

CBSE Class 12 Physics Question Paper 2020 with Solution PDF-Set 55/1/3



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 comprises **four** Sections – **A, B, C** and **D**.
- (ii) There are **37** questions in the question paper. **All** questions are compulsory.
- (iii) **Section A** – Questions no. **1 to 20** are very short answer type questions, carrying **one** mark each.
- (iv) **Section B** – Questions no. **21 to 27** are short answer type questions, carrying **two** marks each.
- (v) **Section C** – Questions no. **28 to 34** are long answer type questions, carrying **three** marks each.
- (vi) **Section D** – Questions no. **35 to 37** are also long answer type questions, carrying **five** marks each.
- (vii) There is no overall choice in the question paper. However, an internal choice has been provided in 2 questions of 1 mark, 2 questions of 2 marks, 1 question of three marks and all the 3 questions of five marks. You have to attempt only one of the choices in such questions.
- (viii) In addition to this, separate instructions are given with each section and question, wherever necessary.
- (ix) Use of calculators and log tables is not permitted.

You may use the following values of physical constants wherever necessary.

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

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

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

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

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

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

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

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

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

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

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

Section A (20 marks)

Note : Select the most appropriate option from those given below each question :

1. A biconvex lens of glass having refractive index 1.47 is immersed in a liquid. It becomes invisible and behaves as a plane glass plate. The refractive index of the liquid is [1 mark]

- (A) 1.47
- (B) 1.62
- (C) 1.33
- (D) 1.51

Correct Answer: (A) 1.47

Solution:

Concept:

- The power of a lens in a medium is $P = (n_g/n_l - 1)(1/R_1 - 1/R_2)$, where n_g and n_l are the glass and liquid refractive indices.
- When the indices match, light does not refract at the glass-liquid boundary.

Step 1: Apply the condition of invisibility The curved surfaces of a biconvex lens normally bend light because glass and its surrounding medium have different refractive indices. Becoming invisible means that the boundary has no optical contrast, so the relative refractive index must be unity:

$$n_g/n_l = 1.$$

This also makes the lens power zero.

Step 2: Compare the given choices With $n_g = 1.47$, index matching gives $n_l = 1.47$. Options (B), (C) and (D) all differ from the glass index, so each leaves a nonzero relative-index contrast and hence finite lens power.

Step 3: Conclusion The liquid has refractive index 1.47. Hence, the correct option is (A).

Quick Tip to Solve: For an invisible immersed lens, equate the refractive indices of the lens and liquid.

2. For a glass prism, the angle of minimum deviation will be smallest for the light of [1 mark]

- (A) red colour.
- (B) blue colour.
- (C) yellow colour.
- (D) green colour.

Correct Answer: (A) red colour.

Solution:

Concept:

- For a prism of angle A , $n = \sin[(A + \delta_m)/2] / \sin(A/2)$, where δ_m is minimum deviation.
- In ordinary glass, refractive index decreases as the wavelength increases.

Step 1: Relate deviation to refractive index For a fixed prism angle,

$$\delta_m = 2 \sin^{-1}[n \sin(A/2)] - A.$$

Thus, in the physical range for emergence, the minimum deviation increases with refractive index. The least-deviated colour must therefore have the smallest refractive index.

Step 2: Compare the colours Red light has the longest wavelength among red, yellow, green and blue. Under normal dispersion in glass, $n_{\text{red}} < n_{\text{yellow}} < n_{\text{green}} < n_{\text{blue}}$. Therefore blue, yellow and green each suffer more minimum deviation than red.

Step 3: Conclusion The angle of minimum deviation is smallest for red light. Hence, the correct option is (A).

Quick Tip to Solve: For ordinary glass, remember: longer wavelength means smaller index and smaller prism deviation.

3. Which of the following statements is not correct according to Rutherford model?

[1 mark]

- (A) Most of the space inside an atom is empty.
- (B) The electrons revolve around the nucleus under the influence of coulomb force acting on them.
- (C) Most part of the mass of the atom and its positive charge are concentrated at its centre.
- (D) The stability of atom was established by the model.

Correct Answer: (D) The stability of atom was established by the model.

Solution:

Concept:

- Rutherford scattering implies a small, massive, positively charged nucleus and mostly empty atomic space.
- A revolving electron is an accelerated charge and would radiate energy according to classical electrodynamics.

Step 1: Check the established features Options (A) and (C) describe the nuclear atom: most volume is empty, while most mass and all positive nuclear charge are concentrated in the very small central nucleus. Option (B) describes the electrostatic attraction providing centripetal force for the orbiting electrons in Rutherford's model.

Step 2: Identify the limitation An orbiting electron continuously changes velocity direction and therefore accelerates. Classically it should radiate, lose orbital energy and spiral into the nucleus. Rutherford's model consequently could not explain why atoms remain stable; it did not establish stability as claimed in option (D).

Step 3: Conclusion The statement that atomic stability was established is not correct. Hence, the correct option is (D).

Quick Tip to Solve: When asked for the incorrect Rutherford statement, check whether it claims to explain atomic stability.

4. Photons of energies 1 eV and 2 eV are successively incident on a metallic surface of work function 0.5 eV. The ratio of kinetic energy of most energetic photoelectrons in the two cases will be [1 mark]

- (A) 1 : 2
- (B) 1 : 1
- (C) 1 : 3
- (D) 1 : 4

Correct Answer: (C) 1 : 3

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = E_{\gamma} - \phi$, where ϕ is the work function.
- The same surface has the same work function for both incident photon energies.

Step 1: Calculate both maximum kinetic energies The work function is $\phi = 0.5$ eV. Both photon energies exceed it, so emission occurs in both cases. Subtract the work function separately:

$$K_1 = 1 - 0.5 = 0.5 \text{ eV},$$

$$K_2 = 2 - 0.5 = 1.5 \text{ eV}.$$

Step 2: Form and check the ratio The requested ratio is in the order of the incident energies:

$$K_1 : K_2 = 0.5 : 1.5 = 1 : 3.$$

The tempting 1 : 2 is the ratio of photon energies, not electron kinetic energies. The equal-energy and 1 : 4 choices also disagree with the two calculated values.

Step 3: Conclusion The ratio is $\boxed{1 : 3}$. Hence, the correct option is (C).

Quick Tip to Solve: Subtract the work function from each photon energy before taking the kinetic-energy ratio.

5. The magnetic dipole moment of a current carrying coil does not depend upon [1 mark]

- (A) number of turns of the coil.
- (B) cross-sectional area of the coil.
- (C) current flowing in the coil.
- (D) material of the turns of the coil.

Correct Answer: (D) material of the turns of the coil.

Solution:

Concept:

- The magnetic dipole moment of a planar coil is $m = NIA$, with N turns, current I , and area vector A .
- Its magnitude is $m = NIA$; the area is that enclosed by each turn.

Step 1: Identify the direct dependencies For a coil with identical turns, each turn contributes magnetic moment IA , and the contributions add to NIA . Thus increasing the number of turns, the enclosed area or the specified current increases the magnetic moment. These are precisely the quantities in

options (A), (B) and (C).

Step 2: Check the material choice The material of the wire is absent from $m = NIA$. It can affect electrical resistance and hence current for a specified voltage, but once the current is given, the magnetic moment of the current loop depends on its current and geometry, not the material of its turns.

Step 3: Conclusion The magnetic dipole moment does not depend directly on the material of the turns. Hence, the correct option is (D).

Quick Tip to Solve: Use $m = NIA$ at the stated current; distinguish enclosed coil area from the wire cross section.

6. The conductivity of a metal decreases with the increase in temperature on account of [1 mark]

- (A) decrease in number density of electrons.
- (B) decrease in resistivity.
- (C) decrease in relaxation time.
- (D) increase in mean free path.

Correct Answer: (C) decrease in relaxation time.

Solution:

Concept:

- Drude conductivity is $\sigma = ne^2\tau/m_e$, where n is electron number density and τ is relaxation time.
- Heating a metal increases lattice vibrations and electron scattering.

Step 1: Explain the effect of heating As temperature rises, metal ions vibrate more strongly about their equilibrium positions. Conduction electrons then encounter more frequent scattering, reducing the average time between successive collisions, called relaxation time τ . Since σ is proportional to τ , conductivity decreases.

Step 2: Exclude the other options The conduction-electron number density is approximately unchanged in an ordinary metal, so (A) is not the principal cause. A decrease in resistivity would increase conductivity because $\sigma = 1/\rho$, ruling out (B). Increased scattering shortens rather than lengthens the mean free path, ruling out (D).

Step 3: Conclusion The conductivity decreases because the relaxation time decreases. Hence, the correct option is (C).

Quick Tip to Solve: For a heated metal, link stronger lattice vibrations to shorter relaxation time and lower conductivity.

7. Two unequal resistors are connected in series across a battery. Then the

[1 mark]

- (A) potential difference across each resistor is the same.
- (B) current in the smaller resistor is larger.
- (C) potential difference across the bigger resistor is greater.
- (D) power dissipated in both resistors is the same.

Correct Answer: (C) potential difference across the bigger resistor is greater.

Solution:

Concept:

- In series, charge conservation gives the same current I through every resistor.
- Ohm's law gives $V = IR$, and power at the common current is $P = I^2 R$.

Step 1: Compare the potential differences Let $R_b > R_s$ be the bigger and smaller resistances. Their currents are equal because there is a single path for charge. Thus

$$\frac{V_b}{V_s} = \frac{IR_b}{IR_s} = \frac{R_b}{R_s} > 1.$$

The bigger resistor has the greater potential difference.

Step 2: Test the remaining statements Unequal resistances carrying the same current have unequal voltage drops, so (A) fails. The smaller resistor cannot carry a larger current in a series circuit, so (B) fails. Their powers satisfy $P_b/P_s = R_b/R_s > 1$, and are unequal, so (D) also fails.

Step 3: Conclusion The potential difference across the bigger resistor is greater. Hence, the correct option is (C).

Quick Tip to Solve: For resistors in series, first fix the common current, then compare voltages using $V = IR$.

8. A point charge is situated at an axial point of a small electric dipole at a large distance from it. The charge experiences a force F . If the distance of the charge is doubled, the force acting on the charge will become

[1 mark]

- (A) $2F$
- (B) $F/2$
- (C) $F/4$
- (D) $F/8$

Correct Answer: (D) $F/8$

Solution:

Concept:

- Far from a small dipole, its axial electric field magnitude is $E_{\text{axial}} = 2p/(4\pi\epsilon_0 r^3)$, with dipole moment p .
- The force magnitude on a fixed point charge q is $F = |q|E$.

Step 1: Identify the distance dependence The point is at a distance large compared with the dipole separation, so the dipole approximation applies. The axial field and hence the force on the same test charge vary as r^{-3} . This is not the inverse-square field of an isolated monopole charge.

Step 2: Double the distance Keeping the dipole moment and test charge unchanged,

$$\frac{F_{\text{new}}}{F} = \frac{r^3}{(2r)^3} = \frac{1}{8}.$$

Thus neither increasing the force to $2F$ nor reducing it merely to $F/2$ or $F/4$ is consistent with the cubic distance dependence.

Step 3: Conclusion The new force is $F/8$. Hence, the correct option is (D).

Quick Tip to Solve: For a distant dipole use the inverse cube law; doubling distance reduces force by eight.

9. If the net electric flux through a closed surface is zero, then we can infer

[1 mark]

- (A) no net charge is enclosed by the surface.
- (B) uniform electric field exists within the surface.
- (C) electric potential varies from point to point inside the surface.
- (D) charge is present inside the surface.

Correct Answer: (A) no net charge is enclosed by the surface.

Solution:

Concept:

- Gauss's law states that $\Phi_E = \oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the algebraic enclosed charge.
- Zero net flux constrains the enclosed net charge, not the field at individual points.

Step 1: Apply Gauss's law Substituting the stated zero flux gives $Q_{\text{enc}} = \epsilon_0 \Phi_E = 0$. Thus positive and negative enclosed charges, if present, must have zero algebraic sum. A closed surface can also enclose no charges at all.

Step 2: Check the remaining options A uniform field is possible but is not implied, so (B) is not a necessary inference. The potential may be constant or may vary depending on the charge configuration, excluding (C) as a necessary statement. Charge need not be present inside at all, so (D) is also not implied.

Step 3: Conclusion No net charge is enclosed by the surface. The correct option is (A).

Quick Tip to Solve: When flux is zero, write the algebraic enclosed charge as zero; do not infer that the local electric field is zero.

10. The focal length of the objective of a compound microscope is

[1 mark]

- (A) greater than the focal length of eyepiece.
- (B) lesser than the focal length of eyepiece.
- (C) equal to the focal length of eyepiece.
- (D) equal to the length of its tube.

Correct Answer: (B) lesser than the focal length of eyepiece.

Solution:

Concept:

- A compound microscope uses a short-focal-length objective to form a magnified real intermediate image.
- The eyepiece acts as a magnifier for that intermediate image; in the usual microscope $f_o < f_e$.

Step 1: Identify the objective requirement The object is placed just beyond the focus of the objective. Its small focal length gives a large linear magnification, approximately $|m_o| \simeq L/f_o$, where L is the effective tube length. Reducing f_o therefore increases the objective magnification.

Step 2: Compare the printed alternatives The eyepiece also has a short focal length, but the objective has the smaller one. Hence (A) reverses the required relation, and (C) does not describe the standard compound microscope. The tube length is much larger than the objective focal length, so (D) is incorrect.

Step 3: Conclusion The objective focal length is lesser than the eyepiece focal length: $f_o < f_e$. The correct option is (B).

Quick Tip to Solve: For a compound microscope remember that the objective has the smaller focal length and supplies the first magnification.

11. The number of turns of a solenoid are doubled without changing its length and area of cross-section. The self-inductance of the solenoid will become _____ times.

[1 mark]

Solution:

Concept:

- For a long solenoid, $L = \mu N^2 A / \ell$, where N is its turn count, A its cross-sectional area, ℓ its length and μ its permeability.
- For unchanged geometry and core material, self-inductance is proportional to the square of the number of turns.

Step 1: Write the initial and final inductance Initially $L = \mu N^2 A / \ell$. The new turn count is $N' = 2N$; neither the length nor the area changes. With the same material, the new inductance is $L' = \mu (2N)^2 A / \ell$.

Step 2: Evaluate the ratio Dividing the final expression by the initial one cancels all unchanged quantities:

$$\frac{L'}{L} = \frac{(2N)^2}{N^2} = 4.$$

The square dependence arises because more turns both increase the magnetic field for a given current and increase the total flux linkage.

Step 3: Conclusion The self-inductance becomes 4 times its original value. The blank is 4.

Quick Tip to Solve: For a turn-count change at fixed solenoid geometry, square the turn-count ratio to obtain the inductance ratio.

12. According to Bohr's atomic model, the circumference of the electron orbit is always an _____ multiple of de Broglie wavelength. [1 mark]

Solution:

Concept:

- Bohr's angular-momentum condition is $mvr = n\hbar = nh/(2\pi)$, with $n = 1, 2, 3, \dots$
- The electron's de Broglie wavelength is $\lambda = h/(mv)$. A stable orbit supports a complete standing wave.

Step 1: Combine the two relations Multiplying Bohr's condition by 2π and dividing by mv gives $2\pi r = nh/(mv)$. On substituting the de Broglie wavelength this becomes $2\pi r = n\lambda$.

Step 2: Interpret the orbit circumference Since n is a positive integer, a whole number of wavelengths fits around the orbit. The electron wave then joins smoothly to itself after one revolution, satisfying the standing-wave condition. A non-integral number would not give this allowed-orbit condition.

Step 3: Conclusion The orbit circumference is an integer (integral) multiple of the de Broglie wavelength. The blank is integer.

Quick Tip to Solve: Replace $h/(mv)$ with the de Broglie wavelength in Bohr quantisation to get circumference equal to n wavelengths.

OR

12. In β -decay, the parent and daughter nuclei have the same number of _____. [1 mark]

Solution:

Concept:

- The mass number $A = Z + N$ counts the total nucleons: protons plus neutrons.
- In beta decay a neutron and a proton interconvert, while the total number of nucleons remains unchanged.

Step 1: Follow beta-minus decay In β^- decay the nuclear transformation is $n \rightarrow p + e^- + \bar{\nu}_e$. One neutron becomes one proton, so the daughter has $Z' = Z + 1$ and $N' = N - 1$. Thus $A' = Z' + N' = Z + N = A$.

Step 2: Identify what remains the same The same conclusion holds for β^+ decay, where a proton becomes a neutron and Z decreases by one. Parent and daughter do not have the same proton or neutron count individually. They have the same total number of nucleons, equivalently the same mass

number.

Step 3: Conclusion The parent and daughter nuclei have the same number of nucleons. The blank is nucleons.

Quick Tip to Solve: In beta decay keep the mass number unchanged; proton and neutron counts change by equal and opposite amounts.

13. A ray of light on passing through an equilateral glass prism, suffers a minimum deviation equal to the angle of the prism. The value of refractive index of the material of the prism is _____. [1 mark]

Solution:

Concept:

- At minimum deviation, a prism in air has refractive index $\mu = \sin[(A + \delta_m)/2] / \sin(A/2)$, where A is the prism angle.
- An equilateral prism has $A = 60^\circ$. At minimum deviation its ray path is symmetric.

Step 1: Insert the given prism data The deviation is stated to equal the prism angle, so $\delta_m = A = 60^\circ$. Therefore $(A + \delta_m)/2 = 60^\circ$, while $A/2 = 30^\circ$. These are the angles needed in the minimum-deviation formula.

Step 2: Calculate the refractive index Substitution gives

$$\mu = \frac{\sin 60^\circ}{\sin 30^\circ} = \frac{\sqrt{3}/2}{1/2} = \sqrt{3}.$$

Refractive index is dimensionless. The internal refraction angles are each 30° , consistent with the symmetric minimum-deviation path.

Step 3: Conclusion The refractive index of the glass is $\sqrt{3}$, approximately 1.73.

Quick Tip to Solve: For an equilateral prism with minimum deviation equal to its angle, use the sine ratio $\sin 60^\circ / \sin 30^\circ$.

14. The magnetic field lines are _____ by a paramagnetic substance. [1 mark]

Solution:

Concept:

- A paramagnetic substance acquires a weak magnetisation in the direction of an applied magnetic field.
- Its magnetic susceptibility is positive, $\chi_m > 0$, so its relative permeability $\mu_r = 1 + \chi_m$ is slightly greater than unity.

Step 1: Identify the response to the applied field The atomic magnetic dipoles in a paramagnetic

substance tend to align with the external magnetic field. Their contribution therefore reinforces the applied field inside the substance, although the effect is weak.

Step 2: Relate this response to the field lines Since the magnetic field is slightly stronger within the material, the field lines become slightly more closely spaced there. Thus they are drawn into the paramagnetic substance. A diamagnetic substance would instead repel the lines, because its induced magnetisation opposes the applied field.

Step 3: Conclusion The magnetic field lines are **attracted** by a paramagnetic substance; equivalently, they are slightly concentrated inside it.

Quick Tip to Solve: Remember that positive susceptibility means field lines crowd slightly into a paramagnetic material.

15. Laminated iron sheets are used to minimize _____ currents in the core of a transformer. [1 mark]

Solution:

Concept:

- A changing magnetic flux induces circulating eddy currents inside a conducting iron core, by Faraday's law.
- These currents dissipate electrical energy as heat. Insulated laminations interrupt large current loops and raise their resistance.

Step 1: Identify the core loss The alternating current in the primary produces a time-varying magnetic flux through the transformer core. Induced currents can circulate within a solid conducting core even without an external wire connection. These internal loops are called eddy currents and cause unwanted heating.

Step 2: Explain the effect of laminations The core is divided into thin iron sheets insulated from one another. The insulation prevents currents from flowing freely between sheets and breaks up large conducting loops. The higher loop resistance and smaller available loop area reduce the eddy currents and their heating loss while allowing the core to carry magnetic flux.

Step 3: Conclusion Laminated iron sheets minimize eddy currents. The blank is eddy.

Quick Tip to Solve: Associate lamination with eddy-current reduction; choosing suitable magnetic material chiefly addresses hysteresis loss.

16. The nuclear radius of ${}_{13}^{27}\text{Al}$ is 3.6 fermi. Find the nuclear radius of ${}_{29}^{64}\text{Cu}$. [1 mark]

Solution:

Concept:

- Nuclear radius follows $R = R_0 A^{1/3}$, where A is the mass number and R_0 is approximately the same for all nuclei.
- For two nuclei, dividing their radius formulae eliminates the unknown constant R_0 .

Step 1: Select the relevant mass numbers For aluminium, $A_{\text{Al}} = 27$ and $R_{\text{Al}} = 3.6$ fm. For copper, $A_{\text{Cu}} = 64$. The atomic numbers 13 and 29 do not enter the nuclear-radius relation.

Step 2: Use the radius ratio

$$\frac{R_{\text{Cu}}}{R_{\text{Al}}} = \left(\frac{64}{27}\right)^{1/3} = \frac{4}{3}, \quad R_{\text{Cu}} = 3.6 \times \frac{4}{3} \text{ fm}.$$

The cube roots are exact, so no approximation is needed in this substitution.

Step 3: Conclusion The nuclear radius of ${}^{64}_{29}\text{Cu}$ is 4.8 fm , or $4.8 \times 10^{-15} \text{ m}$.

Quick Tip to Solve: Use the mass numbers, then take cube roots before multiplying: 64 and 27 give 4 and 3.

OR

16. A proton and an electron have equal speeds. Find the ratio of de Broglie wavelengths associated with them. [1 mark]

Solution:

Concept:

- The de Broglie wavelength is $\lambda = h/p = h/(mv)$ for a nonrelativistic particle, where h is Planck's constant.
- At equal speeds, wavelength is inversely proportional to particle mass.

Step 1: Write the two wavelengths Let the common speed be v . Then $\lambda_p = h/(m_p v)$ for the proton and $\lambda_e = h/(m_e v)$ for the electron. The same h and v occur in both expressions.

Step 2: Form the ratio in the stated order

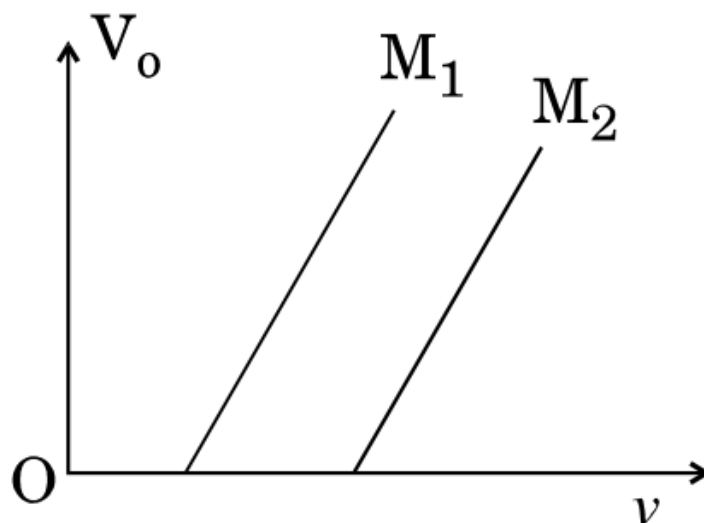
$$\frac{\lambda_p}{\lambda_e} = \frac{h/(m_p v)}{h/(m_e v)} = \frac{m_e}{m_p} \simeq \frac{1}{1836}.$$

The heavier proton therefore has the smaller wavelength. Even at a common relativistic speed, the identical Lorentz factors cancel in this ratio.

Step 3: Conclusion In proton-to-electron order, $\lambda_p : \lambda_e = 1 : 1836$ approximately.

Quick Tip to Solve: Write the particle order beside the ratio first; equal speeds make the mass ratio reverse.

17. The variation of the stopping potential (V_0) with the frequency (ν) of the light incident on two different photosensitive surfaces M_1 and M_2 is shown in the figure. Identify the surface which has greater value of the work function. [1 mark]



Solution:

Concept:

- Einstein's equation gives $eV_0 = h\nu - \phi$, where ϕ is the surface work function.
- At the frequency-axis intercept, $V_0 = 0$, so the threshold frequency is $\nu_0 = \phi/h$.

Step 1: Read the horizontal intercepts The straight line labelled M_2 meets the frequency axis to the right of the line labelled M_1 . Thus the threshold frequency of M_2 is greater: $\nu_{02} > \nu_{01}$.

Step 2: Relate threshold to work function Since $\phi = h\nu_0$ and h is a positive universal constant, the larger threshold frequency corresponds directly to the larger work function. The common slope h/e does not determine which surface has the larger work function.

Step 3: Conclusion M_2 has the greater work function, because its threshold frequency is higher.

Quick Tip to Solve: Compare the frequency-axis intercepts, not the slopes or the heights of the line labels.

18. Why cannot we use Si and Ge in fabrication of visible LEDs? [1 mark]

Solution:

Concept:

- An LED emits photons when injected electrons recombine with holes; the photon energy is approximately the band-gap energy E_g .
- Visible photons require energies of roughly 1.8–3.1 eV, with wavelength related by $\lambda = hc/E_g$.

Step 1: Compare the band gaps with visible photon energies Silicon and germanium have small band gaps, approximately 1.1 eV and 0.7 eV, respectively. These energies are below the visible range, so any corresponding band-gap radiation lies in the infrared.

Step 2: Check the efficiency of light production Both materials also have indirect band gaps. Recombination requires participation of lattice vibrations and is mainly nonradiative, so they are inefficient light emitters. Suitable visible LEDs use materials with appropriate, usually direct, band

gaps.

Step 3: Conclusion Si and Ge cannot serve as useful visible LEDs because their small band gaps correspond to infrared radiation and their indirect gaps make radiative recombination inefficient.

Quick Tip to Solve: For a visible LED, check both band-gap photon energy and efficient radiative recombination.

19. Differentiate between conduction current and displacement current.

[1 mark]

Solution:

Concept:

- Conduction current is associated with transport of free charge carriers through a material.
- Displacement current is associated with a changing electric field: in vacuum $I_d = \epsilon_0 d\Phi_E/dt$, where Φ_E is electric flux.

Step 1: Identify conduction current In a wire, electrons drift under an applied electric field and carry charge across a cross-section. The conduction current is $I_c = dQ/dt$, where dQ is the net charge transported in time dt .

Step 2: Identify displacement current Between the plates of an ideal charging capacitor, no free charge crosses the insulating gap. Nevertheless the electric field and electric flux change with time, producing displacement current. This term, like conduction current, contributes to the magnetic field in the Ampere-Maxwell law.

Step 3: Conclusion Conduction current involves actual flow of free charges; displacement current arises from a time-varying electric field and need not involve charge transport across the region.

Quick Tip to Solve: Use a charging capacitor: the wire carries conduction current and the insulating gap has displacement current.

20. How does an increase in doping concentration affect the width of depletion layer of a p-n junction diode?

[1 mark]

Solution:

Concept:

- The depletion layer contains fixed ionised donors and acceptors left after mobile carriers diffuse and recombine near the junction.
- Its space charge establishes the junction electric field and built-in potential barrier.

Step 1: Relate doping to space-charge density Increasing doping increases the concentration of ionised impurities on the two sides. Thus a given thickness of depleted material contains more fixed charge per unit area than it did at lower doping.

Step 2: Infer the required depleted width The required junction charge and field can then be established over a shorter distance. For an abrupt junction, W varies mainly as $\sqrt{(1/N_A + 1/N_D)}$

at a given barrier potential, where N_A and N_D are acceptor and donor concentrations. The slowly changing built-in potential does not reverse this decrease.

Step 3: Conclusion Increasing the doping concentration makes the depletion layer narrower.

Quick Tip to Solve: More ionised impurities supply the needed space charge within a smaller junction thickness.

Section B (14 marks)

21. Explain the terms ‘depletion layer’ and ‘potential barrier’ in a p-n junction diode. How are the (a) width of depletion layer, and (b) value of potential barrier affected when the p-n junction is forward biased? [2 marks]

Solution:

Concept:

- Carrier diffusion across a p-n junction exposes fixed charged impurity ions, creating a space-charge region and an electric field.
- Forward bias means connecting the p side to the positive terminal and the n side to the negative terminal of a supply.

Step 1: Define the depletion layer Electrons diffuse from the n side to the p side and holes diffuse from the p side to the n side. Near the interface they recombine, leaving positive donor ions on the n side and negative acceptor ions on the p side. The resulting region has very few mobile majority carriers and is called the depletion layer. The fixed ions themselves do not move through the junction.

Step 2: Define the potential barrier The field of these uncovered ions opposes further diffusion of majority carriers. The built-in potential difference across the depletion layer is called the potential barrier. At equilibrium the field-driven drift balances diffusion, so there is no net current through the unbiased junction.

Step 3: Explain the effect of forward bias on both quantities The applied forward voltage opposes the built-in junction field. It drives electrons from the n side and holes from the p side towards the junction, reducing the exposed space-charge region. Hence (a) the depletion-layer width decreases. Also (b) the effective potential barrier decreases: approximately $V_{\text{eff}} = V_{\text{bi}} - V_F$, where V_{bi} is the built-in barrier and V_F is the applied forward voltage. Majority carriers can therefore cross the junction more easily.

Step 4: Conclusion The depletion layer is the region depleted of mobile carriers; the potential barrier is its built-in opposing potential difference. Under forward bias, both the depletion width and the effective barrier decrease.

Quick Tip to Solve: Forward bias opposes the built-in field: remember that both junction width and effective barrier decrease.

22. Using Bohr's atomic model, derive the expression for the velocity of electron revolving in the n^{th} orbit of hydrogen atom. [2 marks]

Solution:

Concept:

- Coulomb attraction supplies the centripetal force: $m_e v_n^2 / r_n = e^2 / (4\pi\epsilon_0 r_n^2)$, where m_e is the electron mass, e the magnitude of its charge and r_n the orbit radius.
- Bohr quantisation requires $m_e v_n r_n = n\hbar = nh / (2\pi)$, where $n = 1, 2, \dots$ and h is Planck's constant.

Step 1: Write the force balance For hydrogen, the nucleus has charge $+e$. Neglecting its motion, the electrostatic force on the electron is directed towards the nucleus. Equating it to the required centripetal force gives

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

Step 2: Eliminate the orbit radius Angular momentum quantisation gives $r_n = nh / (2\pi m_e v_n)$. Substituting into the force equation,

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

Thus the speed decreases inversely with the orbit number; higher allowed orbits have lower electron speeds.

Step 3: Conclusion The electron speed in the n^{th} hydrogen orbit is $v_n = e^2 / (2\epsilon_0 h n) = \alpha c / n$, approximately $2.19 \times 10^6 / n \text{ m s}^{-1}$.

Quick Tip to Solve: Divide the force-balance equation by the quantised angular momentum to eliminate both mass and radius.

OR

22. Explain, how the process of emission of photoelectrons is different from the process of emission of β -particles. [2 marks]

Solution:

Concept:

- Photoelectric emission ejects an existing bound electron from a material after absorption of a photon of energy $h\nu$.
- Beta emission is a spontaneous nuclear transformation governed by the weak interaction; a beta electron is created during the decay rather than released from an atomic orbit.

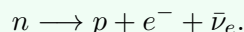
Step 1: Explain photoelectron emission A photon transfers its energy to an electron in the material. If this energy is sufficient to overcome the work function ϕ , the electron can escape:

$$K_{\text{max}} = h\nu - \phi, \quad \nu \geq \nu_0 = \phi / h.$$

Incident light of sufficient frequency is therefore necessary. This process involves electrons outside the nucleus and does not change the nuclear atomic number or mass number.

Step 2: Explain beta-particle emission In beta-minus decay a neutron in an unstable nucleus converts

into a proton, emitting an electron and an electron antineutrino:



The emitted electron is created in this nuclear process; it was not an orbital electron or an electron stored inside the nucleus. The decay is spontaneous and does not require incident light. The daughter has atomic number increased by one while its mass number is unchanged. Beta energies form a continuous spectrum because the available energy is shared with the antineutrino and nuclear recoil.

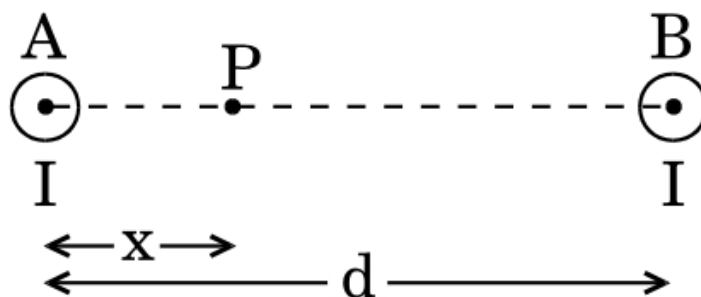
Step 3: Conclusion Photoelectrons are pre-existing atomic/material electrons released by photon absorption; beta-minus particles are electrons created in spontaneous radioactive nuclear decay.

Quick Tip to Solve: Compare the source of the electron, the need for light, and whether the nucleus changes.

23. Two long straight parallel wires A and B separated by a distance d , carry equal current I flowing in same direction as shown in the figure.

(a) Find the magnetic field at a point P situated between them at a distance x from one wire.

(b) Show graphically the variation of the magnetic field with distance x for $0 < x < d$. [2 marks]



Solution:

Concept:

- For a long straight wire, $B = \mu_0 I / (2\pi r)$, where r is perpendicular distance and μ_0 is the permeability of free space.
- The dots in the printed figure mean both currents emerge from the page. The right-hand rule gives anticlockwise fields; take upward on the page as positive.

Step 1: Find the resultant field at P Point P is at distance x to the right of wire A and distance $d - x$ to the left of wire B . Hence $\vec{B}_A$ is upward and $\vec{B}_B$ downward. Superposition gives

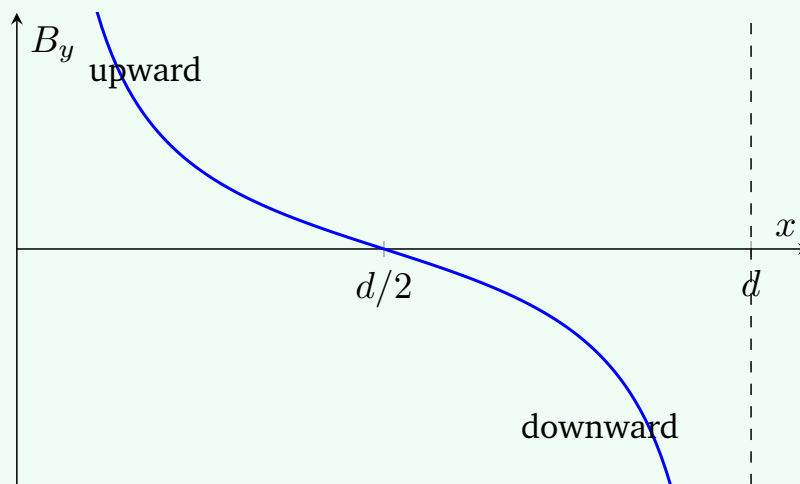
$$\vec{B}(P) = \frac{\mu_0 I}{2\pi} \left(\frac{1}{x} - \frac{1}{d-x} \right) \hat{y} = \frac{\mu_0 I(d-2x)}{2\pi x(d-x)} \hat{y}.$$

The magnitude is the absolute value of this expression.

Step 2: Sketch the signed variation At $x = d/2$, the equal fields cancel. For $0 < x < d/2$ the resultant is upward; for $d/2 < x < d$ it is downward. The signed field tends to $+\infty$ as $x \rightarrow 0^+$ and $-\infty$ as $x \rightarrow d^-$, with vertical asymptotes at both wires. Its derivative is

$$\frac{dB_y}{dx} = -\frac{\mu_0 I}{2\pi} \left(\frac{1}{x^2} + \frac{1}{(d-x)^2} \right) < 0,$$

so the graph decreases continuously through zero. The ideal infinite field near a wire assumes its radius is negligible.



Signed magnetic field between the wires; upward field is positive.

Step 3: Conclusion $B_y = \mu_0 I (1/x - 1/(d-x)) / (2\pi)$; the field vanishes at the midpoint and reverses direction across it.

Quick Tip to Solve: Between equal currents in the same direction, subtract the two fields; use a signed field to show the direction reversal.

24. Define wavefront of a travelling wave. Using Huygens principle, obtain the law of refraction at a plane interface when light passes from a denser to rarer medium. [2 marks]

Solution:

Concept:

- A wavefront is the locus of points of a travelling wave that are in the same phase at a given instant.
- Huygens principle: each point on a wavefront emits secondary wavelets; their forward envelope forms the next wavefront.
- The refractive index satisfies $n = c/v$. Let v_1, n_1 refer to the denser medium and v_2, n_2 to the rarer medium, so $v_2 > v_1$.

Step 1: Construct the refracted wavefront Let incident plane wavefront AB meet the plane interface first at A . In time t , point B reaches the interface at C , so $BC = v_1 t$. During the same time, a secondary wavelet centred at A expands in the second medium to radius $AD = v_2 t$. The tangent CD from C to this wavelet is the refracted wavefront. Thus $AB \perp BC$ and $AD \perp CD$.

Step 2: Relate the angles and speeds Let i and r be the incident and refracted ray angles with the normal. Since rays are perpendicular to their wavefronts, the angles between AB, CD and the

interface AC are respectively i and r . The two right triangles give

$$\sin i = \frac{BC}{AC} = \frac{v_1 t}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{v_2 t}{AC}.$$

Hence $\sin i / \sin r = v_1 / v_2 = n_2 / n_1$. Since $v_2 > v_1$, the refracted ray bends away from the normal. This construction applies when a propagating refracted ray exists, i.e. up to the critical angle.

Step 3: Conclusion The law of refraction is $n_1 \sin i = n_2 \sin r$. The incident ray, refracted ray and interface normal lie in one plane; for denser-to-rarer transmission, $r > i$ at nonzero incidence.

Quick Tip to Solve: Use the same elapsed time for the incident advance and secondary wavelet radius, then divide the two sine relations.

OR

24. Using lens maker's formula, derive the thin lens formula $\frac{1}{f} = \frac{1}{v} - \frac{1}{u}$ for a biconvex lens. [2 marks]

Solution:

Concept:

- For paraxial refraction at a spherical surface, $n_2/v - n_1/u = (n_2 - n_1)/R$. Distances use the Cartesian sign convention, positive along incident light.
- For a thin lens of refractive index μ in air, the lens maker formula is $1/f = (\mu - 1)(1/R_1 - 1/R_2)$.

Step 1: Apply refraction to both surfaces Let the object distance be u , the intermediate image distance after the first surface be v_1 , and the final image distance be v . For the air-to-glass surface,

$$\frac{\mu}{v_1} - \frac{1}{u} = \frac{\mu - 1}{R_1}.$$

For a thin lens, the intermediate image acts as the object for the second surface at essentially the same signed distance v_1 . Thus glass-to-air refraction gives

$$\frac{1}{v} - \frac{\mu}{v_1} = \frac{1 - \mu}{R_2}.$$

Step 2: Add the equations and use the lens maker formula Adding eliminates the intermediate image term:

$$\frac{1}{v} - \frac{1}{u} = (\mu - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right).$$

The right side equals $1/f$ by the lens maker formula. For a biconvex lens with light travelling left to right, $R_1 > 0$ and $R_2 < 0$, consistently giving positive focal length when $\mu > 1$. The derivation assumes a thin lens and rays close to the principal axis.

Step 3: Conclusion The thin lens formula is $\frac{1}{f} = \frac{1}{v} - \frac{1}{u}$.

Quick Tip to Solve: Add the two surface-refraction equations first; the intermediate image distance cancels automatically.

25. Define the term ‘Half-life’ of a radioactive substance. Two different radioactive substances have half-lives T_1 and T_2 and number of undecayed atoms at an instant, N_1 and N_2 , respectively. Find the ratio of their activities at that instant. [2 marks]

Solution:

Concept:

- Radioactive decay obeys $N(t) = N_0 e^{-\lambda t}$, where λ is the decay constant.
- Activity is the positive rate of decay, $A = -dN/dt = \lambda N$, and $\lambda = \ln 2/T_{1/2}$.

Step 1: Define half-life The half-life of a radioactive substance is the time required for the number of undecayed nuclei in a sample to decrease to half its initial value. Equivalently, its activity falls to half its initial value in this time. Setting $N(T_{1/2}) = N_0/2$ in the exponential decay law gives $e^{-\lambda T_{1/2}} = 1/2$, hence $\lambda T_{1/2} = \ln 2$.

Step 2: Calculate and compare the instantaneous activities At the specified instant, the two substances contain N_1 and N_2 undecayed atoms. Their activities are

$$A_1 = \frac{\ln 2}{T_1} N_1, \quad A_2 = \frac{\ln 2}{T_2} N_2.$$

Dividing these expressions cancels the common factor $\ln 2$:

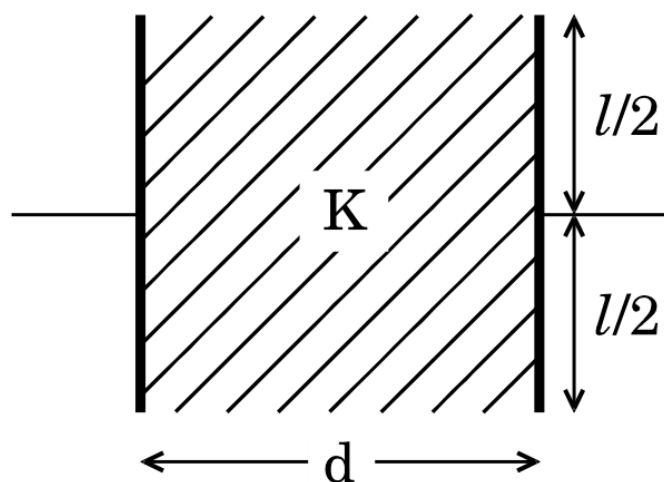
$$\frac{A_1}{A_2} = \frac{N_1/T_1}{N_2/T_2} = \frac{N_1 T_2}{N_2 T_1}.$$

The comparison uses the atom populations at the same instant, so there is no need to calculate their ages or initial populations.

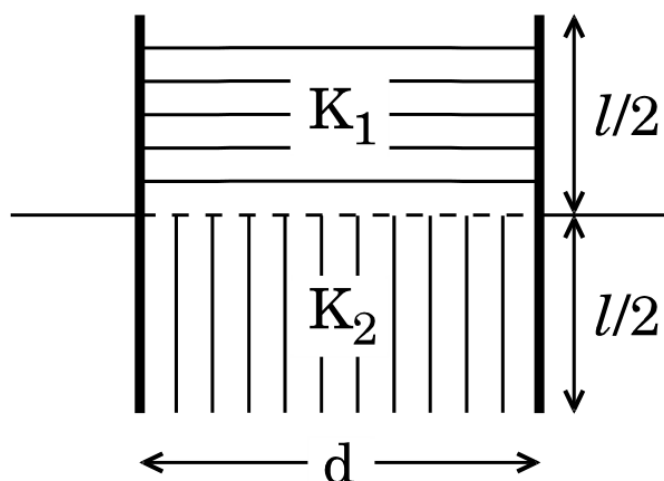
Step 3: Conclusion Half-life is the time for half the initial undecayed nuclei to decay; the activity ratio is $A_1 : A_2 = N_1 T_2 : N_2 T_1$.

Quick Tip to Solve: Activity is proportional to the current number of nuclei and inversely proportional to half-life.

26. The space between the plates of a parallel plate capacitor is completely filled in two ways. In the first case, it is filled with a slab of dielectric constant K . In the second case, it is filled with two slabs of equal dimensions but different dielectric constants K_1 and K_2 respectively as shown in the figure. The capacitance of the capacitor is same in the two cases. Obtain the relationship between K , K_1 and K_2 . [2 marks]



(Case 1)



(Case 2)

Solution:

Concept:

- For a dielectric-filled parallel plate capacitor, $C = \epsilon_0 K A / d$, where A is plate area and d is separation.
- Regions sharing the same plates and potential difference form a parallel combination: $C = C_1 + C_2$.

Step 1: Find the capacitance with one dielectric Let the total plate area be A and the separation be d . Since the dielectric of constant K fills the entire space, the capacitance in case 1 is

$$C_1 = \frac{\epsilon_0 K A}{d}.$$

Fringing effects are neglected, as in the usual parallel plate capacitor formula.

Step 2: Read the geometry and add the two contributions In the printed figure, the slabs occupy the upper and lower halves of the plate area. Each spans the full separation d ; their equal dimensions therefore give area $A/2$ each. Both regions have the same voltage between the common plates, so they are in parallel. Thus

$$C_1 = \frac{\epsilon_0 K_1 A}{2d}, \quad C_2 = \frac{\epsilon_0 K_2 A}{2d},$$

$$C_{II} = C_1 + C_2 = \frac{\epsilon_0 A}{2d} (K_1 + K_2).$$

Equating the two specified capacitances and cancelling $\epsilon_0 A/d$ gives the required relationship.

Step 3: Conclusion $K = \frac{K_1 + K_2}{2}$, or equivalently $2K = K_1 + K_2$.

Quick Tip to Solve: Check which dimension is split: splitting plate area gives parallel capacitors and the arithmetic mean.

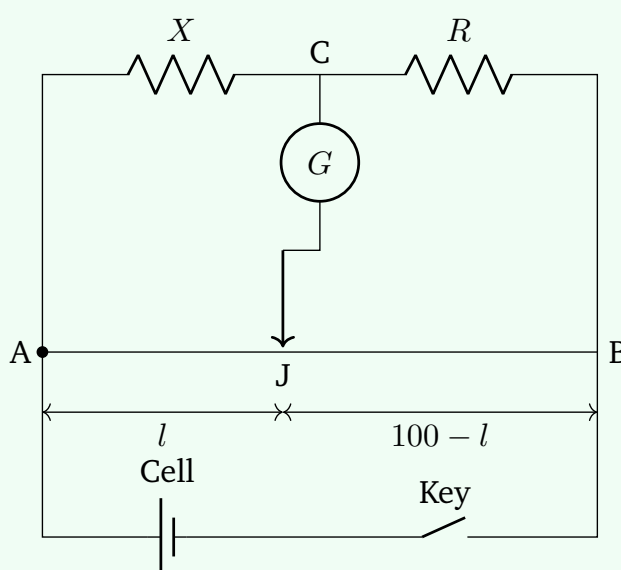
27. Explain the principle of working of a meter bridge. Draw the circuit diagram for determination of an unknown resistance using it. [2 marks]

Solution:

Concept:

- A meter bridge is a practical Wheatstone bridge. At balance the galvanometer carries no current because its two terminals have equal potential.
- For a uniform bridge wire, resistance is proportional to length; hence $X/R = l/(100 - l)$ when X occupies the left gap.

Step 1: Explain the bridge balance principle A uniform wire AB , of length 100 cm, is stretched along a scale. An unknown resistance X and known resistance R form the two upper arms, while wire portions AJ and JB form the lower arms. A cell is connected across A and B , and a galvanometer joins the junction C of X and R to a movable jockey J touching the wire.



Uniform wire AB: 100 cm

Meter bridge circuit: X in the left gap, R in the right gap, and jockey J at balance.

Step 2: Determine the unknown resistance Close the key and move the jockey until the galvanometer shows zero deflection. If $AJ = l$ cm, then $JB = (100 - l)$ cm. The Wheatstone balance condition gives

$$\frac{X}{R} = \frac{r_{AJ}}{r_{JB}} = \frac{l}{100 - l}.$$

Thus the measured balance length and the known resistance determine X . Uniform wire is essential so that the resistance ratio equals the length ratio. Choosing R to place the balance point near the middle improves measurement accuracy.

Step 3: Conclusion The meter bridge works on Wheatstone bridge balance; with the connections

shown, $X = R \frac{l}{100 - l}.$

Quick Tip to Solve: Write the resistance ratio in the same left-to-right order as the wire lengths; use zero deflection.

Section C (21 marks)

28. (a) Write the expression for the speed of light in a material medium of relative permittivity ϵ_r and relative magnetic permeability μ_r .

(b) Write the wavelength range and name of the electromagnetic waves which are used in (i) radar systems for aircraft navigation, and (ii) Earth satellites to observe the growth of the crops. [3 marks]

Solution:

Concept:

- An electromagnetic wave travels in a medium with speed $v = 1/\sqrt{\mu\epsilon}$, where μ is its magnetic permeability and ϵ its electric permittivity.
- Relative properties are defined by $\epsilon = \epsilon_0\epsilon_r$ and $\mu = \mu_0\mu_r$; the vacuum speed is $c = 1/\sqrt{\mu_0\epsilon_0}$.
- The usual school-level spectrum ranges are approximate: microwave wavelengths extend from 1 mm to 0.1 m, while infrared extends from 700 nm to 1 mm.

Step 1: (a) Express the speed using relative properties Substituting the relative permittivity and permeability into the wave-speed relation gives

$$v = \frac{1}{\sqrt{\mu_0\mu_r\epsilon_0\epsilon_r}} = \frac{c}{\sqrt{\epsilon_r\mu_r}}.$$

Here c is the speed of light in vacuum and v is the speed in the specified material medium.

Step 2: (b)(i) Identify the radar radiation Aircraft-navigation radar uses microwaves, with approximate wavelength range 1 mm to 0.1 m. Their short wavelengths permit narrow directional beams; echoes reflected from aircraft or other objects allow the radar to determine their distance and direction.

Step 3: (b)(ii) Identify the radiation for crop observation Earth satellites use infrared radiation to

observe crop growth. The approximate infrared wavelength range is 700 nm to 1 mm. Vegetation has characteristic infrared reflection and emission, so satellite infrared images help distinguish vegetation condition and monitor changes in crop cover.

Step 4: Conclusion $v = c/\sqrt{\epsilon_r \mu_r}$. Radar uses microwaves (1 mm–0.1 m); crop-observation satellites use infrared (700 nm–1 mm).

Quick Tip to Solve: Remember radar as microwaves and vegetation sensing as infrared; insert relative properties under a square root.

29. Give reasons for each of the following:

- (a) The intensity of light at some points on the screen in Young's double slit experiment is zero.
- (b) The intensity of light transmitted by a polaroid is less than the intensity of the unpolarised light incident on it.
- (c) In the single slit diffraction experiment, some coloured fringes around the central white maximum are observed on the screen when one uses a source of white light. [3 marks]

Solution:

Concept:

- Interference intensity is $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$, where ϕ is the phase difference between coherent waves.
- A polaroid transmits only the electric-field component parallel to its transmission axis. For an ideal analyser, Malus's law is $I = I_0 \cos^2 \theta$.
- Single-slit diffraction minima satisfy $a \sin \theta = n\lambda$, where a is the slit width, $n = 1, 2, \dots$, and λ is the wavelength.

Step 1: (a) Explain the zero-intensity points At a dark fringe the path difference is $(2n + 1)\lambda/2$, so the phase difference is $(2n + 1)\pi$. The waves arrive in opposite phase and undergo destructive interference. With equal slit intensities $I_1 = I_2 = I_s$,

$$I = 2I_s(1 + \cos \phi) = 2I_s(1 - 1) = 0.$$

Thus equal and opposite electric-field amplitudes cancel. Exact zero requires equal amplitudes; unequal amplitudes leave a nonzero minimum.

Step 2: (b) Explain the decrease after a polaroid Unpolarised light contains electric-field vibrations in all directions perpendicular to propagation. The polaroid transmits the component along its axis and absorbs the perpendicular component. Averaging $\cos^2 \theta$ over all incident directions gives 1/2; hence an ideal polaroid transmits $I_{\text{out}} = I_{\text{in}}/2$. The transmitted intensity is therefore lower, with practical absorption possibly reducing it further.

Step 3: (c) Explain the coloured diffraction fringes White light contains many wavelengths. At the centre, the path difference across the slit is zero, so all colours have their central maxima at the same position and combine to give white light. Away from the centre, minima and secondary maxima occur

at wavelength-dependent angles. Since $a \sin \theta = n\lambda$, longer wavelengths spread farther than shorter ones. Their diffraction patterns no longer coincide, producing coloured fringes around the central white maximum.

Step 4: Conclusion The three effects arise respectively from destructive interference, selective transmission of one polarisation component, and wavelength-dependent diffraction of white light.

Quick Tip to Solve: For dark fringes check opposite phase and equal amplitudes; for white-light diffraction compare the wavelength dependence of fringe positions.

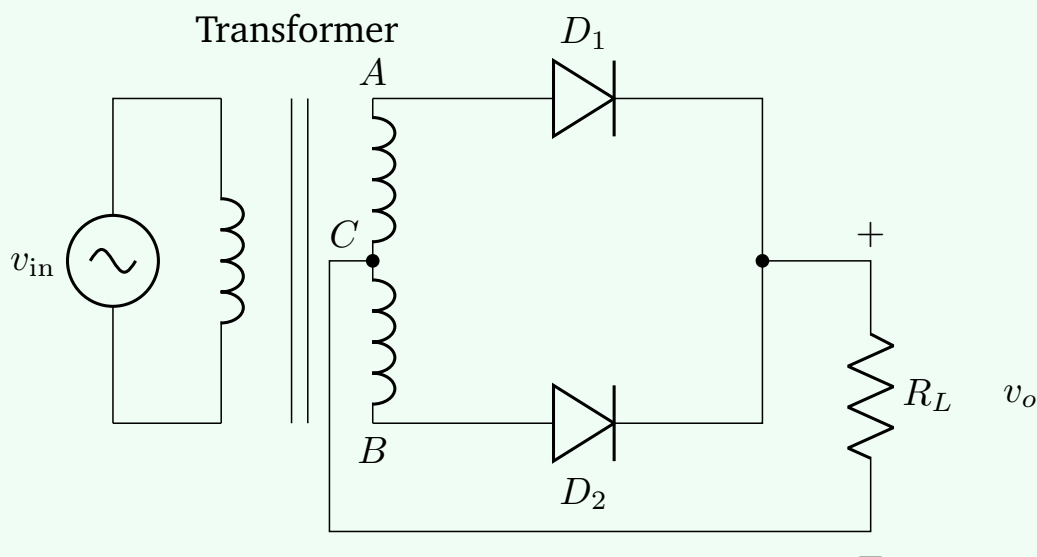
30. Draw the circuit diagram of a full wave rectifier using two p-n junction diodes. Explain its working and show input and output voltage variations. [3 marks]

Solution:

Concept:

- A p-n junction diode conducts under forward bias and blocks under reverse bias. Ideal diodes are assumed for the waveform; a real diode introduces a small forward-voltage drop.
- A centre-tapped secondary supplies equal voltages in opposite phase relative to the centre tap C . The two diodes route both half-cycles through the load in the same direction.
- Full-wave rectification gives a pulsating unidirectional output, $v_o = |V_m \sin \omega t|$, with ripple frequency twice the input frequency.

Step 1: Connect the centre-tapped rectifier The circuit below uses a centre-tapped transformer. Secondary ends A and B connect to the anodes of D_1 and D_2 ; their cathodes join at the positive output terminal. The load R_L is connected between this junction and the centre tap C , which is the return terminal. The transformer primary receives the alternating input.



Two-diode full-wave rectifier with centre-tapped transformer.

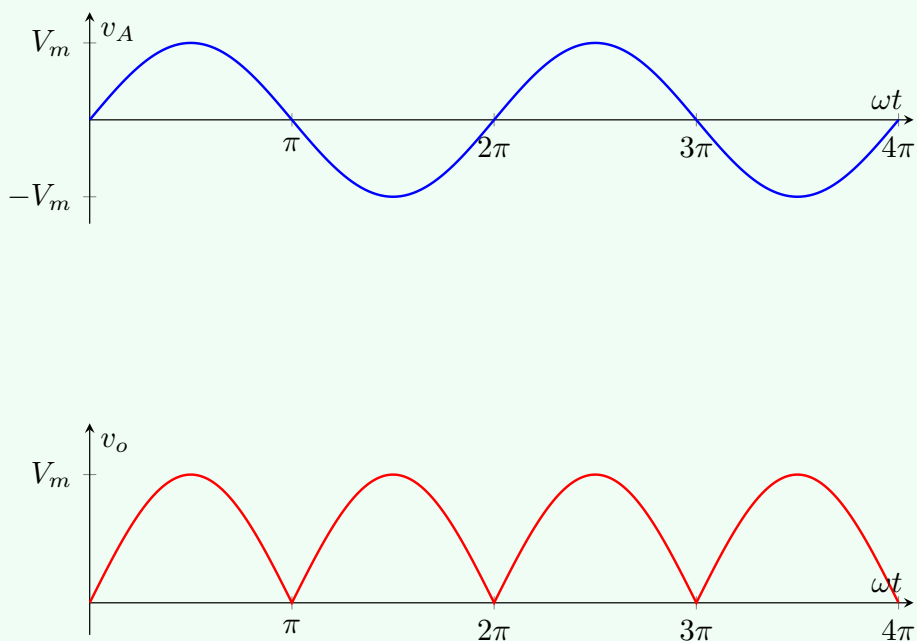
Step 2: Explain the first half-cycle When A is positive relative to C , end B is negative relative to C . Diode D_1 is forward biased and conducts, while D_2 is reverse biased and blocks. Conventional current flows from A through D_1 , down through R_L , and back through C to the upper half of the secondary. The top of the load is positive.

Step 3: Explain the second half-cycle When the secondary polarity reverses, B is positive relative to C . Now D_2 conducts and D_1 blocks. Current flows from B through D_2 , down through the same load, and returns through C to the lower half of the secondary. Its direction in the load is unchanged, so the negative input half-cycle also produces a positive output pulse.

Step 4: Compare the input and output variations The input is sinusoidal and alternates in sign. The output contains a positive pulse in each half-cycle:

$$v_A = V_m \sin \omega t, \quad v_B = -V_m \sin \omega t, \quad v_o = V_m |\sin \omega t|.$$

The output is pulsating dc, not constant dc; two output pulses occur per input cycle, so $f_o = 2f$. The plots show ideal-diode operation.



Sinusoidal input and full-wave rectified output (ideal diodes).

Step 5: Conclusion The two diodes conduct alternately, maintaining one current direction through R_L . Both input half-cycles are rectified and the output pulse frequency is twice the ac frequency.

Quick Tip to Solve: Join both diode cathodes to the load top and return the load to the centre tap; trace each half-cycle separately.

31. Two cells of emf E_1 and E_2 have their internal resistances r_1 and r_2 , respectively. Deduce an expression for the equivalent emf and internal resistance of their parallel combination when connected across an external resistance R . Assume that the two cells are supporting each other.

In case the two cells are identical, each of emf $E = 5\text{ V}$ and internal resistance $r = 2\ \Omega$, calculate the voltage across the external resistance $R = 10\ \Omega$. [3 marks]

Solution:

Concept:

- Cells supporting one another have like terminals joined. At common terminal voltage V , branch currents are $I_1 = (E_1 - V)/r_1$ and $I_2 = (E_2 - V)/r_2$.
- An equivalent cell satisfies $V = E_{\text{eq}} - Ir_{\text{eq}}$, where I is total load current. The external resistor

obeys $V = IR$.

Step 1: (a) Apply the junction and loop laws Kirchhoff's junction law gives $I = I_1 + I_2$. The loops give $E_1 = V + I_1 r_1$ and $E_2 = V + I_2 r_2$. Thus

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

Rearranging into the equivalent-cell form gives

$$V = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} - I \frac{r_1 r_2}{r_1 + r_2}.$$

Compare this with $V = E_{\text{eq}} - I r_{\text{eq}}$. The coefficient independent of current is the equivalent emf, while the coefficient of current is the equivalent internal resistance. Consequently the load current is $I = E_{\text{eq}} / (R + r_{\text{eq}})$. A branch current may be negative if a weaker cell receives current; the same derivation with signed currents still applies.

Step 2: (b) Substitute the identical-cell values For $E_1 = E_2 = E$ and $r_1 = r_2 = r$, the emf remains $E_{\text{eq}} = E = 5 \text{ V}$, while $r_{\text{eq}} = r/2 = 1 \Omega$. Therefore

$$I = \frac{5}{10 + 1} = \frac{5}{11} \text{ A}, \quad V = IR = \frac{5}{11} \times 10 = \frac{50}{11} \text{ V}.$$

The voltage is below the emf due to the internal drop $I r_{\text{eq}}$. Parallel connection reduces internal resistance without adding the cell emfs.

Step 3: Conclusion $E_{\text{eq}} = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2}$, $r_{\text{eq}} = \frac{r_1 r_2}{r_1 + r_2}$. The voltage across R is $50/11 \approx 4.55 \text{ V}$.

Quick Tip to Solve: For identical supporting cells in parallel, keep the emf unchanged and halve internal resistance before applying the voltage divider.

32. A resistance R and a capacitor C are connected in series to an ac source $V = V_0 \sin \omega t$.

(a) Obtain the expression for the instantaneous current (I) in the circuit.

(b) Show graphically variations of V and I as a function of ωt .

[3 marks]

Solution:

Concept:

- For a capacitor, the reactance is $X_C = 1/(\omega C)$. In a series RC circuit, the resistance and capacitive reactance combine as $Z = \sqrt{R^2 + X_C^2}$.
- Current leads the applied voltage by ϕ , where $\tan \phi = X_C/R$. In the sinusoidal steady state, both have angular frequency ω .

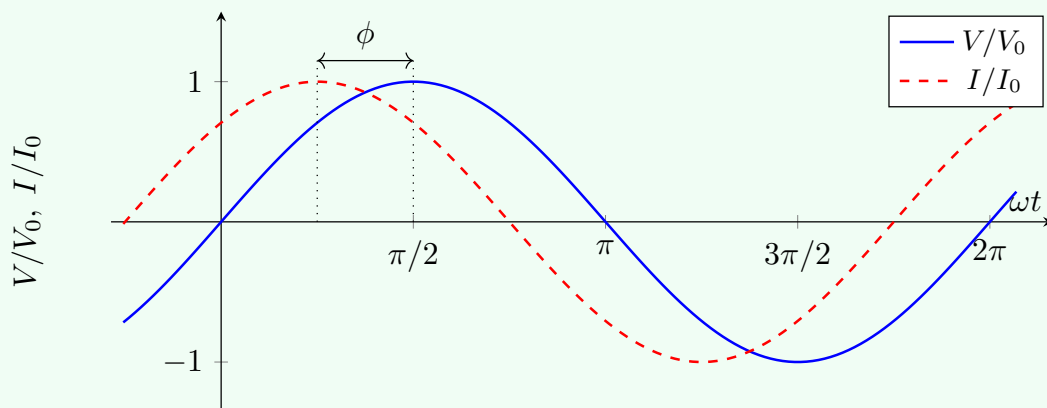
Step 1: (a) Find the impedance and phase Choose current as the phasor reference. The resistor voltage $V_R = I_0 R$ is in phase with current, whereas the capacitor voltage $V_C = I_0 X_C$ lags current by $\pi/2$. Their perpendicular phasor sum gives

$$V_0^2 = (I_0 R)^2 + (I_0 X_C)^2, \quad I_0 = \frac{V_0}{\sqrt{R^2 + (1/\omega C)^2}}.$$

The source voltage lags the current by an angle satisfying $\tan \phi = V_C/V_R = 1/(\omega C R)$, with $0 < \phi < \pi/2$.

$\pi/2$. Thus for the specified source $V = V_0 \sin \omega t$, the current has a positive phase shift. This sign is characteristic of a capacitive circuit.

Step 2: (b) Plot the sinusoidal variations Writing $\theta = \omega t$, plot $V/V_0 = \sin \theta$ and $I/I_0 = \sin(\theta + \phi)$. Normalising each amplitude allows both curves on one ordinate, since volts and amperes cannot share a numerical amplitude scale. The drawing uses a representative phase $\phi = \pi/4$; the actual shift is fixed by R, C, ω . Current reaches its positive maximum at $\theta = \pi/2 - \phi$, before the voltage maximum at $\pi/2$. Both curves repeat after 2π , so their frequencies are equal even though their phases differ.



Normalised voltage and current; representative lead $\phi = \pi/4$.

Step 3: Conclusion $I(t) = \frac{V_0}{\sqrt{R^2 + 1/(\omega^2 C^2)}} \sin(\omega t + \phi)$, where $\phi = \tan^{-1}\left(\frac{1}{\omega CR}\right)$. Current leads voltage by ϕ .

Quick Tip to Solve: In an RC circuit use a positive phase in the current sine: the current peak must appear to the left of the voltage peak.

33. Write an expression of magnetic moment associated with a current (I) carrying circular coil of radius r having N turns.

Consider the above mentioned coil placed in YZ plane with its centre at the origin. Derive expression for the value of magnetic field due to it at point $(x, 0, 0)$. [3 marks]

Solution:

Concept:

- The magnetic moment of a planar coil is $\mathbf{m} = NIA \hat{n}$, with normal direction given by the right-hand rule. For a circle, $A = \pi r^2$.
- Biot-Savart law gives $d\mathbf{B} = (\mu_0 I / 4\pi)(d\mathbf{l} \times \hat{s})/s^2$, where s points from the current element to the observation point.

Step 1: (a) State the magnetic moment The coil lies in the YZ plane, so its area vector is along the X axis. Its moment magnitude is $m = NI\pi r^2$. Choose current anticlockwise as viewed from the positive X side, so $\mathbf{m} = NI\pi r^2 \hat{x}$. Reversing current reverses this vector. The unit is A m^2 .

Step 2: (b) Resolve each element field along the axis For $P = (x, 0, 0)$, every element of the circular coil is at the same distance $s = \sqrt{r^2 + x^2}$. The tangent element $d\mathbf{l}$ is perpendicular to its displacement to P , giving $d\mathbf{B} = \mu_0 I d\mathbf{l} / (4\pi s^2)$. Fields of diametrically opposite elements have cancelling components in the YZ plane and equal axial components. The axial projection factor is

r/s , hence

$$dB_x = \frac{\mu_0 I r d\ell}{4\pi(r^2 + x^2)^{3/2}}.$$

Integrate around a turn using $\oint d\ell = 2\pi r$, and multiply by N for coincident turns:

$$B_x = \frac{\mu_0 N I r}{4\pi(r^2 + x^2)^{3/2}}(2\pi r).$$

This expression reduces at the centre $x = 0$ to $\mu_0 N I / (2r)$, consistent with the centre field of a circular coil. Its direction is along the coil moment; reversing current reverses the field.

Step 3: Conclusion $m = N I \pi r^2$, and $B(x) = \frac{\mu_0 N I r^2}{2(r^2 + x^2)^{3/2}}$. The magnetic field is along the X axis in the direction selected by the right-hand rule.

Quick Tip to Solve: On the loop axis cancel transverse field components by symmetry, then integrate only the axial projection with factor r divided by the element distance.

OR

33. Define current sensitivity of a galvanometer. Write its expression.

A galvanometer has resistance G and shows full scale deflection for current I_g .

(i) How can it be converted into an ammeter to measure current up to I_0 ($I_0 > I_g$)?

(ii) What is the effective resistance of this ammeter?

[3 marks]

Solution:

Concept:

- Current sensitivity is the angular deflection produced per unit current through a galvanometer: $S_I = \theta/I$.
- In a radial magnetic field, equilibrium requires $N I A B = k\theta$, where N is the number of turns, A their area, B the field and k the torsional constant of the suspension.
- Parallel resistances have the same potential difference. A shunt diverts excess current away from the sensitive galvanometer coil.

Step 1: (a) Obtain the current sensitivity The magnetic torque on the current-carrying coil is $N I A B$ in the radial field, and the restoring torque is $k\theta$. Balancing these torques gives

$$N I A B = k\theta, \quad S_I = \frac{\theta}{I} = \frac{N A B}{k}.$$

Thus sensitivity measures deflection per ampere, expressed in rad A^{-1} when deflection is measured in radians. Increasing the number of turns, area or magnetic field, or reducing the torsional constant, increases it.

Step 2: (b)(i) Select a parallel shunt Connect a low resistance S in parallel with the galvanometer of resistance G . At the desired full-scale reading I_0 , the coil must carry only its safe full-scale current I_g ; the shunt carries $I_s = I_0 - I_g$. Equal potential differences across the two branches give

$$I_g G = (I_0 - I_g) S, \quad S = \frac{I_g G}{I_0 - I_g}.$$

The scale is then calibrated to read the total current, and the resulting ammeter is connected in series with the circuit whose current is measured.

Step 3: (b)(ii) Calculate the effective resistance The ammeter resistance is that of the parallel combination, not the sum of the coil and shunt resistances:

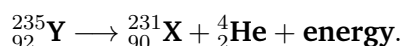
$$R_A = \frac{GS}{G+S} = \frac{G I_g G / (I_0 - I_g)}{G + I_g G / (I_0 - I_g)} = \frac{I_g G}{I_0}.$$

Equivalently, at full scale the voltage across the whole instrument is $I_g G$, so its resistance is that voltage divided by the total current I_0 . Since $I_g < I_0$, this resistance is smaller than G .

Step 4: Conclusion $S_I = NAB/k$. A parallel shunt $S = I_g G / (I_0 - I_g)$ converts the galvanometer into an ammeter of range I_0 , with effective resistance $R_A = I_g G / I_0$.

Quick Tip to Solve: At full scale put only I_g through the coil and $I_0 - I_g$ through the shunt; equate the two branch voltages.

34. The nucleus ${}^{235}_{92}\text{Y}$, initially at rest, decays into ${}^{231}_{90}\text{X}$ by emitting an α -particle.



The binding energies per nucleon of the parent nucleus, the daughter nucleus and α -particle are 7.8 MeV, 7.835 MeV and 7.07 MeV, respectively. Assuming the daughter nucleus to be formed in the unexcited state and neglecting its share in the energy of the reaction, find the speed of the emitted α -particle. (Mass of α -particle = 6.68×10^{-27} kg). [3 marks]

Solution:

Concept:

- Total binding energy equals mass number multiplied by binding energy per nucleon. The energy released in decay is the final total binding energy minus the initial total binding energy.
- For an unexcited daughter and with its recoil energy neglected as instructed, the emitted alpha particle receives the reaction energy: $K_\alpha = Q = \frac{1}{2} m_\alpha v_\alpha^2$.
- Convert energy before using SI mass: $1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$.

Step 1: Calculate the total binding energies The parent has 235 nucleons, the daughter 231, and the alpha particle 4. Multiplying each printed binding energy per nucleon by its own mass number gives

$$B_Y = 235(7.8) = 1833.000 \text{ MeV},$$

$$B_X = 231(7.835) = 1809.885 \text{ MeV},$$

$$B_\alpha = 4(7.07) = 28.280 \text{ MeV}.$$

Step 2: Find the energy released A larger final binding energy corresponds to a smaller final rest mass. Consequently the released energy is

$$Q = B_X + B_\alpha - B_Y = 1809.885 + 28.280 - 1833.000 = 5.165 \text{ MeV}.$$

The positive result confirms energy release. Binding energies per nucleon cannot be subtracted directly because the nuclei have different mass numbers.

Step 3: Convert the alpha-particle energy to speed The daughter is unexcited, and its share of kinetic energy is explicitly neglected. Hence all of Q is assigned to the alpha particle:

$$K_{\alpha} = 5.165(1.602 \times 10^{-13}) = 8.27433 \times 10^{-13} \text{ J.}$$

Using the given alpha-particle mass,

$$v_{\alpha} = \sqrt{\frac{2K_{\alpha}}{m_{\alpha}}} = \sqrt{\frac{2(8.27433 \times 10^{-13})}{6.68 \times 10^{-27}}} = 1.574 \times 10^7 \text{ m s}^{-1}.$$

This is about 0.052 times the speed of light, justifying the nonrelativistic expression. Daughter recoil energy is omitted under the stated approximation.

Step 4: Conclusion The released energy is 5.165 MeV, and the speed of the emitted alpha particle is approximately $1.57 \times 10^7 \text{ m s}^{-1}$.

Quick Tip to Solve: Multiply each binding energy per nucleon by its mass number before taking final minus initial, then convert MeV to joules.

Section D (15 marks)

35. Draw the ray diagram of an astronomical telescope when the final image is formed at infinity. Write the expression for the resolving power of the telescope.

An astronomical telescope has an objective lens of focal length 20 m and eyepiece of focal length 1 cm.

(i) Find the angular magnification of the telescope.

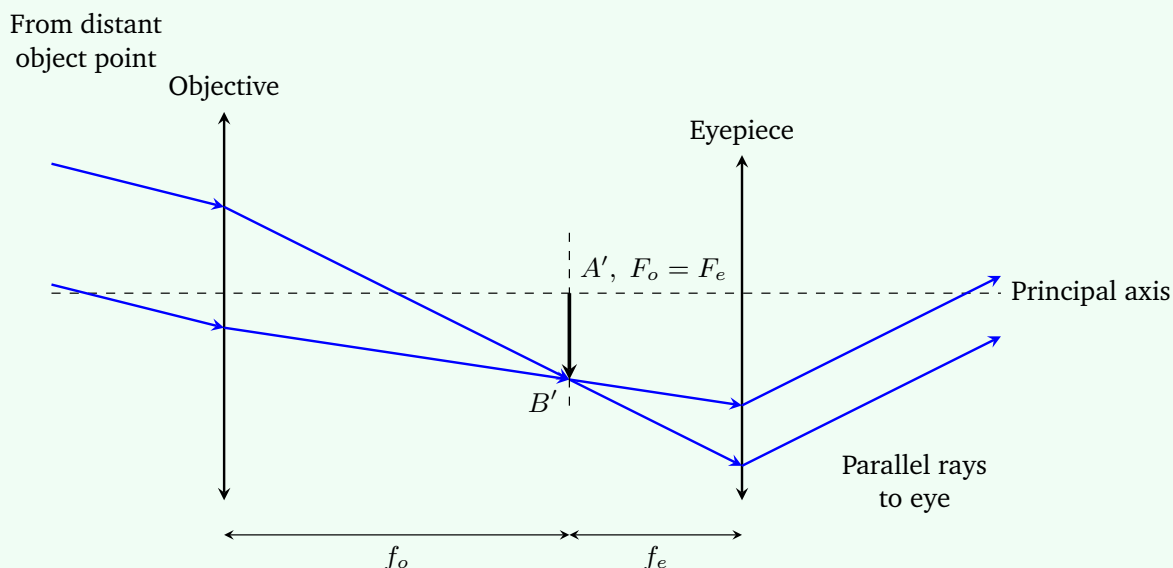
(ii) If this telescope is used to view the Moon, find the diameter of the image formed by the objective lens. Given the diameter of the Moon is $3.5 \times 10^6 \text{ m}$ and radius of lunar orbit is $3.8 \times 10^8 \text{ m}$. [5 marks]

Solution:

Concept:

- In normal adjustment, the objective forms a real inverted image of a distant object in its focal plane. This plane coincides with the first focal plane of the eyepiece, so the emergent rays are parallel and the final image is at infinity.
- The angular magnification is $M = -f_o/f_e$, where f_o and f_e are the objective and eyepiece focal lengths. The minus sign indicates an inverted view.
- For a circular objective of aperture diameter D , Rayleigh's criterion gives $\theta_{\min} = 1.22\lambda/D$. Resolving power is $1/\theta_{\min} = D/(1.22\lambda)$, where λ is the wavelength.

Step 1: (a) Ray diagram for normal adjustment The parallel incident rays from one point of a distant object converge at B' after passing through the objective. The real image $A'B'$ lies at the common focal plane $F_o = F_e$. Since this intermediate image is at the first focus of the eyepiece, rays from B' emerge parallel to one another. Thus the eye receives a final virtual image at infinity. The separation of the two lenses is $f_o + f_e$. The drawing is schematic: the focal-length ratio is exaggerated for clarity.



Astronomical telescope in normal adjustment; parallel emergent rays form the final image at infinity.

Step 2: (a) State the resolving power Two close point sources are just resolved when the central maximum of one diffraction pattern falls on the first minimum of the other. For a circular objective,

$$\theta_{\min} = \frac{1.22\lambda}{D}, \quad \text{RP} = \frac{1}{\theta_{\min}} = \frac{D}{1.22\lambda}.$$

Here $\theta_{\min}$ is measured in radians. A larger objective aperture gives better resolution by reducing the minimum angular separation. Increasing eyepiece magnification alone does not increase this diffraction-limited resolving power.

Step 3: (b)(i) Calculate angular magnification Convert the eyepiece focal length to the same unit as the objective focal length:

$$f_o = 20 \text{ m}, \quad f_e = 1 \text{ cm} = 0.01 \text{ m}.$$

For the normal adjustment shown above,

$$M = -\frac{20}{0.01} = -2000.$$

The magnitude of the angular magnification is 2000; the negative sign expresses inversion, not a negative size.

Step 4: (b)(ii) Calculate the objective image diameter Let the Moon's diameter be $d = 3.5 \times 10^6 \text{ m}$, and its distance be $R = 3.8 \times 10^8 \text{ m}$. Its small angular diameter is $\theta \simeq d/R$. The objective forms its image very nearly in its focal plane, giving image diameter $d' = f_o\theta$. Therefore,

$$\begin{aligned} \theta &= \frac{3.5 \times 10^6}{3.8 \times 10^8} = 9.21 \times 10^{-3} \text{ rad}, \\ d' &= 20 (9.21 \times 10^{-3}) \text{ m} = 0.1842 \text{ m} \simeq 18.4 \text{ cm}. \end{aligned}$$

The lunar-orbit radius supplies the object distance used here. Since it is enormous compared with 20 m, treating the objective image as a focal-plane image is justified. This diameter depends on the objective focal length and the Moon's angular size; the eyepiece only magnifies the view of this image.

Step 5: Conclusion In normal adjustment, the final image is at infinity and $\text{RP} = D/(1.22\lambda)$. The angular magnification is $M = -2000$, with magnitude 2000, and the objective forms a real inverted

Moon image of diameter approximately $0.184 \text{ m} = 18.4 \text{ cm}$.

Quick Tip to Solve: Convert both focal lengths to metres before taking their ratio; for a distant extended object, use objective image size = objective focal length times angular size.

OR

35. An object is placed in front of a concave mirror. It is observed that a virtual image is formed. Draw the ray diagram to show the image formation and hence derive the mirror equation $\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$.

An object is placed 30 cm in front of a plano-convex lens with its spherical surface of radius of curvature 20 cm. If the refractive index of the material of the lens is 1.5, find the position and nature of the image formed.

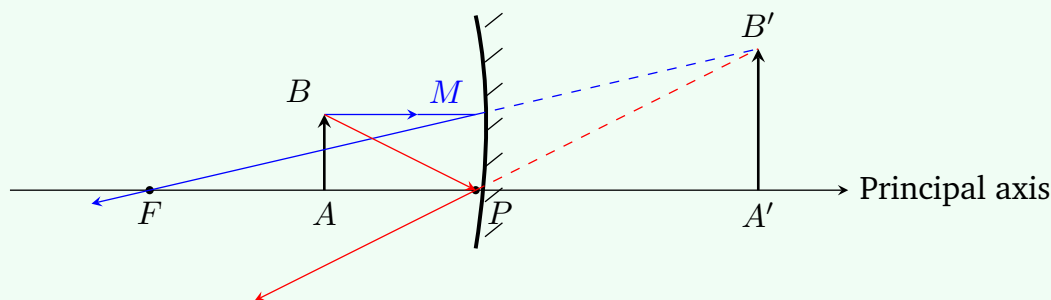
[5 marks]

Solution:

Concept:

- A concave mirror forms a virtual, erect and enlarged image when the object lies between its pole P and focus F . The reflected rays diverge; their backward extensions meet behind the mirror.
- In the Cartesian convention, light travels initially from left to right. Thus the concave mirror has $u < 0$, $f < 0$ and, for its virtual image, $v > 0$. The paraxial approximation makes ray geometry valid for small apertures.
- For a thin lens in air, the lens-maker formula is $1/f = (\mu - 1)(1/R_1 - 1/R_2)$, and the lens formula is $1/v - 1/u = 1/f$. Here μ is the refractive index and R_1, R_2 are signed surface radii.

Step 1: (a) Construct the virtual image Place the object AB between F and P . A ray from B parallel to the principal axis reflects towards F . A second ray from B incident at the pole reflects with equal angles to the axis. Extend both reflected rays backwards behind the mirror: they intersect at B' , with A' on the axis. The image $A'B'$ is virtual, erect and enlarged. Dashed lines in the figure represent these backward extensions, not actual light behind the mirror.



Concave mirror with the object inside its focus; dashed backward extensions locate the virtual image. The mirror surface is represented paraxially at P .

Step 2: (a) Derive the mirror equation from the ray geometry Let the positive distance magnitudes be $AP = a$, $PA' = b$, $PF = F_0$, and the object and image heights be h and h' . From the pole ray, equal angles of incidence and reflection give similar triangles:

$$\frac{h'}{h} = \frac{b}{a}.$$

Let M be the point where the parallel ray meets the mirror. For a small aperture, take M to be vertically above P , so $PM \simeq h$. The reflected ray passes through F , and its backward extension

reaches B' . Similar triangles along this same straight line give

$$\frac{h'}{h} = \frac{F_0 + b}{F_0} = 1 + \frac{b}{F_0}.$$

Equating the two expressions and rearranging,

$$\frac{b}{a} = 1 + \frac{b}{F_0} \implies \frac{1}{F_0} = \frac{1}{a} - \frac{1}{b}.$$

Now use $u = -a$, $v = b$ and $f = -F_0$. Multiplying the last equation by -1 yields the required signed relation $1/f = 1/u + 1/v$. The derivation uses paraxial rays, as does the usual mirror equation.

Step 3: (b) Calculate the focal length of the plano-convex lens Take light to enter the spherical convex face first: $R_1 = +20$ cm, while the plane face has $R_2 = \infty$. Reversing the thin lens gives the same focal length. Substituting $\mu = 1.5$,

$$\frac{1}{f} = (1.5 - 1) \left(\frac{1}{20} - 0 \right) = \frac{1}{40} \text{ cm}^{-1}, \quad f = +40 \text{ cm}.$$

The positive focal length confirms that this is a converging lens.

Step 4: (b) Locate and characterize the image The object is on the incident side, so $u = -30$ cm. The thin-lens equation gives

$$\begin{aligned} \frac{1}{v} &= \frac{1}{f} + \frac{1}{u} = \frac{1}{40} - \frac{1}{30} = -\frac{1}{120} \text{ cm}^{-1}, \\ v &= -120 \text{ cm}, \quad m = \frac{v}{u} = \frac{-120}{-30} = +4. \end{aligned}$$

The negative image distance puts the image on the object's side of the lens. The positive magnification shows that it is erect; its magnitude shows fourfold enlargement. This agrees with the fact that the object is inside the focal length of a converging lens.

Step 5: Conclusion (a) The concave mirror gives a virtual, erect, enlarged image behind it, and the paraxial ray geometry gives $1/f = 1/u + 1/v$. (b) The lens has $f = 40$ cm and forms its image **120 cm** from the lens on the object side; the image is virtual, erect and four times the object's size.

Quick Tip to Solve: Keep mirror and lens sign conventions separate: a virtual mirror image has positive v , whereas this virtual lens image has negative v .

36. (a) Using Gauss law, derive expression for electric field due to a spherical shell of uniform charge distribution σ and radius R at a point lying at a distance x from the centre of shell, such that

(i) $0 < x < R$, and

(ii) $x > R$.

(b) An electric field is uniform and acts along $+x$ direction in the region of positive x . It is also uniform with the same magnitude but acts in $-x$ direction in the region of negative x . The value of the field is $E = 200 \text{ N/C}$ for $x > 0$ and $E = -200 \text{ N/C}$ for $x < 0$. A right circular cylinder of length 20 cm and radius 5 cm has its centre at the origin and its axis along the x -axis so that one flat face is at $x = +10 \text{ cm}$ and the other is at $x = -10 \text{ cm}$.

Find:

(i) The net outward flux through the cylinder.

(ii) The net charge present inside the cylinder.

[5 marks]

Solution:

Concept:

- Gauss's law states $\oint_S \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where $d\vec{A}$ is outward and Q_{enc} is the enclosed charge.
- A uniformly charged spherical shell of radius R and surface charge density σ carries total charge $Q = 4\pi R^2\sigma$. Spherical symmetry makes its field radial and its magnitude constant on a concentric sphere.
- Electric flux through a flat surface in a uniform field is $\Phi = EA \cos \theta$, where θ is the angle between the field and the outward normal. Flux contributions from all portions of a closed surface must be added with their signs.

Step 1: (a)(i) Field inside the spherical shell Choose a concentric spherical Gaussian surface of radius x , with $0 < x < R$. All the shell's charge lies at radius R , so this Gaussian surface encloses no charge. By symmetry, the field is radial and has the same magnitude at every point on the Gaussian surface. Therefore,

$$\oint_S \vec{E} \cdot d\vec{A} = E(x) 4\pi x^2 = \frac{0}{\epsilon_0}.$$

Since $x > 0$, the area is nonzero, and the electric field vanishes throughout the hollow interior. This follows from the shell's spherical symmetry together with Gauss's law; zero enclosed charge by itself would not imply zero field for an arbitrary charge arrangement.

Step 2: (a)(ii) Field outside the spherical shell Now choose a concentric Gaussian sphere of radius $x > R$. It encloses the entire shell, so $Q_{\text{enc}} = 4\pi R^2\sigma$. The radial field is constant in magnitude over this surface and parallel to its outward area vector for positive σ . Gauss's law gives

$$E(x) 4\pi x^2 = \frac{4\pi R^2\sigma}{\epsilon_0},$$

$$\vec{E}(x) = \frac{\sigma R^2}{\epsilon_0 x^2} \hat{r} = \frac{Q}{4\pi\epsilon_0 x^2} \hat{r}.$$

Thus the exterior field is the same as that of a point charge equal to the shell's total charge placed at its centre. The vector expression points outward for positive σ and inward for negative σ .

Step 3: (b)(i) Add the outward flux through both end faces The cylinder has radius $r = 5 \text{ cm} = 0.05 \text{ m}$, so each flat face has area $A = \pi r^2 = 0.0025\pi \text{ m}^2$. On the curved surface, the outward normal is perpendicular to the cylinder axis, while the electric field is along that axis. Hence the curved-surface flux is zero. At the right face, $x = +0.10 \text{ m}$, both $\vec{E} = 200\hat{x} \text{ N/C}$ and the outward normal point along

$+x$. At the left face, $x = -0.10$ m, both $\vec{E} = -200\hat{x}$ N/C and the outward normal point along $-x$. Consequently, both end faces contribute positive outward flux:

$$\begin{aligned}\Phi_{\text{right}} &= 200A, \\ \Phi_{\text{left}} &= (-200)(-A) = 200A, \\ \Phi_{\text{net}} &= 400\pi(0.05)^2 = \pi \text{ N m}^2/\text{C}.\end{aligned}$$

The two contributions add because each field points outward from the cylinder. The change in direction at $x = 0$ does not create any additional boundary face of the closed Gaussian surface.

Step 4: (b)(ii) Calculate the enclosed charge Apply Gauss's law to the entire closed cylinder. Using $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2/(\text{N m}^2)$,

$$\begin{aligned}Q_{\text{enc}} &= \epsilon_0 \Phi_{\text{net}} \\ &= (8.854 \times 10^{-12})\pi \text{ C} \\ &\simeq 2.78 \times 10^{-11} \text{ C}.\end{aligned}$$

The charge is positive, consistent with the electric field pointing away from the plane $x = 0$ on both sides. The cylinder's length fixes the positions of its end faces; the flux depends on their area and the specified field magnitude.

Step 5: Conclusion (a) For $0 < x < R$, $\vec{E} = 0$; for $x > R$, $\vec{E} = \sigma R^2 \hat{r}/(\epsilon_0 x^2)$. (b) The net outward flux is $\pi \text{ N m}^2/\text{C} \simeq 3.14 \text{ N m}^2/\text{C}$, and the enclosed charge is $+2.78 \times 10^{-11} \text{ C}$.

Quick Tip to Solve: On each end face, compare the field with that face's outward normal. Here both reverse on the left, so its flux stays positive and the two face fluxes add.

OR

36. (a) Find the expression for the potential energy of a system of two point charges q_1 and q_2 located at $\vec{r}_1$ and $\vec{r}_2$ respectively in an external electric field $\vec{E}$.

(b) Draw equipotential surfaces due to an isolated point charge $(-q)$ and depict the electric field lines.

(c) Three point charges $+1 \mu\text{C}$, $-1 \mu\text{C}$ and $+2 \mu\text{C}$ are initially infinite distance apart. Calculate the work done in assembling these charges at the vertices of an equilateral triangle of side 10 cm. [5 marks]

Solution:

Concept:

- The external electrostatic potential $V_{\text{ext}}(\vec{r})$ obeys $\vec{E} = -\nabla V_{\text{ext}}$. Bringing a charge q quasistatically to a point changes its external-field potential energy by qV_{ext} , relative to the chosen reference.
- The interaction energy of two point charges separated by $r_{12} = |\vec{r}_1 - \vec{r}_2|$ is kq_1q_2/r_{12} , where $k = 1/(4\pi\epsilon_0)$. Each distinct pair is counted once.
- For an isolated charge $-q$, with $q > 0$, $V = -kq/r$. Constant-potential surfaces are concentric spheres and the field is radial inward, normal to each surface.

Step 1: (a) Bring the first charge into the external field Let the external sources remain fixed. Choose the reference for their potential and take the mutual interaction of initially widely separated charges to be zero. The work required to bring q_1 to $\vec{r}_1$ against the external field is

$$W_1 = q_1 V_{\text{ext}}(\vec{r}_1).$$

This expression uses the external potential only, excluding the potential of the charge itself. The fixed sources' own energy is an unchanged constant and is not part of the energy being calculated.

Step 2: (a) Add the second charge and count the interaction once At $\vec{r}_2$, the potential due to the external sources and the first charge is $V_{\text{ext}}(\vec{r}_2) + kq_1/r_{12}$. Thus

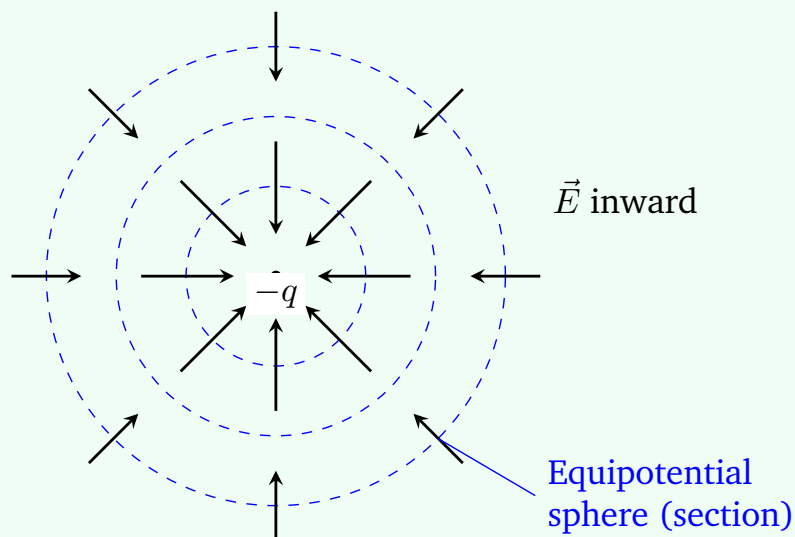
$$W_2 = q_2 V_{\text{ext}}(\vec{r}_2) + \frac{kq_1 q_2}{r_{12}}.$$

Adding the two assembly works gives

$$U = q_1 V_{\text{ext}}(\vec{r}_1) + q_2 V_{\text{ext}}(\vec{r}_2) + \frac{q_1 q_2}{4\pi\epsilon_0 |\vec{r}_1 - \vec{r}_2|}.$$

There is no extra factor of two in the mutual term. For a uniform external field, choose $V_{\text{ext}}(\vec{r}_0) = 0$; then $V_{\text{ext}}(\vec{r}) = -\vec{E} \cdot (\vec{r} - \vec{r}_0)$. A general nonuniform field instead requires its corresponding potential, obtained from the field's line integral.

Step 3: (b) Draw the equipotential surfaces and electric field Since $V = -kq/r$ depends only on distance from the charge, every sphere centred on $-q$ has a constant potential. The circles in the sketch represent sections of these spherical surfaces. The radial arrows point towards the negative charge; they intersect every equipotential at right angles. The potential becomes more negative closer to the charge, and no work is done in moving a test charge along any one surface.



Cross-section of concentric spherical equipotentials about $-q$; radial electric field lines point inward.

Step 4: (c) Calculate the work of assembling the triangle Initially, all pair separations are infinite, so the interaction energy is zero. Quasistatic work by an external agent equals the increase in electrostatic potential energy. For side $a = 10 \text{ cm} = 0.10 \text{ m}$, all three separations are equal:

$$\begin{aligned} W &= \frac{k}{a}(q_1 q_2 + q_2 q_3 + q_3 q_1), \\ q_1 q_2 &= -1 \times 10^{-12} \text{ C}^2, \\ q_2 q_3 &= -2 \times 10^{-12} \text{ C}^2, \\ q_3 q_1 &= +2 \times 10^{-12} \text{ C}^2, \\ W &= \frac{9.0 \times 10^9}{0.10}(-1 \times 10^{-12}) \text{ J} \\ &= -9.0 \times 10^{-2} \text{ J}. \end{aligned}$$

The two pair terms involving $+2\mu\text{C}$ cancel. The negative assembly work means the electric field releases energy and the external agent removes energy to assemble the charges slowly.

Step 5: Conclusion (a) $U = q_1 V_{\text{ext}}(\vec{r}_1) + q_2 V_{\text{ext}}(\vec{r}_2) + kq_1 q_2 / r_{12}$. (b) The equipotentials are concentric spheres with perpendicular inward field lines. (c) The work done in assembling the charges is -0.090 J .

Quick Tip to Solve: For an equilateral triangle, factor out k/a and add the three signed charge products before substituting numbers; attractive pairs contribute negative energy.

37. (a) Derive the expression for the torque acting on the rectangular current carrying coil of a galvanometer. Why is the magnetic field made radial?

(b) An α -particle is accelerated through a potential difference of 10 kV and moves along x -axis. It enters in a region of uniform magnetic field $B = 2 \times 10^{-3}\text{ T}$ acting along y -axis. Find the radius of its path. (Take mass of α -particle = $6.4 \times 10^{-27}\text{ kg}$) [5 marks]

Solution:

Concept:

- A straight conductor of length l , carrying current I perpendicular to a magnetic field B , experiences force $F = BIl$. Equal and opposite forces on the opposite sides of a coil form a couple.
- For a coil of N turns and area A , its magnetic moment is $\mu = NIA$. The torque is $\tau = NIAB \sin \theta$, where θ is the angle between the coil's normal and the magnetic field.
- Acceleration from rest through potential difference V supplies kinetic energy qV . A magnetic field perpendicular to velocity supplies centripetal force without changing the particle's speed.

Step 1: (a) Derive the torque on the rectangular coil Consider a rectangular coil of N turns, with vertical side length l , width b and area $A = lb$, carrying current I . Let the normal to the coil make angle θ with a uniform magnetic field lying perpendicular to the vertical sides. Each vertical side experiences a force of magnitude $F = NBIl$. The current directions in these opposite sides are opposite, so their forces are equal and opposite and form a couple. Their perpendicular separation is $b \sin \theta$. Therefore,

$$\begin{aligned}\tau &= F(b \sin \theta) \\ &= NBIlb \sin \theta = NIAB \sin \theta.\end{aligned}$$

The forces on the remaining two sides give no torque about the coil's vertical suspension axis. The direction of the torque is given by $\tau = \mu \times B$; it tends to align the coil's magnetic moment with the field.

Step 2: (a) Explain the radial magnetic field Concave pole faces and a soft iron cylindrical core produce a radial field in the galvanometer. As the coil turns, the field remains parallel to the plane of the coil at its active sides. Thus the coil normal is perpendicular to the field, so $\theta = 90^\circ$ throughout its useful angular motion. The torque is consequently $\tau = NIAB$, independent of the angle of deflection and directly proportional to current. If the suspension has torsional constant k and the coil settles at deflection ϕ , the restoring torque is $k\phi$. Equilibrium gives $NIAB = k\phi$, or $I = k\phi/(NAB)$. This makes the deflection proportional to current and gives a uniform scale. The soft iron core also strengthens the magnetic field.

Step 3: (b) Find the speed of the accelerated alpha particle An alpha particle has positive charge $q = 2e = 3.2 \times 10^{-19}\text{ C}$. Taking its initial kinetic energy to be negligible, with $V = 10\text{ kV} = 10^4\text{ V}$,

energy conservation gives

$$\begin{aligned}\frac{1}{2}mv^2 &= qV, \\ v &= \sqrt{\frac{2qV}{m}} = \sqrt{\frac{2(3.2 \times 10^{-19})(10^4)}{6.4 \times 10^{-27}}} \\ &= \sqrt{10^{12}} = 1.0 \times 10^6 \text{ m s}^{-1}.\end{aligned}$$

The given mass and the doubled elementary charge must both be used; an alpha particle is not singly charged.

Step 4: (b) Obtain the radius from magnetic force The initial velocity lies along the x -axis and the magnetic field along the y -axis, so they are perpendicular. There is no velocity component along the field: the motion is circular in the xz -plane. For positive charge initially moving along positive x , the initial magnetic force points along positive z . Since the magnetic force always remains perpendicular to velocity, the speed stays constant. Equating its magnitude to the centripetal force gives

$$\begin{aligned}qvB &= \frac{mv^2}{r}, \\ r &= \frac{mv}{qB} = \frac{(6.4 \times 10^{-27})(1.0 \times 10^6)}{(3.2 \times 10^{-19})(2 \times 10^{-3})} \\ &= \frac{6.4 \times 10^{-21}}{6.4 \times 10^{-22}} \text{ m}.\end{aligned}$$

Step 5: Conclusion The coil torque is $\tau = NIAB \sin \theta$. In the radial field, $\tau = NIAB$, making galvanometer deflection proportional to current. The alpha particle follows a circle of radius $r = 10 \text{ m}$.

Quick Tip to Solve: For a particle accelerated through a voltage before entering a perpendicular field, use $r = \sqrt{2mV/q}/B$. For an alpha particle always substitute $q = 2e$.

37. (a) With the help of a labelled diagram, explain the working of a step-up transformer. Give reasons to explain the following:

(i) The core of the transformer is laminated.

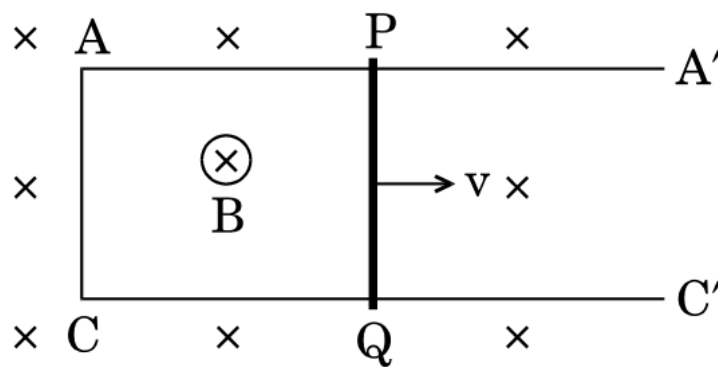
(ii) Thick copper wire is used in windings.

(b) A conducting rod PQ of length 20 cm and resistance $0.1\ \Omega$ rests on two smooth parallel rails of negligible resistance AA' and CC' . It can slide on the rails and the arrangement is positioned between the poles of a permanent magnet producing uniform magnetic field $B = 0.4\ \text{T}$. The rails, the rod and the magnetic field are in three mutually perpendicular directions as shown in the figure. If the ends A and C of the rails are short circuited, find the

(i) external force required to move the rod with uniform velocity $v = 10\ \text{cm/s}$, and

(ii) power required to do so.

[5 marks]



Solution:

Concept:

- A transformer works by mutual induction: an alternating primary current produces a changing magnetic flux Φ in a common iron core, inducing emf in both windings.
- For an ideal transformer, $V_s/V_p = N_s/N_p$, where N_p, N_s are the primary and secondary turns. A step-up transformer has $N_s > N_p$.
- A perpendicular conducting rod moving through a uniform field has motional emf $\varepsilon = Blv$. In a closed circuit, $I = \varepsilon/R$, and the rod experiences magnetic force $F_B = BIl$ opposing motion.

Step 1: (a) Construction and working of a step-up transformer Two insulated copper windings are wound on a common closed soft-iron core. The primary, with N_p turns, is connected to an alternating-voltage source; the secondary, with more turns N_s , supplies the load. The windings are electrically insulated from each other and from the core. Their coupling is magnetic.

The alternating primary current sets up a changing flux in the core. This flux links both coils and induces emfs according to Faraday's law:

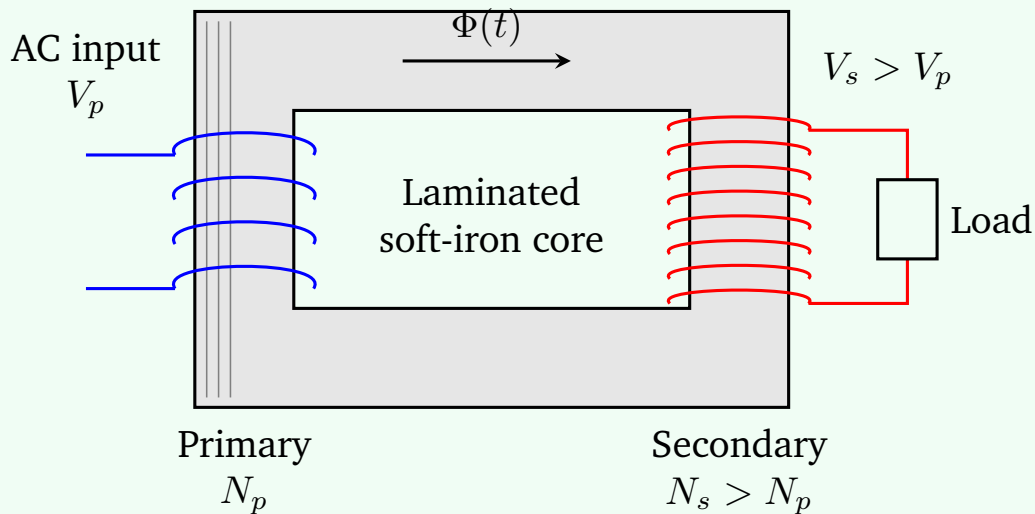
$$E_p = -N_p \frac{d\Phi}{dt}, \quad E_s = -N_s \frac{d\Phi}{dt}.$$

Assuming negligible flux leakage and winding losses, the magnitudes therefore satisfy

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} > 1.$$

Thus the secondary voltage exceeds the input voltage. When a load is connected, secondary current

flows and energy is transferred from the primary circuit through the changing magnetic field. Ideally $V_p I_p = V_s I_s$, so increasing voltage reduces the available secondary current. A steady direct current cannot produce the continuously changing flux needed for normal transformer operation.



Step-up transformer: insulated primary and secondary coils share a laminated soft-iron core; the secondary has more turns.

Step 2: (a)(i), (ii) Reasons for lamination and thick copper windings (i) The alternating flux also induces eddy currents in the conducting core. Dividing the core into thin sheets insulated from each other breaks up large current loops and increases their resistance. This reduces eddy-current heating and the associated energy loss.

(ii) Copper has low resistivity, and using a thick wire increases its cross-sectional area A . Since the winding resistance is $R_w = \rho L/A$, this lowers resistance and reduces copper loss $I^2 R_w$, heating and voltage drop. These features improve transformer efficiency.

Step 3: (b)(i) Determine the induced current and external force Convert the length and speed to SI units:

$$l = 0.20 \text{ m}, \quad v = 0.10 \text{ m s}^{-1}, \quad B = 0.4 \text{ T}, \quad R = 0.1 \Omega.$$

With A and C connected, the rod and rails form a closed conducting loop. Its only appreciable resistance is the rod resistance. The induced emf and current are

$$\begin{aligned} \varepsilon &= Blv = (0.4)(0.20)(0.10) = 0.008 \text{ V}, \\ I &= \frac{\varepsilon}{R} = \frac{0.008}{0.1} = 0.08 \text{ A}. \end{aligned}$$

As the rod moves right, inward magnetic flux increases. Lenz's law gives an anticlockwise induced current, flowing from Q to P in the rod. Its magnetic force is therefore leftward, opposing motion. To maintain uniform speed, the external rightward force must balance it:

$$F_{\text{ext}} = BIl = \frac{B^2 l^2 v}{R} = (0.4)(0.08)(0.20) = 6.4 \times 10^{-3} \text{ N}.$$

Step 4: (b)(ii) Calculate the required mechanical power For uniform motion, the applied mechanical power is force times speed:

$$P_{\text{mech}} = F_{\text{ext}} v = (6.4 \times 10^{-3})(0.10) = 6.4 \times 10^{-4} \text{ W}.$$

There is no change in kinetic energy and the rails are smooth, so this power is converted into Joule heat in the rod. As an independent check,

$$I^2 R = (0.08)^2 (0.1) = 6.4 \times 10^{-4} \text{ W},$$

which agrees with the mechanical input.

Step 5: Conclusion A step-up transformer uses mutual induction with $N_s > N_p$, giving $V_s > V_p$. Lamination reduces eddy-current loss, and thick copper windings reduce resistive heating. The rod requires an external force $6.4 \times 10^{-3} \text{ N}$ to the right and power $6.4 \times 10^{-4} \text{ W}$.

Quick Tip to Solve: Convert both centimetres to metres before using Blv ; check the mechanical power with $I^2 R$ to catch a missing factor of speed.