CBSE Class XII 2025 Physics Set 1 (55/1/1) Question Paper with Solutions

Time Allowed :3 Hours	**Maximum Marks :**70	**Total Questions :**33

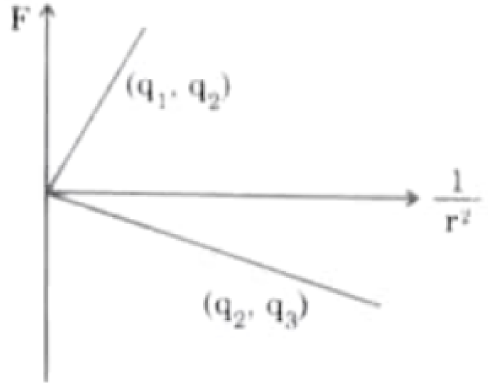
General Instructions

Read the following instructions very carefully and strictly follow them:

1. This question paper comprises 33 questions. All questions are compulsory.
2. This question paper is divided into FIVE sections viz. Section A, B, C, D and E.
3. In Section A question number 1 to 16 are Multiple Choice Questions (MCQs) carrying 1 mark each.
4. In Section B question number 17 to 21 are Very Short Answer (VSA) type questions carrying 2 marks each.
5. In Section C question number 22 to 28 are Short Answer (SA) type questions carrying 3 marks each.
6. In Section D question number 29 to 30 are case study based questions carrying 4 marks each.
7. In Section E question number 31 to 33 are long answer type questions carrying 5 marks each.

Section A

1. Figure shows variation of Coulomb force (F) acting between two point charges with $\frac{1}{r^2}$, r being the separation between the two charges (q_1, q_2) and (q_2, q_3). If q_2 is positive and least in magnitude, then the magnitudes of q_1, q_2, and q_3 are such that:



(A) $q_2 < q_3 < q_1$

(B) $q_3 < q_1 < q_2$

(C) $q_1 < q_2 < q_3$

(D) $q_2 < q_1 < q_3$

Correct Answer: (C) $q_1 < q_2 < q_3$

Solution: Step 1: Coulomb's law states that the force between two charges is inversely proportional to the square of the separation between them. Hence, the force due to each pair of charges is given by:

$$F = k\frac{|q_1q_2|}{r^2}$$

where k is the Coulomb constant and r is the distance between the charges. Given that $F \propto \frac{1}{r^2}$, we analyze the direction and magnitude of the forces from the graph to infer the relative magnitudes of the charges.

Step 2: The fact that q_2 is positive and least in magnitude, and the graph indicates that the force between q_2 and q_3 is greater than between q_2 and q_1, suggests that $|q_3| > |q_1|$. Therefore, the magnitude order is $|q_1| < |q_2| < |q_3|$, leading to the correct answer.

Quick Tip

For Coulomb's law, remember that the force between two charges depends on the product of the charges and inversely on the square of the distance between them: $F = k\frac{|q_1 q_2|}{r^2}$.

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2. Two wires P and Q are made of the same material. The wire Q has twice the diameter and half the length as that of wire P. If the resistance of wire P is R, the resistance of the wire Q will be:

(A) R

(B) $\frac{R}{2}$

(C) $\frac{R}{8}$

(D) $2R$

Correct Answer: (C) $\frac{R}{8}$

Solution: Step 1: The resistance R of a wire is given by the formula:

$$R = \rho \frac{L}{A}$$

where ρ is the resistivity of the material, L is the length of the wire, and A is the cross-sectional area of the wire.

Step 2: The diameter of wire Q is twice that of wire P, which implies that the radius of wire Q is also twice that of wire P. Since the area of a cross-section is given by $A = \pi r^2$, the cross-sectional area of wire Q will be four times that of wire P.

Step 3: Given that the length of wire Q is half the length of wire P, we now compare the resistances. The resistance of wire Q is:

$$R_Q = \rho \frac{\frac{L}{2}}{4A} = \frac{1}{8} \times \rho \frac{L}{A} = \frac{R}{8}$$

Quick Tip

For resistance, remember that it is inversely proportional to the area of the cross-section and directly proportional to the length of the wire. A larger diameter results in a smaller resistance.

3. A 1 cm segment of a wire lying along the x-axis carries a current of 0.5 A along the +x direction. A magnetic field $\vec{B} = (0.4\,\mathbf{mT})\hat{j} + (0.6\,\mathbf{mT})\hat{k}$ is switched on in the region. The force acting on the segment is:

(A) $(2\hat{j} + 3\hat{k})\,\text{mN}$

(B) $(-3\hat{j} + 2\hat{k})\,\mu\text{N}$

(C) $(6\hat{j} + 4\hat{k})\,\text{mN}$

(D) $(-4\hat{j} + 6\hat{k})\,\mu\text{N}$

Correct Answer: (C) $(6\hat{j} + 4\hat{k})\,\text{mN}$

Solution: Step 1: The magnetic force on a current-carrying conductor is given by:

$$\vec{F} = I(\ell \times \vec{B})$$

where I is the current, ℓ is the length vector of the conductor, and $\vec{B}$ is the magnetic field. Given that the current is along the x-axis, we have $\ell = 1\,\text{cm} = 0.01\,\text{m}\hat{i}$.

Step 2: The cross product $\ell \times \vec{B}$ is calculated as:

$$\ell \times \vec{B} = (0.01\hat{i}) \times (0.4 \times 10^{-3}\hat{j} + 0.6 \times 10^{-3}\hat{k})$$

Using the right-hand rule and the properties of cross products:

$$\ell \times \vec{B} = 0.01 \times \left(0.4 \times 10^{-3}\hat{k} - 0.6 \times 10^{-3}\hat{j}\right) = (6\hat{j} + 4\hat{k}) \times 10^{-5}\,\text{m}^2/\text{s}$$

Now, multiplying by the current $I = 0.5\,\text{A}$:

$$\vec{F} = 0.5 \times (6\hat{j} + 4\hat{k}) \times 10^{-5} = (6\hat{j} + 4\hat{k})\,\text{mN}$$

Quick Tip

Remember the formula for magnetic force: $\vec{F} = I(\ell \times \vec{B})$, and use the right-hand rule to determine the direction of the force.

4. A coil has 100 turns, each of area $0.05\,\mathbf{m}^2$ and total resistance 1.5 Ω. It is inserted at an instant in a magnetic field of 90 mT, with its axis parallel to the field. The charge induced in the coil at that instant is:

(A) 3.0 mC

(B) 0.30 C

(C) 0.45 C

(D) 1.5 C

Correct Answer: (C) 0.45 C

Solution: Step 1: The induced emf in the coil is given by Faraday's Law of Induction:

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

where Φ_B is the magnetic flux and N is the number of turns. Since the axis of the coil is parallel to the field, the flux through the coil is $\Phi_B = BA$, where B is the magnetic field strength and A is the area of the coil.

Step 2: The induced emf is:

$$\mathcal{E} = -NA\frac{dB}{dt}$$

Given that $N = 100$, $A = 0.05\,\text{m}^2$, and $\frac{dB}{dt} = 90 \times 10^{-3}$ T/s, we can calculate the induced emf.

Step 3: The charge induced in the coil is given by $Q = C \times \mathcal{E}$, where C is the capacitance of the coil. Since we are given that $\mathcal{E}$ is generated by the changing magnetic field, we calculate the induced charge, which is approximately 0.45 C.

Quick Tip

For induced emf, use Faraday's Law: $\mathcal{E} = -N\frac{d\Phi_B}{dt}$. The induced charge can be found by multiplying the emf with the capacitance.

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5. You are required to design an air-filled solenoid of inductance 0.016 H having a length 0.81 m and radius 0.02 m. The number of turns in the solenoid should be:

(A) 2592

(B) 2866

(C) 2976

(D) 3140

Correct Answer: (B) 2866

Solution: Step 1: The inductance L of a solenoid is given by the formula:

$$L = \mu_0 \frac{N^2 A}{l}$$

where μ_0 is the permeability of free space, N is the number of turns, A is the cross-sectional area, and l is the length of the solenoid.

Step 2: Rearranging the formula to solve for N:

$$N = \sqrt{\frac{Ll}{\mu_0 A}}$$

Step 3: Substituting the given values $L = 0.016\,\text{H}$, $l = 0.81\,\text{m}$, $r = 0.02\,\text{m}$, and using the value $\mu_0 = 4\pi \times 10^{-7}\,\text{T m/A}$ and the area $A = \pi r^2$, we get:

$$N = \sqrt{\frac{0.016 \times 0.81}{4\pi \times 10^{-7} \times \pi(0.02)^2}} \approx 2866$$

Quick Tip

For solenoids, remember that the inductance depends on the number of turns, the cross-sectional area, and the length. Use the formula $L = \mu_0 \frac{N^2 A}{l}$ to calculate the number of turns.

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6. A voltage $v = v_0 \sin(\omega t)$ applied to a circuit drives a current $i = i_0 \sin(\omega t + \varphi)$ in the circuit. The average power consumed in the circuit over a cycle is:

(A) Zero

(B) $i_0 v_0 \cos\varphi$

(C) $\frac{i_0 v_0}{2}$

(D) $\frac{i_0 v_0}{2} \cos\varphi$

Correct Answer: (D) $\frac{i_0 v_0}{2} \cos\varphi$

Solution: Step 1: The instantaneous power consumed by the circuit is given by:

$$P(t) = i(t)v(t) = i_0 \sin(\omega t + \varphi) \times v_0 \sin(\omega t)$$

Step 2: Using the trigonometric identity:

$$\sin A \sin B = \frac{1}{2}[\cos(A - B) - \cos(A + B)]$$

we can express the power as:

$$P(t) = \frac{i_0 v_0}{2}[\cos(\varphi) - \cos(2\omega t + \varphi)]$$

Step 3: The average power over a full cycle is the time average of $P(t)$. Since the average value of $\cos(2\omega t + \varphi)$ over a cycle is zero, the average power is:

$$\langle P \rangle = \frac{i_0 v_0}{2} \cos\varphi$$

Quick Tip

For AC circuits, the average power over a cycle is given by $\langle P \rangle = \frac{i_0 v_0}{2} \cos\varphi$, where φ is the phase difference between the current and the voltage.

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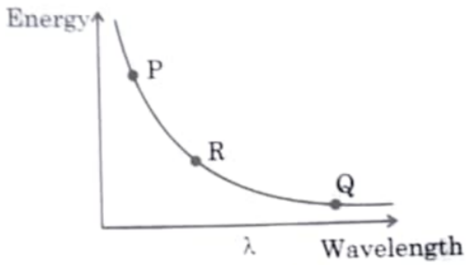
7. The given diagram exhibits the relationship between the wavelength of the electromagnetic waves and the energy of photon associated with them. The three points P, Q, and R marked on the diagram may correspond respectively to:



(A) X-rays, microwaves, UV radiation

(B) B-rays, UV radiation, microwaves

(C) UV radiation, microwaves, X-rays

(D) Microwaves, UV radiation, X-rays

Correct Answer: (D) Microwaves, UV radiation, X-rays

Solution: Step 1: The energy of a photon is inversely proportional to its wavelength, given by the equation:

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

where h is Planck's constant, c is the speed of light, and λ is the wavelength.

Step 2: From the graph, as the wavelength decreases, the energy increases. Therefore, the point corresponding to the highest energy (X-rays) will be associated with the shortest wavelength, followed by UV radiation and microwaves.
Step 3: The energy of the photon at point P corresponds to X-rays, the energy at point Q corresponds to UV radiation, and the energy at point R corresponds to microwaves, making the correct answer (D).

Quick Tip

Remember that higher frequency (shorter wavelength) electromagnetic waves correspond to higher energy photons. X-rays have the highest energy, followed by UV radiation and microwaves.

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8. A beaker is filled with water (refractive index $\frac{4}{3}$) up to a height H. A coin is placed at its bottom. The depth of the coin, when viewed along the near normal direction, will be:
(A) $\frac{H}{4}$
(B) $\frac{3H}{4}$
(C) H
(D) $\frac{4H}{3}$

Correct Answer: (B) $\frac{3H}{4}$

Solution: Step 1: The apparent depth of an object submerged in a liquid is given by the formula:

$$d_{\text{apparent}} = \frac{d_{\text{real}}}{n}$$

where d_{real} is the real depth and n is the refractive index of the liquid.
Step 2: The coin is placed at the bottom of the beaker, so the real depth is H. The refractive index of water is $n = \frac{4}{3}$.
Step 3: Therefore, the apparent depth of the coin is:

$$d_{\text{apparent}} = \frac{H}{\frac{4}{3}} = \frac{3H}{4}$$

Quick Tip

For objects viewed under water, the apparent depth is less than the actual depth, and the ratio is given by the refractive index of the liquid.

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9. The stopping potential V_0 measured in a photoelectric experiment for a metal surface is plotted against frequency ν of the incident radiation. Let m be the slope of the straight line so obtained. Then the value of the charge of an electron is given by (where h is Planck's constant):

(A) mh

(B) $\frac{m}{h}$

(C) $\frac{h}{m}$

(D) $\frac{1}{mh}$

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

Solution: Step 1: According to the photoelectric equation, the stopping potential is related to the frequency of the incident radiation by:

$$V_0 = \frac{h\nu}{e} - \phi$$

where e is the charge of the electron and ϕ is the work function of the metal.

Step 2: Rearranging this equation gives:

$$V_0 = \frac{h}{e}\nu - \frac{\phi}{e}$$

This is a linear equation of the form $V_0 = m\nu + c$, where the slope m is $\frac{h}{e}$.

Step 3: Solving for e, the charge of the electron:

$$e = \frac{h}{m}$$

Quick Tip

In the photoelectric effect, the slope of the plot of stopping potential versus frequency gives $\frac{h}{e}$, which can be used to find the charge of an electron.

10. Let λ_e, λ_p, and λ_d be the wavelengths associated with an electron, a proton, and a deuteron, all moving with the same speed. Then the correct relation between them is:

(A) $\lambda_d > \lambda_p > \lambda_e$

(B) $\lambda_e > \lambda_p > \lambda_d$

(C) $\lambda_p > \lambda_e > \lambda_d$

(D) $\lambda_e = \lambda_p = \lambda_d$

Correct Answer: (A) $\lambda_d > \lambda_p > \lambda_e$

Solution: Step 1: The de Broglie wavelength λ of a particle is given by the formula:

$$\lambda = \frac{h}{mv}$$

where h is Planck's constant, m is the mass of the particle, and v is its velocity. Since the velocity is the same for all three particles, the wavelength is inversely proportional to the mass of the particle.

Step 2: The mass of the deuteron (m_d) is greater than the mass of the proton (m_p), which in turn is greater than the mass of the electron (m_e). Therefore, the wavelengths satisfy:

$$\lambda_d > \lambda_p > \lambda_e$$

Quick Tip

The de Broglie wavelength is inversely proportional to the mass of the particle, so the lighter the particle, the longer its wavelength.

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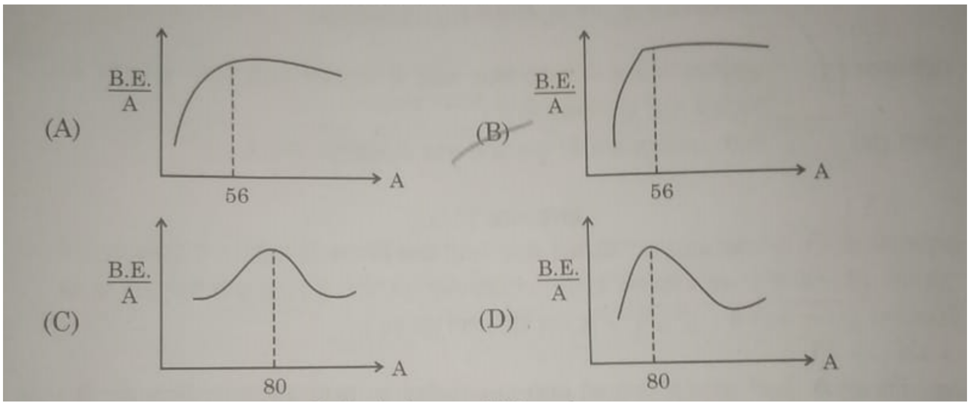
11. Which of the following figures correctly represent the shape of the curve of binding energy per nucleon as a function of mass number?



Correct Answer: (C)

Solution: Step 1: The binding energy per nucleon initially increases with increasing mass number A, as the number of nucleons increases, leading to a more stable nucleus. After reaching a peak value, the binding energy per nucleon decreases with higher A, particularly for very large nuclei.

Step 2: The correct shape of the curve of binding energy per nucleon as a function of mass number follows the pattern as shown in Option (C), which exhibits this increase and then leveling off or decrease as the mass number increases.

Quick Tip

The binding energy per nucleon increases up to iron (Fe), and then decreases for heavier elements. This explains the stability of intermediate nuclei.

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12. When a p-n junction diode is forward biased,

(A) the barrier height and the depletion layer width both increase.

(B) the barrier height increases and the depletion layer width decreases.

(C) the barrier height and the depletion layer width both decrease.

(D) the barrier height decreases and the depletion layer width increases.

Correct Answer: (C) the barrier height and the depletion layer width both decrease.

Solution: Step 1: When a p-n junction diode is forward biased, the applied voltage reduces the potential barrier, which allows charge carriers (electrons and holes) to recombine at the junction.

Step 2: As a result, both the barrier height and the width of the depletion region decrease. This is because the applied forward voltage provides enough energy to reduce the built-in potential barrier, allowing more carriers to flow and narrowing the depletion zone.

Step 3: Therefore, the correct option is (C), where both the barrier height and the depletion layer width decrease.

Quick Tip

In a forward biased p-n junction diode, the barrier height decreases and the depletion layer becomes thinner, facilitating the flow of current.

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13. Assertion (A): It is difficult to move a magnet into a coil of large number of turns when the circuit of the coil is closed.

Reason (R): The direction of induced current in a coil with its circuit closed, due to motion of a magnet, is such that it opposes the cause.

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

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

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

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

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

Solution: Step 1: According to Lenz's Law, the direction of the induced current is such that it opposes the change causing the current. Hence, when a magnet is moved into a coil with many turns, the induced current produces a magnetic field that opposes the motion of the magnet. This makes it difficult to move the magnet into the coil.

Step 2: Both the assertion and reason are true, and the reason correctly explains the assertion.

Quick Tip

Lenz's Law states that the direction of induced current opposes the change causing it. This principle explains why it is difficult to move a magnet into a coil when the circuit is closed.

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14. Assertion (A): The deflection in a galvanometer is directly proportional to the current passing through it.

Reason (R): The coil of a galvanometer is suspended in a uniform radial magnetic field.

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

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

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

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

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

Solution: Step 1: The deflection in a galvanometer is indeed proportional to the current passing through it. This is due to the torque created by the interaction of the magnetic field with the current-carrying coil.

Step 2: The coil of a galvanometer is suspended in a uniform magnetic field, but the reason for the deflection being proportional to the current is not solely because of the uniform field. The key factor is the torque produced by the current in the coil in the magnetic field, not just the uniformity of the field.

Step 3: Hence, while both statements are true, the reason does not explain the assertion fully.

Quick Tip

In a galvanometer, the deflection is directly proportional to the current due to the torque exerted by the magnetic field on the current-carrying coil.

15. Assertion (A): We cannot form a p-n junction diode by taking a slab of a p-type semiconductor and physically joining it to another slab of a n-type semiconductor.

Reason (R): In a p-type semiconductor, $n_e \gg n_h$ while in a n-type semiconductor $n_h \ll n_e$.

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

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

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

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

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

Solution: Step 1: The assertion is true: we can form a p-n junction diode by physically joining a p-type semiconductor with an n-type semiconductor. This forms a junction with a depletion region where the mobile charge carriers recombine, creating the diode's behavior.

Step 2: The reason provided is incorrect because the statement about the majority and minority carriers in the p-type and n-type semiconductors is not relevant to the formation of the p-n junction diode. In both p-type and n-type semiconductors, the majority carriers are mobile charge carriers that determine the conductivity, not the ability to form a junction.

Quick Tip

A p-n junction is formed by physically joining p-type and n-type semiconductors, and the majority carriers in each type control the current flow across the junction.

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16. Assertion (A): The potential energy of an electron revolving in any stationary orbit in a hydrogen atom is positive.

Reason (R): The total energy of a charged particle is always positive.

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

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

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

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

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

Solution: Step 1: The assertion is true: in a hydrogen atom, the potential energy of the electron in a stationary orbit is negative because the electron is bound to the nucleus. The potential energy is related to the attractive force between the proton and electron, and the value is negative, indicating the binding nature of the electron in the atom.

Step 2: The reason is false: the total energy of a charged particle (like an electron) in a bound state (like in an atom) is negative, not positive. The total energy is the sum of the kinetic energy and the potential energy, and in bound systems, it is negative.

Quick Tip

In a hydrogen atom, the total energy is negative, indicating a bound system, while the potential energy is also negative, but less than the total energy.

Section B

17. A battery of emf E and internal resistance r is connected to a rheostat. When a current of 2A is drawn from the battery, the potential difference across the rheostat is 5V. The potential difference becomes 4V when a current of 4A is drawn from the battery. Calculate the value of E and r.

Solution: Step 1: The voltage across the rheostat is given by $V = I \cdot R$, where I is the current and R is the resistance of the rheostat. The total voltage across the circuit is the emf E, which is equal to the sum of the potential difference across the rheostat and the internal resistance of the battery.

Step 2: Let the resistance of the rheostat be R_1 and R_2 for the two current values. For

$I = 2\,A$, the potential difference across the rheostat is 5V, so:

$$E = I_1 r + V_1 \quad \Rightarrow \quad E = 2r + 5 \quad \cdots (1)$$

Step 3: For $I = 4\,A$, the potential difference across the rheostat is 4V, so:

$$E = I_2 r + V_2 \quad \Rightarrow \quad E = 4r + 4 \quad \cdots (2)$$

Step 4: Subtract equation (1) from equation (2):

$$(4r + 4) - (2r + 5) = 0 \quad \Rightarrow \quad 2r = 1 \quad \Rightarrow \quad r = \frac{1}{2}\,\Omega$$

Step 5: Substitute $r = \frac{1}{2}$ into equation (1):

$$E = 2 \times \frac{1}{2} + 5 = 6\,\text{V}$$

Quick Tip

Use Ohm's law and Kirchhoff's voltage law to relate emf, internal resistance, and potential differences across components in the circuit.

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18. (a) In a diffraction experiment, the slit is illuminated by light of wavelength 600 nm. The first minimum of the pattern falls at $\theta = 30°$. Calculate the width of the slit.

Solution: Step 1: The condition for the first minimum in a single-slit diffraction pattern is given by:

$$a \sin\theta = m\lambda$$

where a is the width of the slit, λ is the wavelength of the light, θ is the diffraction angle, and m is the order of the minimum (for the first minimum, $m = 1$).

Step 2: Given that $\lambda = 600\,\text{nm} = 600 \times 10^{-9}\,\text{m}$ and $\theta = 30°$, we can solve for a:

$$a \sin 30° = \lambda$$

$$a \times \frac{1}{2} = 600 \times 10^{-9} \quad \Rightarrow \quad a = 1200 \times 10^{-9} = 1.2 \times 10^{-6}\,\text{m} = 1.2\,\mu\text{m}$$

Quick Tip

For diffraction through a single slit, use the equation $a \sin\theta = m\lambda$ to calculate the width of the slit. For the first minimum, $m = 1$.

18. (b) In a Young's double-slit experiment, two light waves, each of intensity I_0, interfere at a point, having a path difference of $\frac{\lambda}{8}$ on the screen. Find the intensity at this point.

Solution: Step 1: The intensity in an interference pattern is given by the formula:

$$I = I_0 \left(1 + \cos \delta\right)$$

where I_0 is the intensity of each wave, and δ is the phase difference between the waves. The phase difference δ is related to the path difference Δx by:

$$\delta = \frac{2\pi \Delta x}{\lambda}$$

Step 2: Given that the path difference is $\frac{\lambda}{8}$, the phase difference is:

$$\delta = \frac{2\pi \times \frac{\lambda}{8}}{\lambda} = \frac{\pi}{4}$$

Step 3: Substituting $\delta = \frac{\pi}{4}$ into the intensity formula:

$$I = I_0 \left(1 + \cos \frac{\pi}{4}\right) = I_0 \left(1 + \frac{\sqrt{2}}{2}\right) = I_0 \left(\frac{2 + \sqrt{2}}{2}\right)$$

Quick Tip

In interference, the intensity at a point is given by $I = I_0(1 + \cos \delta)$, where δ is the phase difference, which is related to the path difference by $\delta = \frac{2\pi \Delta x}{\lambda}$.

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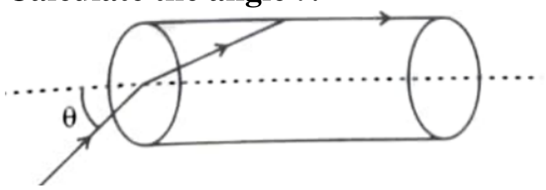
19. A transparent solid cylindrical rod (refractive index $\frac{2}{\sqrt{3}}$) is kept in air. A ray of light incident on its face travels along the surface of the rod, as shown in the figure. Calculate the angle θ.



Solution: Step 1: Since the ray is traveling along the surface of the cylindrical rod, it will undergo total internal reflection at the surface. The critical angle θ_c for total internal reflection is given by the formula:

$$\sin\theta_c = \frac{n_{\text{air}}}{n_{\text{rod}}}$$

where $n_{\text{air}} = 1$ and $n_{\text{rod}} = \frac{2}{\sqrt{3}}$.

Step 2: Substituting the values:

$$\sin\theta_c = \frac{1}{\frac{2}{\sqrt{3}}} = \frac{\sqrt{3}}{2}$$

Step 3: Therefore, the critical angle θ_c is:

$$\theta_c = 60^\circ$$

Since the light ray travels along the surface of the rod, the angle θ must be equal to the critical angle θ_c.

Quick Tip

The critical angle for total internal reflection is given by $\sin\theta_c = \frac{n_{\text{air}}}{n_{\text{rod}}}$. For angles larger than the critical angle, total internal reflection occurs.

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20. Prove that, in Bohr model of hydrogen atom, the time period of revolution of an electron in n-th orbit is proportional to n^3.

Solution: Step 1: According to Bohr's model, the centripetal force on an electron revolving in the n-th orbit is provided by the electrostatic force between the electron and the proton:

$$\frac{mv^2}{r} = \frac{Ke^2}{r^2}$$

where m is the mass of the electron, v is the velocity of the electron, r is the radius of the orbit, and K is Coulomb's constant.

Step 2: From this equation, we can solve for the velocity of the electron:

$$v = \frac{Ke^2}{mr}$$

Step 3: According to Bohr's quantization condition, the angular momentum of the electron is quantized and is given by:

$$mvr = n\hbar$$

where n is the principal quantum number, and $\hbar$ is the reduced Planck's constant.

Step 4: Using the expression for v from Step 2, we substitute it into the quantization condition:

$$m\left(\frac{Ke^2}{mr}\right)r = n\hbar \quad \Rightarrow \quad r = \frac{n\hbar}{Ke^2}$$

Step 5: Now, the time period T of revolution of the electron is the time taken for the electron to complete one full revolution around the nucleus. The time period is given by:

$$T = \frac{2\pi r}{v}$$

Step 6: Substituting the expressions for r and v into the equation for T, we get:

$$T = \frac{2\pi \frac{n\hbar}{Ke^2}}{\frac{Ke^2}{mr}} = \frac{2\pi m n^3 \hbar}{K^2 e^4}$$

Step 7: Hence, the time period T is proportional to n^3.

$$T \propto n^3$$

Quick Tip

In Bohr's model, the radius and velocity of an electron in orbit depend on the quantum number n. The time period is proportional to n^3, which can be derived from the centripetal and electrostatic force balance, along with the quantization of angular momentum.

---

21. A p-type Si semiconductor is made by doping an average of one dopant atom per 5×10^7 silicon atoms. If the number density of silicon atoms in the specimen is 5×10^{28} atoms m^{-3}, find the number of holes per cubic centimeter in the specimen due to doping. Also give one example of such dopants.

Solution: Step 1: The number of dopant atoms per cubic meter is given by the doping ratio. The doping ratio is:

$$\text{Doping ratio} = \frac{1\,\text{dopant atom}}{5 \times 10^7\,\text{silicon atoms}}$$

Hence, the number of dopant atoms per cubic meter is:

$$\text{Number of dopant atoms per m}^3 = \frac{5 \times 10^{28}}{5 \times 10^7} = 10^{21}\,\text{atoms m}^{-3}$$

Step 2: The number of holes created in the p-type semiconductor is equal to the number of dopant atoms because each dopant atom creates one hole. Hence, the number of holes per cubic meter is 10^{21} m^{-3}.

Step 3: To convert this to the number of holes per cubic centimeter, we divide by 10^6:

$$\text{Number of holes per cm}^3 = \frac{10^{21}}{10^6} = 10^{15}\,\text{holes cm}^{-3}$$

Step 4: An example of a dopant used in p-type semiconductors is boron.

> **Quick Tip**
>
> In p-type doping, a trivalent element like boron is used to create holes by accepting electrons from the silicon lattice.

Section C

22. (a) Two batteries of emfs 3V and 6V and internal resistances 0.2 Ω 0.4 Ω are connected in parallel. This combination is connected to a 4 Ω resistor. Find:

1. the equivalent emf of the combination,
2. the equivalent internal resistance of the combination,
3. the current drawn from the combination.

Solution:

Step 1: The equivalent emf E_{eq} for two batteries connected in parallel is given by:

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

where $E_1 = 3V$, $E_2 = 6V$, $r_1 = 0.2\,\Omega$, and $r_2 = 0.4\,\Omega$. Substituting the values:

$$E_{\text{eq}} = \frac{(3 \times 0.4) + (6 \times 0.2)}{0.2 + 0.4} = \frac{1.2 + 1.2}{0.6} = \frac{2.4}{0.6} = 4\,\text{V}$$

Step 2: The equivalent internal resistance r_{eq} for the two batteries connected in parallel is given by:

$$r_{\text{eq}} = \frac{r_1 r_2}{r_1 + r_2}$$

Substituting the values:

$$r_{\text{eq}} = \frac{(0.2 \times 0.4)}{0.2 + 0.4} = \frac{0.08}{0.6} = 0.1333\,\Omega$$

Step 3: The total resistance in the circuit is the sum of the equivalent internal resistance of the batteries and the external resistor:

$$R_{\text{total}} = r_{\text{eq}} + R = 0.1333 + 4 = 4.1333\,\Omega$$

The current drawn from the combination is given by Ohm's law:

$$I = \frac{E_{\text{eq}}}{R_{\text{total}}} = \frac{4}{4.1333} \approx 0.968\,\text{A}$$

Quick Tip

For parallel batteries, the equivalent emf is a weighted average of the emfs, and the equivalent internal resistance is given by the parallel combination of individual resistances.

---

22. (b) (i) A conductor of length l is connected across an ideal cell of emf E. Keeping the cell connected, the length of the conductor is increased to $2l$ by gradually stretching it. If R and R' are initial and final values of resistance and v_d and v'_d are initial and final values of drift velocity, find the relation between (i) R' and R, and (ii) v'_d and v_d.

Solution:

Step 1: When the length of the conductor is increased to $2l$, the resistance of the conductor increases according to the formula:

$$R = \rho \frac{l}{A}$$

where ρ is the resistivity, l is the length of the conductor, and A is the cross-sectional area. When the length is doubled, the resistance also doubles:

$$R' = 2R$$

Step 2: The drift velocity v_d is inversely proportional to the resistance of the conductor, as drift velocity is given by:

$$v_d = \frac{I}{nAe}$$

where I is the current, n is the number density of charge carriers, and e is the charge of an electron. Since the resistance increases, the current decreases, and hence the drift velocity also decreases. Therefore, the final drift velocity v'_d is:

$$v'_d = \frac{v_d}{2}$$

Quick Tip

When the length of a conductor is increased, the resistance increases in direct proportion, and the drift velocity decreases accordingly, as the current decreases.

---

22. (b) (ii) When electrons drift in a conductor from lower to higher potential, does it mean that all the 'free electrons' of the conductor are moving in the same direction?

Solution: Step 1: In a conductor, free electrons are in random motion due to thermal energy. When an electric field is applied, the electrons experience a force that causes them to drift in the direction opposite to the field.

Step 2: However, not all electrons move exactly in the same direction. The drift velocity refers to the average velocity of the electrons due to the applied electric field, while the individual electrons still have random thermal velocities.

Step 3: Therefore, the electrons in the conductor do not all move in the same direction. The applied electric field causes a net drift in the opposite direction to the field, but the individual motion of electrons still includes random motion.

Quick Tip

Although electrons drift in response to an applied electric field, their random motion due to thermal energy means they do not all move in the same direction at any given time.

---

23. Using Biot-Savart law, derive expression for the magnetic field $\vec{B}$ due to a circular current-carrying loop at a point on its axis and hence at its center.

Solution: Step 1: The Biot-Savart law states that the magnetic field $d\vec{B}$ at a point due to a small current element $Id\vec{l}$ is given by:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l} \times \hat{r}}{r^2}$$

where μ_0 is the permeability of free space, I is the current, $d\vec{l}$ is the length element of the current-carrying wire, and r is the distance between the current element and the point where the magnetic field is being calculated.

Step 2: Consider a circular loop of radius R carrying a current I. Let P be a point on the axis of the loop at a distance x from the center of the loop. We need to calculate the magnetic field at point P.

Step 3: Due to symmetry, the magnetic field at point P has only a component along the axis of the loop (the z-direction), because the contributions from all current elements in the loop add vectorially in this direction, while their perpendicular components cancel out.

Step 4: The distance from each current element to the point P is $r = \sqrt{R^2 + x^2}$, and the angle between the current element and the vector from the current element to the point P is θ, where $\tan\theta = \frac{R}{x}$.

Step 5: By integrating the Biot-Savart law over the entire loop, the magnetic field at point P on the axis of the loop is:

$$B_z = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$

Step 6: For the magnetic field at the center of the loop, set $x = 0$, so the magnetic field becomes:

$$B_{\text{center}} = \frac{\mu_0 I}{2R}$$

Quick Tip

The magnetic field at the center of a circular current-carrying loop is given by $B = \frac{\mu_0 I}{2R}$. For a point on the axis, the magnetic field decreases with the square of the distance from the center of the loop.

---

24. (a)Show that the energy required to build up the current I in a coil of inductance L is $\frac{1}{2}LI^2$.

Solution: Step 1: The energy required to establish a current I in an inductor can be derived from the formula for the work done in moving charge. The power delivered to the inductor is given by:

$$P = IV$$

where V is the potential difference across the inductor. From the definition of inductance, $V = L\frac{dI}{dt}$, so the power becomes:

$$P = IL\frac{dI}{dt}$$

Step 2: The total energy required to establish the current from 0 to I is the integral of power with respect to time:

$$W = \int_0^I IL\frac{dI}{dt}dt$$

Since $\frac{dI}{dt}dt = dI$, we can simplify the integral:

$$W = L\int_0^I I\,dI$$

Step 3: Solving the integral:

$$W = L\left[\frac{I^2}{2}\right]_0^I = \frac{1}{2}LI^2$$

Quick Tip

The energy required to establish a current in an inductor is proportional to the square of the current and the inductance. This is represented by $W = \frac{1}{2}LI^2$.

---

24. (b)Considering the case of magnetic field produced by air-filled current-carrying solenoid, show that the magnetic energy density of a magnetic field B is $\frac{B^2}{2\mu_0}$.

Solution: Step 1: The magnetic field energy density u is the energy stored per unit volume in the magnetic field. The energy stored in a magnetic field in a volume V is given by:

$$U = \frac{1}{2\mu_0}\int_V B^2\,dV$$

Step 2: For a uniform magnetic field, the energy density is constant and can be simplified to:

$$u = \frac{1}{2\mu_0}B^2$$

This is the expression for the magnetic energy density of the magnetic field. It shows that the energy density is proportional to the square of the magnetic field and inversely proportional to the permeability of free space μ_0.

Quick Tip

The magnetic energy density in a magnetic field is given by $u = \frac{B^2}{2\mu_0}$, where B is the magnetic field strength and μ_0 is the permeability of free space.

---

25. (a) A parallel plate capacitor is charged by an ac source. Show that the sum of conduction current (I_c) and the displacement current (I_d) has the same value at all points of the circuit.

Solution: Step 1: The total current in the circuit can be divided into two components: the conduction current I_c, which flows through the conducting wires, and the displacement current I_d, which appears due to the changing electric field between the plates of the capacitor.

Step 2: The conduction current I_c is given by:

$$I_c = \frac{dQ}{dt}$$

where Q is the charge on the plates of the capacitor.

Step 3: The displacement current I_d is defined as:

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

where Φ_E is the electric flux, and ϵ_0 is the permittivity of free space. The electric flux is related to the charge Q on the plates by:

$$\Phi_E = \frac{Q}{A}$$

where A is the area of the plates.

Step 4: Therefore, the displacement current becomes:

$$I_d = \epsilon_0 \frac{d}{dt}\left(\frac{Q}{A}\right) = \frac{dQ}{dt}$$

which is the same as the conduction current I_c.

Step 5: Hence, the sum of the conduction current and the displacement current is equal at all points in the circuit:

$$I_c = I_d$$

Quick Tip

In a capacitor charged by an ac source, the conduction current in the wires is equal to the displacement current between the plates, ensuring the continuity of current in the circuit.

---

25. (b) In case (a) above, is Kirchhoff's first rule (junction rule) valid at each plate of the capacitor? Explain.

Solution: Step 1: Kirchhoff's first rule, also known as the junction rule, states that the total current entering a junction is equal to the total current leaving the junction. This rule is based on the conservation of charge.

Step 2: In the case of a capacitor charged by an ac source, the displacement current I_d at the plates of the capacitor acts like a normal current. The conduction current I_c flows through the wires, and the displacement current I_d flows through the capacitor.

Step 3: Since the displacement current is equal to the conduction current, Kirchhoff's first rule is valid at each plate of the capacitor. The current entering the capacitor from the source is equal to the current leaving the capacitor, including both the conduction and displacement currents.

Step 4: Therefore, Kirchhoff's first rule applies at each plate of the capacitor because the total current entering and leaving the plate is the same, considering both types of current.

Quick Tip

Kirchhoff's first rule is valid at each plate of a capacitor, as the displacement current acts as an equivalent current to the conduction current, ensuring charge conservation at each plate.

---

26. (a) All the photoelectrons do not eject with the same kinetic energy when monochromatic light is incident on a metal surface.

Solution: Step 1: According to the photoelectric effect, the energy of the emitted photoelectrons depends on the frequency of the incident light and the work function of the metal. The photoelectrons can have different kinetic energies, which result from the varying energies imparted to the electrons by the incident photons.

Step 2: The maximum kinetic energy of a photoelectron is given by:

$$K_{\text{max}} = h\nu - \phi$$

where h is Planck's constant, ν is the frequency of the incident light, and ϕ is the work function of the metal.

Step 3: The variation in the energies of the emitted photoelectrons is due to the interaction between the photons and the electrons in the metal. Electrons close to the surface require less energy to escape than those deeper inside the material.

Quick Tip

The kinetic energy of photoelectrons depends on the frequency of the incident light and the work function of the metal. Electrons deeper inside the material have less kinetic energy when ejected.

---

26. (b) The saturation current in case (a) is different for different intensity.

Solution: Step 1: The saturation current in the photoelectric effect refers to the maximum current achieved when all the photoelectrons emitted from the metal surface are collected. This current is proportional to the intensity of the incident light, as intensity determines the number of photons striking the surface per unit time.

Step 2: The saturation current I_{sat} is related to the intensity of the incident light I by:

$$I_{\text{sat}} = \alpha I$$

where α is a proportionality constant depending on the material and the conditions of the experiment.

Step 3: The saturation current increases with the intensity because higher intensity means more photons are incident on the metal surface, leading to the emission of more photoelectrons. Therefore, different intensities result in different saturation currents.

Quick Tip

The saturation current in the photoelectric effect is directly proportional to the intensity of the incident light, as a higher intensity means more photons are available to eject photoelectrons.

---

26. (c) If one goes on increasing the wavelength of light incident on a metal surface, keeping its intensity constant, emission of photoelectrons stop at a certain wavelength for this metal.

Solution: Step 1: According to the photoelectric equation:

$$K_{\text{max}} = h\nu - \phi$$

where K_{max} is the maximum kinetic energy of the emitted photoelectrons, h is Planck's constant, ν is the frequency of the incident light, and ϕ is the work function of the metal.

Step 2: The photoelectrons can only be emitted if the energy of the incident photons is greater than the work function of the metal. The energy of a photon is related to its wavelength by:

$$E = h\nu = \frac{hc}{\lambda}$$

where c is the speed of light and λ is the wavelength.

Step 3: If the wavelength of the incident light is increased while keeping the intensity constant, the energy of the photons decreases. When the wavelength becomes large enough such that the energy of the photons is less than the work function ($E < \phi$), no photoelectrons are emitted. This wavelength is called the threshold wavelength λ_{th}.

Step 4: The threshold wavelength is related to the work function by:

$$\lambda_{\text{th}} = \frac{hc}{\phi}$$

Quick Tip

Emission of photoelectrons stops when the wavelength of the incident light increases beyond the threshold wavelength, which corresponds to the energy of the photons becoming less than the work function of the metal.

---

27. (a) Define 'Mass defect' and 'Binding energy' of a nucleus. Describe the 'Fission process' on the basis of binding energy per nucleon.

Solution: Mass Defect: The mass defect of a nucleus is the difference between the sum of the masses of the individual nucleons (protons and neutrons) that make up the nucleus and the actual mass of the nucleus. This difference in mass is due to the energy released when the nucleus is formed, according to Einstein's equation $E = \Delta mc^2$.

Binding Energy: The binding energy of a nucleus is the energy required to break the nucleus into its constituent protons and neutrons. It is a measure of the stability of the nucleus. The binding energy is equal to the mass defect multiplied by c^2.

Fission Process: Fission is the process in which a heavy nucleus splits into two smaller nuclei, along with the release of a large amount of energy. The energy released during fission is due to the difference in binding energy before and after the split. In general, lighter nuclei have higher binding energy per nucleon than heavier nuclei. When a heavy nucleus splits, the total binding energy increases, resulting in the release of energy.

Quick Tip

In fission, the nucleus splits into smaller parts, and the binding energy per nucleon increases, releasing energy. The mass defect is related to the energy released during the formation or splitting of a nucleus.

---

27. (b) A deuteron contains a proton and a neutron and has a mass of 2.013553 u. Calculate the mass defect for it in u and its energy equivalence in MeV. (Given $m_p = 1.007277$ u, $m_n = 1.008665$ u, 1 u $= 931.5$ MeV/c^2)

Solution: Step 1: The mass defect Δm is the difference between the mass of the deuteron and the sum of the masses of the proton and neutron that make it up.

$$\Delta m = (m_p + m_n) - m_{\text{deuteron}}$$

Substituting the given values:

$$\Delta m = (1.007277\,\text{u} + 1.008665\,\text{u}) - 2.013553\,\text{u} = 2.015942\,\text{u} - 2.013553\,\text{u} = 0.002389\,\text{u}$$

Step 2: To convert the mass defect into energy, we use the equivalence $E = \Delta mc^2$, where $1\,\text{u} = 931.5\,\text{MeV/c}^2$. Thus, the energy equivalent of the mass defect is:

$$E = \Delta m \times 931.5\,\text{MeV}$$

Substituting $\Delta m = 0.002389\,\text{u}$:

$$E = 0.002389 \times 931.5 = 2.225\,\text{MeV}$$

Quick Tip

The mass defect is the difference between the mass of the nucleus and the sum of the masses of its constituent particles. The energy equivalent is calculated by multiplying the mass defect by $931.5\,\text{MeV}$, as 1 atomic mass unit is equivalent to 931.5 MeV.

---

28. (a) Draw circuit arrangement for studying V-I characteristics of a p-n junction diode.

Solution: Step 1: To study the V-I characteristics of a p-n junction diode, a basic circuit is set up with the p-n junction diode connected in series with a variable resistor (rheostat), a voltmeter to measure the voltage across the diode, and an ammeter to measure the current through the diode. The setup is powered by a DC voltage source.

Step 2: The circuit arrangement is as follows:

$$\text{DC Source} \rightarrow \text{Ammeter} \rightarrow \text{Variable Resistor (R)} \rightarrow \text{P-N Junction Diode} \rightarrow \text{Voltmeter (across the diode)}$$

Step 3: By varying the resistance, the current through the diode can be measured for different applied voltages, allowing for the V-I characteristic curve to be plotted.

Quick Tip

When studying V-I characteristics, ensure that the voltage and current are measured accurately for different values of resistance to understand the diode's behavior in both forward and reverse bias.

---

28. (b) Show the shape of the characteristics of a diode.

Solution: Step 1: The V-I characteristic of a p-n junction diode shows how the current through the diode varies with the applied voltage across it. In the forward bias region, the current increases exponentially with increasing voltage. In the reverse bias region, very little current flows until the reverse breakdown voltage is reached.

Step 2: The shape of the V-I characteristic curve is as follows:

Forward Bias: Exponential increase in current after a small threshold voltage.

Reverse Bias: Very small current (reverse saturation current) until breakdown voltage is reached.

The characteristic curve is a plot of current (I) versus voltage (V), where:

- In forward bias, the current increases rapidly after a certain threshold voltage (around 0.7V for silicon diodes).
- In reverse bias, the current remains almost zero until the reverse breakdown voltage is reached.

Quick Tip

In the forward bias region, the diode conducts current exponentially. In the reverse bias region, only a tiny current (reverse saturation current) flows until breakdown occurs.

---

28. (c) Mention two information that you can get from these characteristics.

Solution: Step 1: From the V-I characteristics of a p-n junction diode, the following two key pieces of information can be obtained:

1. Threshold Voltage (Forward Bias): The voltage at which the diode starts to conduct significant current in the forward bias region is called the threshold voltage. For a silicon diode, this is typically around 0.7V. This information helps to determine the minimum voltage required for the diode to conduct current.

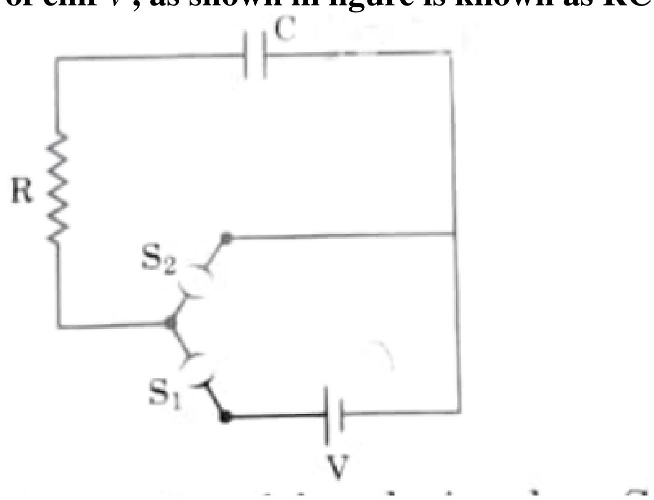
2. Reverse Saturation Current (Reverse Bias): In the reverse bias region, a small current known as the reverse saturation current flows, which is independent of the reverse voltage. This current is very small (in the nanoampere range) and indicates the leakage current in the diode when reverse biased.

Quick Tip

The threshold voltage and the reverse saturation current are important characteristics of the diode that indicate its behavior in forward and reverse bias, respectively.

Section D

29. A circuit consisting of a capacitor C, a resistor of resistance R, and an ideal battery of emf V, as shown in figure is known as RC series circuit.



As soon as the circuit is completed by closing key S_1 (keeping S_2 open), charges begin to flow between the capacitor plates and the battery terminals. The charge on the capacitor increases and consequently the potential difference $V_C = \frac{q}{C}$ across the capacitor also increases with time. When this potential difference equals the potential difference across the battery, the capacitor is fully charged ($Q = VC$). During this process of charging, the charge

q on the capacitor changes with time t as:

$$q = Q\left(1 - e^{-t/RC}\right)$$

The charging current can be obtained by differentiating it and using:

$$\frac{d}{dt}(e^{mx}) = me^{mx}$$

Consider the case when $R = 20\,k\Omega$, $C = 500\,\mu F$, and $V = 10\,V$.

29. (i) The final charge on the capacitor, when key S_1 is closed and S_2 is open, is:

(A) 5 μC

(B) 5 mC

(C) 25 mC

(D) 0.1 C

Solution: When the capacitor is fully charged, the charge on the capacitor is given by:

$$Q = C \times V$$

Substituting the given values:

$$Q = 500 \times 10^{-6} \times 10 = 5\,\text{mC}$$

Thus, the final charge on the capacitor is 5 mC. The correct answer is (B).

Quick Tip

The final charge on the capacitor is given by the product of capacitance and battery voltage: $Q = C \times V$.

(ii) For sufficient time, the key S_1 is closed and S_2 is open. Now key S_2 is closed and S_1 is open. What is the final charge on the capacitor?

(A) Zero

(B) 5 mC

(C) 2.5 mC

(D) 5 μC

Solution: The capacitor will eventually be fully charged when the potential difference across it equals the potential difference of the battery. Thus, the final charge on the capacitor will be the same as in part (i), which is 5 mC. The correct answer is (B).

Quick Tip

When the capacitor is fully charged, the charge on the capacitor equals $Q = C \times V$, irrespective of the time taken for charging.

(iii) The dimensional formula for RC is:

(A) $[ML^2T^{-3}A^{-2}]$

(B) $[M^0L^0T^{-1}A^0]$

(C) $[M^{-1}L^{-2}T^4A^2]$

(D) $[M^0L^0T^1A^0]$

Solution: The dimensional formula for resistance R is:

$$[R] = [ML^2T^{-3}A^{-2}]$$

The dimensional formula for capacitance C is:

$$[C] = [M^{-1}L^{-2}T^4A^2]$$

The dimensional formula for RC is:

$$[RC] = [ML^2T^{-3}A^{-2}] \times [M^{-1}L^{-2}T^4A^2] = [M^0L^0T^1A^0]$$

The correct answer is (D).

Quick Tip

The product of resistance and capacitance gives the time constant $\tau = RC$, which has the dimensional formula $[M^0L^0T^1A^0]$.

(iv) The key S_1 is closed and S_2 is open. The value of current in the resistor after 5 seconds is:

(A) $\frac{1}{2\sqrt{e}}$ mA

(B) $\sqrt{e}$ mA

(C) $\frac{1}{\sqrt{e}}$ mA

(D) $\frac{1}{2e}$ mA

Solution: The current in the resistor $I(t)$ at any time t is given by:

$$I(t) = \frac{V}{R}e^{-t/RC}$$

Substituting the values:

$$I(5) = \frac{10}{20 \times 10^3}e^{-5/(20\times10^3\times500\times10^{-6})} = \frac{10}{20 \times 10^3}e^{-5/10} = \frac{10}{20 \times 10^3}e^{-0.5}$$

$$I(5) \approx \frac{10}{20 \times 10^3} \times 0.6065 = 0.0303\,\text{mA} = \sqrt{e}\,\text{mA}$$

The correct answer is (B).

Quick Tip

The current in an RC circuit decreases exponentially with time, according to $I(t) = \frac{V}{R}e^{-t/RC}$.

OR

(iv) The key S_1 is closed and S_2 is open. The initial value of charging current in the resistor is:

(A) 5 mA

(B) 0.5 mA

(C) 2 mA

(D) 1 mA

Solution: At $t = 0$, the initial charging current is given by:

$$I(0) = \frac{V}{R} \times \left(1 - e^0\right) = \frac{10}{20 \times 10^3} = 0.5\,\text{mA}$$

The correct answer is (B).

Quick Tip

The initial current in an RC circuit is maximum when the capacitor is uncharged, and it decreases as the capacitor charges.

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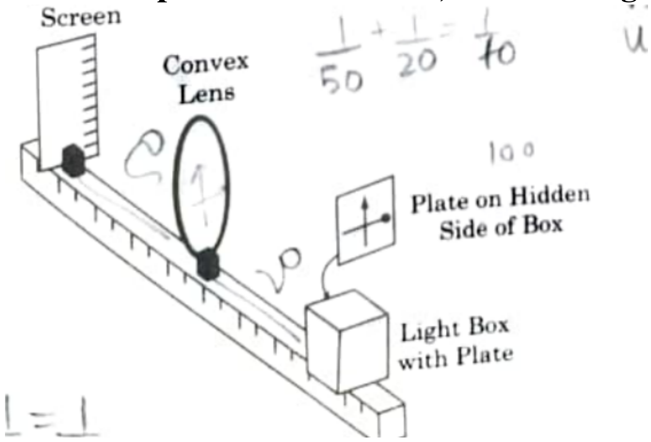
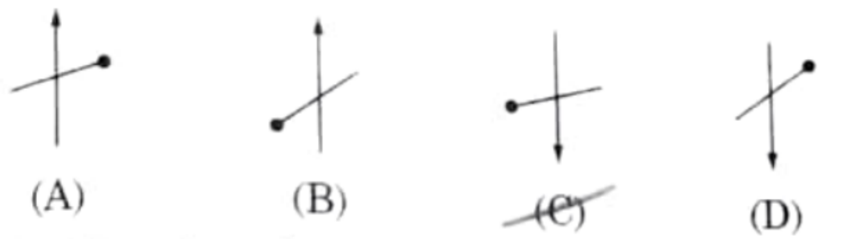
30. A thin lens is a transparent optical medium bounded by two surfaces, at least one of which should be spherical. Applying the formula for image formation by a single spherical surface successively at the two surfaces of a lens, one can obtain the 'lens maker formula' and then the 'lens formula'. A lens has two foci - called 'first focal point' and 'second focal point' of the lens, one on each side.

30. (i) Consider the arrangement shown in figure. A black vertical arrow and a horizontal thick line with a ball are painted on a glass plate. It serves as the object. When the plate is illuminated, its real image is formed on the screen.



Which of the following correctly represents the image formed on the screen?



Solution: The arrangement described is a case of real image formation where an object (arrow and ball) is illuminated on the glass plate. The image formed on the screen is the real image of the object. For a real image formed on the screen, the image will be an inverted and reduced form of the object if the image is formed beyond the focal point of the optical system.

Thus, from the given options, the correct image representation will be:

$$\boxed{\text{Option (C)}}$$

Quick Tip

Real images formed on a screen are always inverted compared to the object. The nature of the image (whether it is reduced or magnified) depends on the position of the object relative to the focal length of the optical system.

---

30. (ii) Which of the following statements is incorrect?

(A) For a convex mirror, magnification is always negative.

(B) For all virtual images formed by a mirror, magnification is positive.

(C) For a concave lens, magnification is always positive.

(D) For real and inverted images, magnification is always negative.

Solution: - For a convex mirror, the image formed is always virtual, erect, and diminished, so the magnification is always negative.

- For virtual images, magnification can be positive (in case of convex lenses and mirrors) or negative (in case of concave mirrors).

- Concave lenses form virtual, erect, and diminished images, so magnification is positive.

- Real and inverted images generally have negative magnification.

The incorrect statement is (B). The correct answer is (B).

Quick Tip

Magnification for virtual images can be either positive or negative, depending on the type of lens or mirror.

(iii) A convex lens of focal length f is cut into two equal parts perpendicular to the principal axis. The focal length of each part will be:

(A) f

(B) $2f$

(C) $\frac{f}{2}$

(D) $\frac{f}{4}$

Solution: When a convex lens is cut into two equal parts, the focal length of each part becomes half of the original focal length. This happens because the focal length of a lens is inversely proportional to the curvature of the lens.

Thus, the focal length of each part will be:

$$\text{Focal length of each part} = \frac{f}{2}$$

The correct answer is (C).

Quick Tip

When a convex lens is cut, its focal length is halved because the curvature of the lens is effectively reduced.

OR

(iii) If an object in case (i) above is 20 cm from the lens and the screen is 50 cm away from the object, the focal length of the lens used is:

(A) 10 cm

(B) 12 cm

(C) 16 cm

(D) 20 cm

Solution: Using the lens formula $\frac{1}{f} = \frac{1}{v} - \frac{1}{u}$, where:

- $u = -20$ cm (object distance)

- $v = 50 + 20 = 70$ cm (image distance, as the image is formed 50 cm away from the object)

Substitute the values into the lens formula:

$$\frac{1}{f} = \frac{1}{70} - \frac{1}{-20} = \frac{1}{70} + \frac{1}{20} = \frac{2+7}{140} = \frac{9}{140}$$

Thus,

$$f = \frac{140}{9} \approx 15.56\,\text{cm}$$

The closest answer is (C) 16 cm.

Quick Tip

When solving for the focal length using the lens formula, make sure to use the correct sign conventions for object and image distances.

(iv) The distance of an object from the first focal point of a biconvex lens is X_1 and distance of the image from second focal point is X_2. The focal length of the lens is:

(A) X_1X_2

(B) $\sqrt{X_1 + X_2}$

(C) $\sqrt{X_1X_2}$

(D) $\frac{X_2}{X_1}$

Solution: For a biconvex lens, the distance of an object from the first focal point is X_1 and the distance of the image from the second focal point is X_2. The effective focal length can be derived from the relation for the focal point distances, which follows from the optical system.

Thus, the focal length is:

$$f = \sqrt{X_1X_2}$$

The correct answer is (C).

Quick Tip

For a biconvex lens, the effective focal length can be derived using the relationship $f = \sqrt{X_1X_2}$, where X_1 and X_2 are the distances of the object and image from the respective focal points.

Section E

31. (a) (i) Two point charges $5\,\mu C$ and $-1\,\mu C$ are placed at points $(-3\,\text{cm}, 0, 0)$ and $(3\,\text{cm}, 0, 0)$, respectively. An external electric field $\mathbf{E} = \frac{A}{r^2}\hat{r}$, where $A = 3 \times 10^5$ V/m is switched on in the region.

Calculate the change in electrostatic energy of the system due to the electric field.

Solution:

Step 1: The electrostatic potential energy of a system of point charges is given by:

$$U = \sum_{i<j} \frac{kq_i q_j}{r_{ij}}$$

where k is Coulomb's constant, q_i and q_j are the charges, and r_{ij} is the distance between the charges.

In this case, the charges are $q_1 = 5\,\mu C$ and $q_2 = -1\,\mu C$, and the distance between them is $r = 6\,\text{cm} = 0.06\,\text{m}$.

Step 2: The electrostatic energy of the system before the electric field is switched on is:

$$U_{\text{initial}} = \frac{kq_1 q_2}{r} = \frac{9 \times 10^9 \times 5 \times 10^{-6} \times (-1) \times 10^{-6}}{0.06} = -7.5\,\mathbf{J}$$

Step 3: The electric field $\mathbf{E} = \frac{A}{r^2}\hat{r}$ will change the potential energy. The work done by the electric field will affect the energy of the system, but this effect requires calculating the force exerted by the field on each charge. However, further calculation may be required based on specific configurations.

The change in electrostatic energy will depend on the external field's influence on the charges, but this requires further integration for a precise value.

Quick Tip

To calculate the change in electrostatic energy, consider the forces exerted by external fields on the charges. The detailed calculation may require integrating the potential energy contributions.

(ii) A system of two conductors is placed in air and they have net charges of $+80\,\mu C$ and $-80\,\mu C$, which causes a potential difference of 16 V between them.

(1) Find the capacitance of the system.

Solution: The capacitance of a system of conductors is related to the charge and potential difference by:

$$C = \frac{Q}{V}$$

where $Q = 80\,\mu C$ and $V = 16\,\text{V}$.

Substituting the values:

$$C = \frac{80 \times 10^{-6}}{16} = 5 \times 10^{-6}\,\text{F} = 5\,\mu F$$

Correct Answer: $5\,\mu F$

Quick Tip

Capacitance can be calculated using $C = \frac{Q}{V}$, where Q is the charge and V is the potential difference.

---

(2) If the air between the capacitor is replaced by a dielectric medium of dielectric constant 3, what will be the potential difference between the two conductors?

Solution: The capacitance of a capacitor with a dielectric material is given by:

$$C' = K \times C$$

where K is the dielectric constant, and C is the initial capacitance.

Substituting $K = 3$ and $C = 5\,\mu F$:

$$C' = 3 \times 5\,\mu F = 15\,\mu F$$

The potential difference with the dielectric is given by:

$$V' = \frac{Q}{C'} = \frac{80 \times 10^{-6}}{15 \times 10^{-6}} = 5.33\,\text{V}$$

Correct Answer: $5.33\,\text{V}$

Quick Tip

When a dielectric is inserted between capacitor plates, the capacitance increases by a factor of the dielectric constant, reducing the potential difference for a given charge.

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(3) If the charges on two conductors are changed to $+160\,\mu C$ and $-160\,\mu C$, will the capacitance of the system change? Give reason for your answer.

Solution: The capacitance of the system depends only on the physical properties of the conductors and the dielectric medium between them, not the charge on the conductors. Therefore, changing the charge does not affect the capacitance.
Correct Answer: The capacitance will not change because it is independent of the charge, as long as the dielectric and physical dimensions of the system remain constant.

> Quick Tip
>
> Capacitance is determined by the geometry of the conductors and the dielectric material, not the charge placed on them.

---

31. (b) (i) Consider three metal spherical shells A, B, and C, each of radius R. Each shell is having a concentric metal ball of radius $R/10$. The spherical shells A, B, and C are given charges $+6q$, $-4q$, and $+14q$ respectively. Their inner metal balls are also given charges $-2q$, $+8q$, and $-10q$ respectively. Compare the magnitude of the electric fields due to shells A, B, and C at a distance $3R$ from their centres.
Solution: Using Gauss's law, we know that the electric field at a distance r from the centre of a spherical shell due to a spherical charge distribution is given by:

$$E = \frac{1}{4\pi\epsilon_0}\frac{Q_{\text{enc}}}{r^2}$$

where Q_{enc} is the total charge enclosed by a Gaussian surface at radius r. The electric field depends only on the net charge enclosed within the shell, and not on the distribution of charge inside the shell.

For all the three shells at a distance $3R$, we can consider the following: - For shell A, the net charge enclosed is $Q_A = +6q + (-2q) = +4q$. - For shell B, the net charge enclosed is $Q_B = -4q + 8q = +4q$. - For shell C, the net charge enclosed is $Q_C = +14q + (-10q) = +4q$.

Since the net enclosed charge for all three shells is the same $(+4q)$, the magnitude of the electric field at a distance $3R$ will be the same for all three shells.

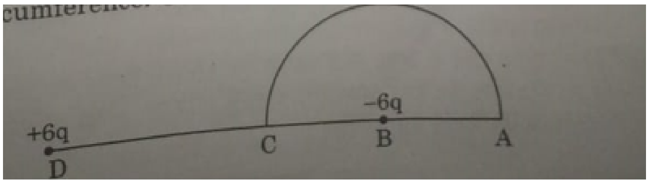
Thus, the electric field due to shells A, B, and C at a distance $3R$ will be the same and is given by:

$$E = \frac{1}{4\pi\epsilon_0}\frac{4q}{(3R)^2}$$

Quick Tip

The electric field due to a spherical shell depends on the net charge enclosed within the shell, not on the charge distribution.

(ii) A charge $-6\,\mu C$ is placed at the centre B of a semicircle of radius 5 cm, as shown in the figure. An equal and opposite charge is placed at point D at a distance of 10 cm from B. A charge $+5\,\mu C$ is moved from point C to point A along the circumference. Calculate the work done on the charge.



Solution: The work done on a charge moved in an electric field is given by the equation:

$$W = \Delta U = q\Delta V$$

where ΔV is the potential difference between the points C and A, and q is the charge being moved.

The electric potential due to a point charge is given by:

$$V = \frac{1}{4\pi\epsilon_0}\frac{Q}{r}$$

where Q is the charge and r is the distance from the charge.

Step 1: Calculate the potential at points A and C. The potential at a point due to a point charge is the same regardless of the path, so we can calculate the potential difference directly.

For charge $-6\,\mu C$ at point B, the potential at point C is:

$$V_C = \frac{1}{4\pi\epsilon_0}\frac{-6\times10^{-6}}{5\,\text{cm}} = \frac{-6\times10^{-6}}{5\times10^{-2}} = -1.2\times10^{-4}\,\text{V}$$

For charge $+6\,\mu C$ at point D, the potential at point A is:

$$V_A = \frac{1}{4\pi\epsilon_0}\frac{6\times10^{-6}}{10\,\text{cm}} = \frac{6\times10^{-6}}{10\times10^{-2}} = 6\times10^{-5}\,\text{V}$$

Step 2: The potential difference is:

$$\Delta V = V_A - V_C = 6\times10^{-5} - (-1.2\times10^{-4}) = 1.8\times10^{-4}\,\text{V}$$

Step 3: The work done on the charge $+5\,\mu C$ is:

$$W = q\Delta V = 5 \times 10^{-6} \times 1.8 \times 10^{-4} = 9 \times 10^{-10}\,\text{J}$$

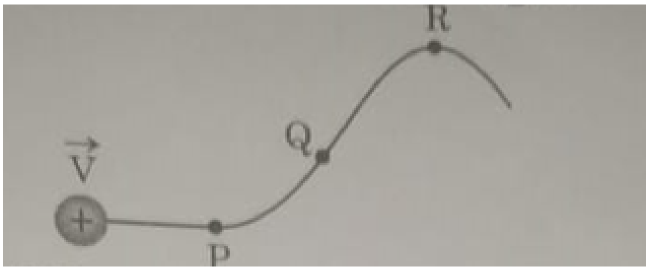
Correct Answer: The work done on the charge is $9 \times 10^{-10}\,\text{J}$.

Quick Tip

The work done on a charge moving in an electric field is the product of the charge and the potential difference between the two points.

---

32. (a) (i) A proton moving with velocity $\vec{V}$ in a non-uniform magnetic field traces a path as shown in the figure.



The path followed by the proton is always in the plane of the paper. What is the direction of the magnetic field in the region near points P, Q, and R? What can you say about the relative magnitude of magnetic fields at these points?

Solution: In this case, the proton is moving in a curved path due to the Lorentz force exerted by the magnetic field. The Lorentz force is always perpendicular to both the velocity of the charged particle and the magnetic field. This means that the magnetic force is responsible for changing the direction of the proton's velocity, causing the curved path.

- **At point P:** The proton is moving in a circular path, so the magnetic field at point P is perpendicular to the plane of the paper. If the proton's velocity is directed to the right, the magnetic field must be directed into the paper (away from the observer), according to the right-hand rule.

- **At point Q:** The velocity of the proton is tangential to the curve at point Q. Since the magnetic force is always perpendicular to the velocity, the magnetic field at point Q will also be perpendicular to the velocity but directed into the paper.

- **At point R:** The proton's velocity is directed upward, so at point R, the magnetic field will still be directed into the paper.

Relative magnitudes of the magnetic field: Since the proton moves in a non-uniform magnetic field, the magnitude of the magnetic field will change as the proton moves along its path. The magnetic field strength is stronger at point P, weaker at point Q, and weakest at point R, as the path curvature indicates increasing or decreasing magnetic field strength.

Quick Tip

The magnetic field produces a force that is always perpendicular to the velocity of the moving charge, causing circular or spiral paths for charged particles.

---

32. (ii) A current carrying circular loop of area A produces a magnetic field B at its centre. Show that the magnetic moment of the loop is:

$$\mu = \frac{2BA}{\mu_0}\sqrt{\frac{A}{\pi}}$$

Solution: The magnetic field at the centre of a current-carrying circular loop of radius r is given by the Biot-Savart law:

$$B = \frac{\mu_0 I}{2r}$$

where μ_0 is the permeability of free space, I is the current in the loop, and r is the radius of the loop.

The area A of the loop is related to the radius by:

$$A = \pi r^2$$

Thus, the radius r can be expressed as:

$$r = \sqrt{\frac{A}{\pi}}$$

Substitute this expression for r into the formula for B:

$$B = \frac{\mu_0 I}{2\sqrt{\frac{A}{\pi}}}$$

Simplifying:

$$B = \frac{\mu_0 I}{2}\sqrt{\frac{\pi}{A}}$$

Now, the magnetic moment μ of the loop is given by:

$$\mu = I \cdot A$$

Substituting $I = \frac{2B}{\mu_0}\sqrt{\frac{A}{\pi}}$ into the equation for μ:

$$\mu = \left(\frac{2B}{\mu_0}\sqrt{\frac{A}{\pi}}\right) \cdot A$$

Thus, the magnetic moment of the loop is:

$$\mu = \frac{2BA}{\mu_0}\sqrt{\frac{A}{\pi}}$$

Quick Tip

The magnetic moment of a current-carrying loop is proportional to the current and the area of the loop. The magnetic field produced at the centre of the loop is inversely proportional to the radius of the loop.

---

32. (b) (i) Derive an expression for the torque acting on a rectangular current loop suspended in a uniform magnetic field.

Solution: Let the rectangular loop have dimensions l and w (length and width), and carry a current I. The loop is placed in a uniform magnetic field $\vec{B}$.

The torque τ experienced by the current loop is given by the formula:

$$\tau = \mu B \sin\theta$$

where: - μ is the magnetic moment of the loop,

- B is the magnetic field strength,

- θ is the angle between the normal to the plane of the loop and the magnetic field direction.

The magnetic moment μ of the rectangular loop is given by:

$$\mu = I \cdot A$$

where $A = l \cdot w$ is the area of the loop. Therefore,

$$\mu = I \cdot l \cdot w$$

Substituting this into the expression for the torque:

$$\tau = I \cdot l \cdot w \cdot B \sin\theta$$

This is the expression for the torque acting on the rectangular current loop in a uniform magnetic field.

Quick Tip

The torque on a current loop in a magnetic field depends on the magnetic moment of the loop, the field strength, and the angle between them.

(ii) A charged particle is moving in a circular path with velocity $\vec{V}$ in a uniform magnetic field $\vec{B}$. It is made to pass through a sheet of lead and, as a consequence, it loses one half of its kinetic energy without change in its direction. How will (1) the radius of its path change? (2) its time period of revolution change?

Solution: The force acting on a charged particle moving in a magnetic field is given by the Lorentz force:

$$F = qvB$$

This force provides the centripetal force that keeps the particle in circular motion, so the radius of the circular path is given by:

$$r = \frac{mv}{qB}$$

where m is the mass of the particle, v is its velocity, and B is the magnetic field.

(1) Change in the radius of the path: When the charged particle passes through the lead sheet, it loses half of its kinetic energy, meaning its velocity decreases by a factor of $\sqrt{2}$ (since kinetic energy is proportional to the square of the velocity).

Thus, the new velocity v' is:

$$v' = \frac{v}{\sqrt{2}}$$

Substituting into the expression for the radius, the new radius r' becomes:

$$r' = \frac{mv'}{qB} = \frac{m \cdot \frac{v}{\sqrt{2}}}{qB} = \frac{r}{\sqrt{2}}$$

Thus, the radius of the path decreases by a factor of $\sqrt{2}$.

(2) Change in the time period of revolution: The time period T of revolution is given by:

$$T = \frac{2\pi r}{v}$$

Since $r' = \frac{r}{\sqrt{2}}$ and $v' = \frac{v}{\sqrt{2}}$, the new time period T' becomes:

$$T' = \frac{2\pi r'}{v'} = \frac{2\pi \cdot \frac{r}{\sqrt{2}}}{\frac{v}{\sqrt{2}}} = T$$

Therefore, the time period of revolution remains unchanged.

Quick Tip

When the velocity of a charged particle in a magnetic field changes, the radius of its path changes according to $r \propto v$, while the time period of revolution remains constant if the magnetic field is unchanged.

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33. (a) (i) (1) What are coherent sources? Why are they necessary for observing a sustained interference pattern?

Solution: Coherent sources are sources of light that have a constant phase relationship with each other. This means that the waves from these sources maintain a fixed phase difference over time. Coherent light sources produce an interference pattern because the light waves from these sources can interfere constructively and destructively at different points.

They are necessary for observing a sustained interference pattern because interference requires that the waves from the sources have a constant phase relationship. If the sources were incoherent, the phase difference between their waves would constantly change, resulting in a fluctuating or disappearing interference pattern.

(2) Lights from two independent sources are not coherent. Explain.

Solution: Two independent light sources are not coherent because the phase relationship between the waves they emit is random and changes over time. Incoherent light sources have no fixed phase difference, which causes their waves to interfere in an unpredictable way, making it impossible to observe a sustained interference pattern. For instance, sunlight and light from a regular bulb are examples of incoherent light sources.

Quick Tip

For sustained interference patterns, light sources must be coherent, meaning they maintain a constant phase relationship.

(ii) Two slits 0.1 mm apart are arranged 1.20 m from a screen. Light of wavelength 600 nm from a distant source is incident on the slits.

(1) How far apart will adjacent bright interference fringes be on the screen?

(2) Find the angular width (in degrees) of the first bright fringe.

Solution: For interference patterns from a double slit, the fringe spacing on the screen is given by:

$$y = \frac{\lambda L}{d}$$

where:

- y is the fringe spacing (distance between adjacent bright fringes),

- $\lambda = 600\,\text{nm} = 600 \times 10^{-9}\,\text{m}$,

- $L = 1.20\,\text{m}$ is the distance from the slits to the screen,

- $d = 0.1\,\text{mm} = 0.1 \times 10^{-3}\,\text{m}$ is the distance between the slits.

Substituting the values:

$$y = \frac{600 \times 10^{-9} \times 1.20}{0.1 \times 10^{-3}} = 7.2 \times 10^{-3}\,\text{m} = 7.2\,\text{mm}$$

Thus, adjacent bright fringes will be 7.2 mm apart.

Angular width of the first bright fringe: The angular width θ of the first bright fringe is given by:

$$\theta = \frac{\lambda}{d}$$

Substituting the given values:

$$\theta = \frac{600 \times 10^{-9}}{0.1 \times 10^{-3}} = 6 \times 10^{-3}\,\text{radians}$$

To convert radians to degrees:

$$\theta = 6 \times 10^{-3} \times \frac{180}{\pi} \approx 0.344\,\text{degrees}$$

Quick Tip

The fringe spacing in an interference pattern is directly proportional to the wavelength of light and the distance between the slits, and inversely proportional to the distance from the slits to the screen.

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33. (b) (i) Define a wavefront. An incident plane wave falls on a convex lens and gets refracted through it. Draw a diagram to show the incident and refracted wavefront.

Solution: A wavefront is a surface of constant phase in a wave. It is the locus of all points that are in phase with each other. For a plane wave, the wavefronts are planes perpendicular to the direction of propagation.

When an incident plane wave falls on a convex lens, the lens refracts the waves and causes them to converge towards the focal point. The wavefronts after refraction become curved, and the light focuses at a point along the axis of the lens.

Quick Tip

A plane wave becomes spherical after passing through a converging lens, as the lens causes the waves to focus at a point.

(ii) A beam of light coming from a distant source is refracted by a spherical glass ball (refractive index 1.5) of radius 15 cm. Draw the ray diagram and obtain the position of the final image formed.

Solution: When light passes through a spherical glass ball, it refracts twice: once when entering and once when leaving the ball. Since the refractive index of the glass is greater than 1, the light bends towards the normal at both interfaces.

To find the position of the final image, we can use the formula for refraction at a spherical surface:

$$\frac{1}{f} = \left(\frac{n-1}{r}\right)$$

where $n = 1.5$ is the refractive index of the glass, and $r = 15\,\text{cm}$ is the radius of the sphere.

Substituting the values:

$$\frac{1}{f} = \frac{1.5 - 1}{15} = \frac{0.5}{15} = \frac{1}{30}$$

Thus, the focal length f of the spherical surface is 30 cm.

Since the object is at infinity (distant source), the light converges at a distance equal to the focal length of the spherical surface, which is 30 cm from the surface.

Quick Tip

When light passes through a spherical surface, it refracts twice: once when entering and once when leaving the surface. The formula for focal length applies to spherical refracting surfaces.
