length 24 cm and L_2 a concave lens of focal length 18 cm are placed coaxially at a separation of 45 cm . A 1 cm tall object is placed in front of the lens L_1 at a distance of 36 cm . Find the location and height of the image formed by the combination. [5 marks]

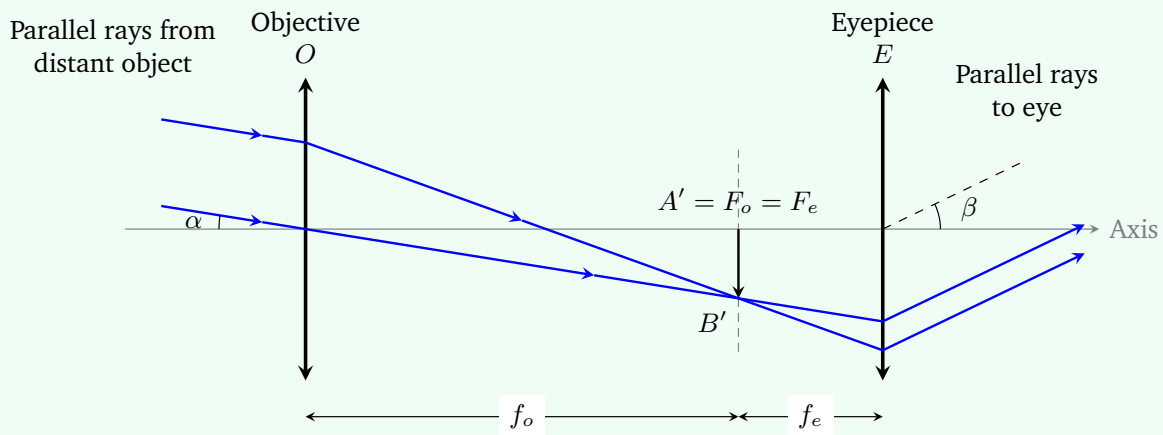
Solution:

Concept:

- In normal adjustment, an astronomical telescope has its objective's second focal plane coincident with the eyepiece's first focal plane. Its final image is at infinity and its tube length is $f_o + f_e$.
- Angular magnifying power is $M = \beta/\alpha$, where α is the angle subtended by the distant object at the unaided eye and β is the angle subtended by the final image at the eye through the telescope.
- For each thin lens, use the Cartesian convention: $1/f = 1/v - 1/u$ and transverse magnification $m = v/u$. Distances are measured from that lens; the direction of incident light is positive.

Step 1: (i) Construct the telescope in normal adjustment The objective O , with large aperture and long focal length f_o , receives parallel rays from a distant off-axis object. It forms a real, inverted

intermediate image $A'B'$ in its second focal plane. Place the short-focal-length eyepiece E so that $A'B'$ also lies in its first focal plane. Rays from each point of this image emerge parallel from the eyepiece, producing the final magnified, inverted image at infinity. The eye views the emerging parallel beam without accommodation.



Astronomical telescope in normal adjustment (schematic): $A'B'$ lies in the common focal plane and the emerging rays are parallel.

Step 2: (i) Derive the angular magnifying power Let the magnitude of the intermediate image height be h . In the paraxial approximation, the small angles in radians satisfy

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

Dividing gives $|M| = (h/f_e)/(h/f_o) = f_o/f_e$. The intermediate image and hence the final image are inverted relative to the original object, so their signed angular directions are opposite. Thus the signed magnifying power is $M = -f_o/f_e$; when only the magnitude is required it is quoted as f_o/f_e .

Step 3: (ii) Find the image formed by the convex lens Set L_1 at $x = 0$ and L_2 at $x = 45$ cm, with light travelling to the right. For the first lens,

$$u_1 = -36 \text{ cm}, \quad f_1 = +24 \text{ cm}.$$

Hence

$$\frac{1}{v_1} = \frac{1}{f_1} + \frac{1}{u_1} = \frac{1}{24} - \frac{1}{36} = \frac{1}{72},$$

$$v_1 = +72 \text{ cm}, \quad m_1 = \frac{72}{-36} = -2.$$

Without L_2 , the first lens would form a real image at $x = 72$ cm, with height $h_1 = m_1 h_0 = -2$ cm.

Step 4: (ii) Use the converging beam as a virtual object for the concave lens The rays reach L_2 before meeting at the first image. Their intended meeting point lies $72 - 45 = 27$ cm to the right of L_2 . It is therefore a virtual object for this lens, giving $u_2 = +27$ cm, while the concave lens has $f_2 = -18$ cm.

$$\frac{1}{v_2} = \frac{1}{f_2} + \frac{1}{u_2} = -\frac{1}{18} + \frac{1}{27} = -\frac{1}{54},$$

$$v_2 = -54 \text{ cm}, \quad m_2 = \frac{-54}{27} = -2.$$

The emerging rays diverge and their backward extensions meet 54 cm to the left of L_2 . The image coordinate is $x = 45 - 54 = -9$ cm. The total transverse magnification is $m_1 m_2 = (-2)(-2) = +4$, so

$$h = m_1 m_2 h_0 = +4 \text{ cm.}$$

Step 5: Conclusion (i) For a telescope in normal adjustment, $M = -f_o/f_e$, with magnitude f_o/f_e , and the lens separation is $f_o + f_e$. (ii) The combination forms a virtual, erect image of height 4 cm, located 54 cm to the left of L_2 , equivalently 9 cm to the left of L_1 .

Quick Tip to Solve: Locate the first image on a common coordinate axis before applying the second lens formula. Here it lies beyond L_2 , so its object distance is positive: $u_2 = +27 \text{ cm}$.

OR

33(b). (i) Explain the working principle of an optical fibre with the help of a diagram. Mention one use of a light pipe.

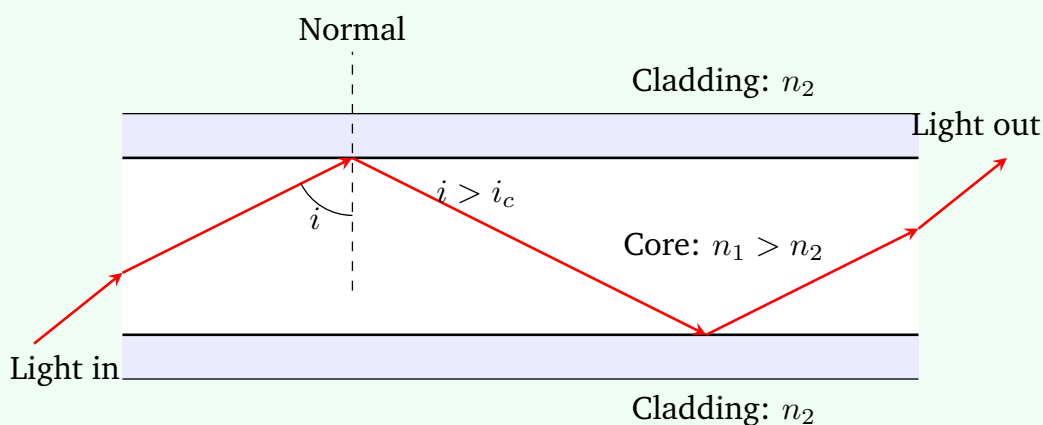
(ii) A ray of light is incident at an angle of 60° on one face of a prism with the prism angle $A = 60^\circ$. The ray passes symmetrically through the prism. Find the angle of minimum deviation (δ_m) and refractive index of the material of the prism. If the prism is immersed in water, how will δ_m be affected? Justify your answer. [5 marks]

Solution:

Concept:

- Total internal reflection occurs when light travels from an optically denser medium to a rarer medium and its angle of incidence exceeds the critical angle. For core and cladding indices $n_1 > n_2$, $\sin i_c = n_2/n_1$.
- In a prism, $r_1 + r_2 = A$ and $\delta = i + e - A$. At minimum deviation the path is symmetric: $i = e$ and $r_1 = r_2 = A/2$.
- The relative refractive index is $n_{\text{rel}} = \sin[(A + \delta_m)/2] / \sin(A/2)$; in air it equals the prism's refractive index to the usual approximation.

Step 1: (i) Explain guidance by total internal reflection An optical fibre consists of a transparent core of refractive index n_1 , surrounded by a cladding of lower refractive index n_2 . Light entering the core within the suitable range of angles strikes the core-cladding boundary with incidence angle $i > i_c$, measured from the normal. It undergoes total internal reflection at successive encounters with this boundary, so it is guided along the fibre with little loss. The cladding maintains the required refractive-index contrast and protects the guiding core. Light pipes are used in medical endoscopes to illuminate and inspect internal organs.



Repeated total internal reflection in an optical fibre; the incidence angle is measured from the normal.

Step 2: (ii) Use the symmetric path to find minimum deviation Since the ray passes symmetrically through the prism, it is in the minimum-deviation condition. The emergence angle equals the given incidence angle, while the two refraction angles are equal:

$$e = i = 60^\circ, \quad r_1 = r_2 = \frac{A}{2} = 30^\circ.$$

Substitute in the deviation relation:

$$\delta_m = i + e - A = 60^\circ + 60^\circ - 60^\circ = 60^\circ.$$

Step 3: Calculate the prism's refractive index Apply Snell's law at the first face, taking the refractive index of air as unity:

$$n_p = \frac{\sin i}{\sin r_1} = \frac{\sin 60^\circ}{\sin 30^\circ} = \frac{\sqrt{3}/2}{1/2} = \sqrt{3} \simeq 1.73.$$

This also follows directly from the minimum-deviation formula with $A = 60^\circ$ and $\delta_m = 60^\circ$.

Step 4: Explain the change on immersion in water In water, the relevant index is the prism's index relative to water, n_p/n_w , which is smaller than its index relative to air. The minimum-deviation relation becomes

$$\sin\left(\frac{A + \delta'_m}{2}\right) = \frac{n_p}{n_w} \sin \frac{A}{2}.$$

With the same prism angle, the right side decreases because $n_w > 1$. Therefore the angle on the left decreases and so does δ'_m . Physically, the smaller optical contrast between prism and surroundings produces less bending. This compares the minimum deviations in the two surrounding media, each at its own symmetric ray position.

Step 5: Conclusion An optical fibre guides light by repeated total internal reflection; one use of a light pipe is medical endoscopy. The prism has $\delta_m = 60^\circ$ and $n_p = \sqrt{3} \simeq 1.73$. Its minimum deviation decreases when immersed in water because its relative refractive index decreases.

Quick Tip to Solve: A symmetric prism path immediately gives $e = i$, $r = A/2$ and $\delta_m = 2i - A$; use the index relative to the surrounding medium after immersion.

Section E (8 marks)

34(a). Electrostatics deals with the study of forces, fields and potentials arising from static charges. Force and electric field, due to a point charge is basically determined by Coulomb's law. For symmetric charge configurations, Gauss's law, which is also based on Coulomb's law, helps us to find the electric field. A charge/a system of charges like a dipole experience a force/torque in an electric field. Work is required to be done to provide a specific orientation to a dipole with respect to an electric field.

Answer the following questions based on the above :

(a) Consider a uniformly charged thin conducting shell of radius R . Plot a graph showing the variation of $|\vec{E}|$ with distance r from the centre, for points $0 \leq r \leq 3R$. [1 mark]

Solution:

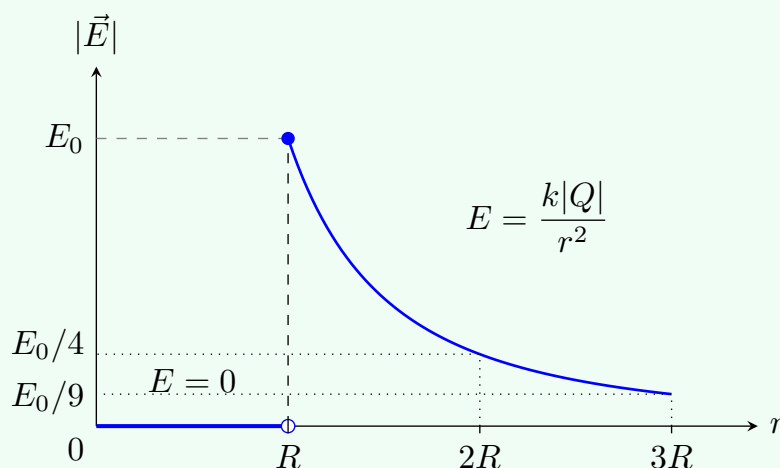
Concept:

- In electrostatic equilibrium a uniformly charged conducting spherical shell has zero electric field everywhere inside it.
- Outside a spherical shell, Gauss's law gives the field magnitude $E = k|Q|/r^2$, where $k = 1/(4\pi\epsilon_0)$, Q is the shell's charge and r is distance from its centre.

Step 1: Establish the two radial regions A spherical Gaussian surface with $r < R$ encloses no charge, so spherical symmetry and Gauss's law give $E = 0$. A surface outside the shell encloses its full charge. Thus

$$E(r) = \begin{cases} 0, & 0 \leq r < R, \\ \frac{k|Q|}{r^2}, & R < r \leq 3R. \end{cases}$$

Step 2: Plot the jump and inverse-square decrease Write $E_0 = k|Q|/R^2$. The inner surface limit is zero and the outer surface limit is E_0 , giving a discontinuity at $r = R$. For the exterior curve, $E(2R) = E_0/4$ and $E(3R) = E_0/9$. The field approaches zero as distance increases but does not reach zero at $3R$. The dashed vertical line in the sketch indicates the jump, not a continuous range of field values at the surface.

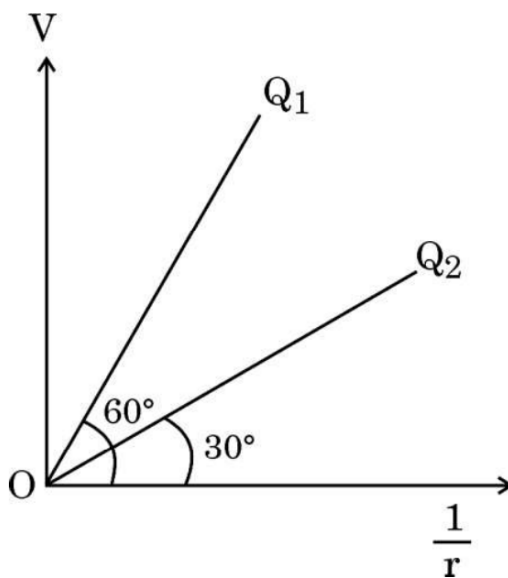


Field magnitude of a charged conducting shell from its centre to $3R$; $E_0 = k|Q|/R^2$.

Step 3: Conclusion The graph lies on the r -axis for $0 \leq r < R$, jumps to $k|Q|/R^2$ just outside R , then decreases as $1/r^2$ to $k|Q|/(9R^2)$ at $3R$.

Quick Tip to Solve: First draw the zero interior field, then anchor the exterior curve at E_0 , $E_0/4$ and $E_0/9$ for R , $2R$, $3R$.

34(b). The figure shows the variation of potential V with $\frac{1}{r}$ for two point charges Q_1 and Q_2 , where V is the potential at a distance r due to a point charge. Find $\frac{Q_1}{Q_2}$. [1 mark]



Solution:

Concept:

- The potential of a point charge, with zero at infinity, is $V = kQ/r$, where $k = 1/(4\pi\epsilon_0)$.
- On plotting V against $1/r$, the straight-line slope is kQ . For common axis scales, the ratio of slopes equals the ratio of charges.

Step 1: Read the slopes from the printed inclinations The steeper line is labelled Q_1 and makes 60°

with the horizontal $1/r$ -axis. The line labelled Q_2 makes 30° with that same axis. Both slopes are positive, so both charges are positive. Use each line's inclination to the horizontal, rather than an angle measured from the vertical.

Step 2: Form the charge ratio using the two slopes Writing $x = 1/r$, the potential relation is $V = kQx$. Thus $m_1 = kQ_1$ and $m_2 = kQ_2$. Any common plotting-scale factor cancels in their ratio:

$$\frac{Q_1}{Q_2} = \frac{m_1}{m_2} = \frac{\tan 60^\circ}{\tan 30^\circ} = \frac{\sqrt{3}}{1/\sqrt{3}} = 3.$$

Step 3: Conclusion The requested ratio is $Q_1/Q_2 = 3$, or $Q_1 : Q_2 = 3 : 1$; the steeper line represents the larger positive charge.

Quick Tip to Solve: For a V -versus- $1/r$ graph, charge is proportional to slope: take the tangent of each angle measured from the horizontal.

34(c). An electric dipole of dipole moment of $6 \times 10^{-7} \text{ C}\cdot\text{m}$ is kept in a uniform electric field of 10^4 N/C such that the dipole moment and the electric field are parallel. Calculate the potential energy of the dipole. [2 marks]

Solution:

Concept:

- The potential energy of a dipole in a uniform electric field is $U = -\vec{p} \cdot \vec{E} = -pE \cos \theta$, where θ is the angle between its dipole moment and the field.
- The conventional zero of potential energy is the perpendicular orientation, $\theta = 90^\circ$. The parallel orientation is the minimum-energy, stable equilibrium.

Step 1: Identify the angle and data The dipole moment and electric field are parallel, so $\theta = 0^\circ$ and $\cos \theta = 1$. The supplied magnitudes are $p = 6 \times 10^{-7} \text{ C m}$ and $E = 10^4 \text{ N C}^{-1}$. The word parallel fixes the sign of the energy; it is not the antiparallel orientation.

Step 2: Substitute in the energy formula Using the dot-product expression,

$$U = -(6 \times 10^{-7})(10^4) \cos 0^\circ = -6 \times 10^{-3} \text{ J}.$$

Here $\text{C m} \times \text{N C}^{-1} = \text{N m} = \text{J}$. The negative sign means the energy lies below the chosen perpendicular reference, as expected for alignment with the field.

Step 3: Conclusion The potential energy is $U = -6 \times 10^{-3} \text{ J}$, or -6 mJ .

Quick Tip to Solve: Write the angle before substituting: parallel gives $-pE$, whereas antiparallel gives $+pE$.

34(c). An electric dipole of dipole moment $\vec{p}$ is initially kept in a uniform electric field $\vec{E}$ such that $\vec{p}$ is perpendicular to $\vec{E}$. Find the amount of work done in rotating the dipole to a position at which $\vec{p}$ becomes antiparallel to $\vec{E}$. [2 marks]

Solution:

Concept:

- For a dipole in a uniform electric field, $U(\theta) = -pE \cos \theta$, where p and E denote magnitudes and θ is the angle between the two vectors.
- When the dipole is rotated slowly without a net change of kinetic energy, the work done by an external agent is $W_{\text{ext}} = U_f - U_i$. Work done by the electric field has the opposite sign.

Step 1: Evaluate the initial and final energies Initially the dipole is perpendicular to the field, so $\theta_i = 90^\circ$ and $U_i = -pE \cos 90^\circ = 0$. Finally it is antiparallel, so $\theta_f = 180^\circ$ and $U_f = -pE \cos 180^\circ = pE$. The field tends to align the dipole with itself, so this rotation must be performed against the electric torque.

Step 2: Find the work required for rotation The energy supplied by the external agent is

$$W_{\text{ext}} = \Delta U = pE(\cos 90^\circ - \cos 180^\circ) = pE.$$

This is positive because the dipole is taken from zero potential energy to a higher-energy orientation. If the question were asking for work done by the electric field during this same rotation, its value would instead be $-pE$.

Step 3: Conclusion The amount of work required to rotate the dipole is $W = pE$, done by the external agent.

Quick Tip to Solve: Use final minus initial potential energy; the perpendicular reference has zero energy and antiparallel has $+pE$.

35(a). The lens maker's formula is useful to design lenses of desired focal lengths using surfaces of suitable radii of curvature. The focal length also depends on the refractive index of the material of the lens and the surrounding medium. The refractive index depends on the wavelength of the light used. The power of a lens is related to its focal length.

Answer the following questions based on the above :

(a) How will the power of a lens be affected with an increase of wavelength of light?

[1 mark]

Solution:

Concept:

- For a thin lens in air, $P = 1/f = (\mu - 1)K$, where $K = 1/R_1 - 1/R_2$ is fixed by its two surface curvatures.
- Under normal dispersion, the refractive index μ of lens glass decreases as the wavelength increases.

Step 1: Relate wavelength to refraction Increasing the wavelength decreases μ , so the factor $\mu - 1$ becomes smaller. The radii of curvature of the same lens remain unchanged.

Step 2: Infer the change in power Therefore the magnitude $|P| = |\mu - 1| |K|$ decreases and the magnitude of the focal length increases. For a convex lens its positive power decreases; for a concave

lens the negative power moves towards zero.

Step 3: Conclusion The lens becomes less powerful: its power decreases in magnitude as the wavelength increases.

Quick Tip to Solve: For the same glass lens, red light is bent less than blue light and has a larger focal-length magnitude.

35(b). The radius of curvature of two surfaces of a convex lens is R each. For what value of μ of its material will its focal length become equal to R ? [1 mark]

Solution:

Concept:

- The thin-lens maker formula in air is $1/f = (\mu - 1)(1/R_1 - 1/R_2)$, where the radii carry Cartesian signs.
- For a symmetric biconvex lens with light travelling from left to right, $R_1 = +R$ and $R_2 = -R$.

Step 1: Insert the two signed radii Although the magnitudes of both radii are R , their signs are opposite. Hence

$$\frac{1}{f} = (\mu - 1) \left(\frac{1}{R} - \frac{1}{-R} \right) = \frac{2(\mu - 1)}{R}.$$

Step 2: Apply the stated focal length Setting $f = R$ gives $1/R = 2(\mu - 1)/R$. Cancelling the nonzero radius yields $1 = 2(\mu - 1)$, so $\mu - 1 = 1/2$. The refractive index is dimensionless.

Step 3: Conclusion The required refractive index is $\mu = \frac{3}{2} = 1.5$.

Quick Tip to Solve: Equal radius magnitudes do not mean equal signed radii: a biconvex lens uses $+R$ and $-R$.

35(c). The focal length of a concave lens of $\mu = 1.5$ is 20 cm in air. It is completely immersed in water of $\mu = \frac{4}{3}$. Calculate its focal length in water. [2 marks]

Solution:

Concept:

- For a thin lens immersed in a medium, $1/f = (\mu_l/\mu_m - 1)K$, where μ_l and μ_m are the absolute refractive indices of the lens and medium, and $K = 1/R_1 - 1/R_2$.
- The curvatures, and therefore K , remain unchanged on immersion. A concave glass lens has negative focal length both in air and in water here, since the glass remains optically denser.

Step 1: Use the signed focal length in air The given 20 cm is the magnitude. For a concave lens, $f_a = -20$ cm. Thus

$$\frac{1}{f_a} = (1.5 - 1)K = \frac{1}{2}K.$$

The negative sign must be retained while calculating the new focal length.

Step 2: Calculate the relative index in water With $\mu_l = 3/2$ and $\mu_w = 4/3$, the relative refractive

index is

$$\frac{\mu_l}{\mu_w} = \frac{3/2}{4/3} = \frac{9}{8}, \quad \frac{1}{f_w} = \left(\frac{9}{8} - 1\right) K = \frac{1}{8}K.$$

Dividing the water expression by the air expression gives $f_a/f_w = (1/8)/(1/2) = 1/4$, and therefore $f_w = 4(-20)$ cm. The weaker refractive-index contrast makes the lens less divergent.

Step 3: Conclusion The focal length in water is $f_w = -80$ cm, with magnitude 80 cm.

Quick Tip to Solve: Use the relative index μ_l/μ_w , and preserve the negative focal length of the concave lens.

OR

35(c). An object is placed in front of a lens which forms its erect image of magnification 3. The power of the lens is 5 D. Calculate the distance of the object and the image from the lens. [2 marks]

Solution:

Concept:

- The power and focal length satisfy $P = 1/f$, with f in metres and P in dioptres. Positive power describes a converging lens.
- With Cartesian signs, the thin-lens formula is $1/f = 1/v - 1/u$, and transverse magnification is $m = v/u$. An erect image has positive magnification.

Step 1: Find the focal length and image relation From $P = +5$ D,

$$f = \frac{1}{5} \text{ m} = +20 \text{ cm}.$$

Since the image is erect and magnified three times, $m = +3$, so $v = 3u$. For a real object in front of the lens, $u < 0$; consequently $v < 0$, which identifies the image as virtual and on the object side.

Step 2: Solve the lens equation Substituting $v = 3u$ and $f = 20$ cm,

$$\frac{1}{20} = \frac{1}{3u} - \frac{1}{u} = -\frac{2}{3u}.$$

Thus $3u = -40$ cm, giving $u = -40/3$ cm and $v = 3u = -40$ cm. As a check, the object distance magnitude is less than f , which is the required placement for a convex lens to form an erect, enlarged virtual image.

Step 3: Conclusion The object is 13.3 cm in front of the lens; its virtual image is 40 cm from the lens on the same side. The signed distances are $u = -40/3$ cm, $v = -40$ cm.

Quick Tip to Solve: Erect means $m = +3$, so use $v = 3u$; do not add the mirror-formula minus sign to lens magnification.