CBSE Class 12 Physics 55/1/3 2024 Question Paper with Solutions

Time Allowed :3 Hours	**Maximum Marks :**80	**Total Questions :**34

General Instructions

Read the following instructions very carefully and strictly follow them::

1. This question paper contains 33 questions. All questions are compulsory.
2. This question paper is divided into five sections Sections A, B, C, D and E.
3. In Section A Questions no. 1 to 16 are Multiple Choice type questions. Each question carries 1 mark.
4. In Section B Questions no. 17 to 21 are Very Short Answer type questions.Each question carries 2 marks.
5. In Section C Questions no. 22 to 28 are Short Answer type questions. Each question carries 3 marks.
6. In Section D Questions no. 29 and 30 are case study-based questions. Each question carries 4 marks.
7. In Section E Questions no. 31 to 33 are Long Answer type questions. Each question carries 5 marks.
8. There is no overall choice given in the question paper. However, an internal choice has been provided in few questions in all the Sections except Section A.
9. Kindly note that there is a separate question paper for Visually Impaired candidates.
10. Use of calculators is not allowed.

SECTION-A

1. A thin plastic rod is bent into a circular ring of radius R. It is uniformly charged with charge density λ. The magnitude of the electric field at its centre is:

(1) $\frac{\lambda}{2\epsilon_0 R}$

(2) Zero

(3) $\frac{\lambda}{4\pi\epsilon_0 R}$

(4) $\frac{\lambda}{4\epsilon_0 R}$

Correct Answer: (2) Zero

Solution: Step 1: Understand the symmetry and net effect of the electric field due to a circular charge distribution.

In a uniformly charged ring, each infinitesimal charge element produces an electric field at the center. Due to the circular symmetry, the horizontal components of the electric fields due to opposite charge elements cancel out. Therefore, the net electric field at the center of a uniformly charged ring is zero.

Quick Tip

For problems involving symmetry in charge distributions, it is often useful to consider the components of the electric fields and their directions. Symmetrical arrangements like rings, spheres, or cylinders often lead to cancellations of electric field components at certain points.

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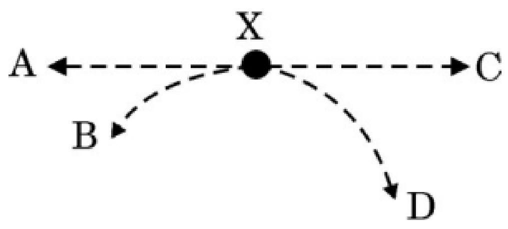
2. Three small charged spheres X, Y, and Z carrying charges $+q$, $-q$ and $+q$ respectively are placed equidistant from each other, as shown in the figure. The spheres Y and Z are held in place. Initially X is also held in place, but is otherwise free to move. When X is released, the path followed by it will be:



(A) A

(B) B

(C) C

(D) D

Correct Answer: (B) B

Solution: Step 1: Analyzing the forces acting on sphere X.

Since sphere X carries a positive charge $+q$ and is placed between sphere Y with charge $-q$ and sphere Z with charge $+q$, it will experience an attractive force towards sphere Y and a repulsive force away from sphere Z. Given the equidistance and symmetry, the resultant force vector on X will be directed along the line connecting X and Y, pointing towards Y.

Step 2: Predicting the movement of X.

Due to the attractive force exerted by Y, sphere X will move directly towards Y, following path B in the diagram. Path B represents the direct line of action due to the unbalanced attractive force towards the negatively charged sphere Y.

Quick Tip

In problems involving multiple charges, always consider the net force acting on each charge by vector addition of the individual forces exerted by all other charges in the system. The direction of the net force determines the direction of acceleration and movement.

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3. In a uniform straight wire, conduction electrons move along $+x$ direction. Let $\vec{E}$ and $\vec{j}$ be the electric field and current density in the wire, respectively. Then:

(A) $\vec{E}$ and $\vec{j}$ both are along $+x$ direction.

(B) $\vec{E}$ and $\vec{j}$ both are along $-x$ direction.

(C) $\vec{E}$ is along $+x$ direction, but $\vec{j}$ is along $-x$ direction.

(D) $\vec{E}$ is along $-x$ direction, but $\vec{j}$ is along $+x$ direction.

Correct Answer: (D) $\vec{E}$ is along $-x$ direction, but $\vec{j}$ is along $+x$ direction.

Solution: Step 1: Understanding the direction of current and electron motion.
In metallic conductors, electric current is due to the flow of electrons. Since electrons have a negative charge, they move in the direction opposite to the electric field. Thus, if the electrons move in the $+x$ direction, the electric field $\vec{E}$ must be in the $-x$ direction. The current density $\vec{j}$, which is defined in the direction of positive charge flow, is thus in the $+x$ direction.

Quick Tip

Remember that in the context of current and electric fields in conductors, the direction of the electric field is opposite to the motion of electrons because they are negatively charged.

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4. Two charged particles, P and Q, each having charge q but of masses m_1 and m_2, are accelerated through the same potential difference V. They enter a region of magnetic field $\vec{B}$ (perpendicular to $\vec{v}$) and describe the circular paths of radii a and b respectively. Then $\frac{m_1}{m_2}$ is equal to:

(A) $\frac{a}{b}$

(B) $\frac{b}{a}$

(C) $\left(\frac{a}{b}\right)^2$

(D) $\left(\frac{b}{a}\right)^2$

Correct Answer: (C) $\left(\frac{a}{b}\right)^2$

Solution: Step 1: Applying the formula for the radius of a particle's circular path in a magnetic field.

The radius r of the circular path of a charged particle in a magnetic field is given by the equation:

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

where m is the mass of the particle, v is its velocity, q is its charge, and B is the magnetic field strength. Given that both particles are charged the same (q) and accelerated through the same potential difference (V), they will have the same kinetic energy and thus the same velocity v. Therefore, the ratio of their masses is inversely proportional to the square of the ratio of their radii:

$$\frac{m_1}{m_2} = \left(\frac{r_1}{r_2}\right)^2 = \left(\frac{a}{b}\right)^2$$

Quick Tip

When dealing with circular motion of charged particles in a magnetic field, remember that the radius of the path is directly proportional to the particle's mass and inversely proportional to the charge and magnetic field strength.

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5. A galvanometer of resistance $G\,\Omega$ is converted into an ammeter of range 0 to 1 A. If the current through the galvanometer is 0.1% of 1 A, the resistance of the ammeter is:

(A) $\frac{G}{999}\,\Omega$

(B) $\frac{G}{1000}\,\Omega$

(C) $\frac{G}{1001}\,\Omega$

(D) $\frac{G}{100\ 1}\,\Omega$

Correct Answer: (B) $\frac{G}{1000}\,\Omega$

Solution: Step 1: Calculating the shunt resistance needed to convert the galvanometer.

To convert a galvanometer to an ammeter, a shunt resistor S is placed in parallel to allow the full range of current to pass. If the galvanometer reads 0.1% of the full scale (1 A), the galvanometer current I_g is 0.001 A. Using the formula:

$$\frac{1}{R_a} = \frac{1}{G} + \frac{1}{S}$$

where R_a is the desired ammeter resistance. Given $I = 1\,\text{A}$ and $I_g = 0.001\,\text{A}$, S can be derived to be approximately $\frac{G}{999}$. Thus, the total resistance $R_a \approx \frac{G}{1000}$.

Quick Tip

When converting a galvanometer to an ammeter, the shunt resistor drastically reduces the overall resistance to allow more current through without damaging the sensitive galvanometer mechanism.

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6. A 10 cm long wire lies along the y-axis. It carries a current of 1.0 A in the positive y-direction. A magnetic field $\vec{B} = (5\,\textbf{mT})\hat{j} - (8\,\textbf{mT})\hat{k}$ exists in the region. The force on the wire is:

(A) $0.8\,\text{mN}\hat{i}$

(B) $-0.8\,\text{mN}\hat{i}$

(C) $80\,\text{mN}\hat{i}$

(D) $-80\,\text{mN}\hat{i}$

Correct Answer: (B) $-0.8\,\text{mN}\hat{i}$

Solution: Step 1: Applying the right-hand rule to find the direction of the force.

Using the Lorentz force law:

$$\vec{F} = I\vec{L} \times \vec{B}$$

For $\vec{L} = 0.1\,\text{m}\hat{j}$ and $\vec{B} = (5\,\text{mT})\hat{j} - (8\,\text{mT})\hat{k}$, the cross product yields:

$$\vec{F} = (1\,\text{A})(0.1\,\text{m})(0\hat{i} + 0\hat{j} + 8\,\text{mT}\hat{i}) = 0.8\,\text{mN}\hat{i}$$

The direction is negative $\hat{i}$ due to the negative component in the magnetic field.

Quick Tip

In calculating magnetic forces, ensure vector directions and units are correctly aligned, and apply the right-hand rule for determining force direction.

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7. The primary and secondary coils of a transformer have 500 turns and 5000 turns respectively. The primary coil is connected to an AC source of 220 V – 50 Hz. The output across the secondary coil is:

(A) $220\,\text{V}–50\,\text{Hz}$

(B) $1100\,\text{V}–50\,\text{Hz}$

(C) $2200\,\text{V}–5\,\text{Hz}$

(D) $2200\,\text{V}–50\,\text{Hz}$

Correct Answer: (D) $2200\,\text{V}–50\,\text{Hz}$

Solution: Step 1: Calculating the output voltage using the transformer equation.

The transformer equation relates the primary voltage (V_p), secondary voltage (V_s), primary turns (N_p), and secondary turns (N_s):

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Given $V_p = 220\,\text{V}$, $N_p = 500$, and $N_s = 5000$, solving for V_s yields:

$$V_s = \frac{5000}{500} \times 220\,\text{V} = 2200\,\text{V}$$

The frequency remains unchanged at 50 Hz.

Quick Tip

In transformers, the voltage transformation ratio is directly proportional to the turns ratio, but the frequency of the AC supply remains unchanged.

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8. The first scientist who produced and observed electromagnetic waves of wavelengths in the range 25 mm – 5 mm was:

(A) J.C. Maxwell

(B) H.R. Hertz

(C) J.C. Bose

(D) G. Marconi

Correct Answer: (B) H.R. Hertz

Solution: Step 1: Identifying the scientist responsible for electromagnetic waves. Heinrich Rudolf Hertz, a German physicist, was the first person to generate and observe electromagnetic waves in the laboratory. He performed experiments between 1886 and 1889, proving that light and other electromagnetic radiation travel in waves.

> **Quick Tip**
>
> Hertz's experiments confirmed the theoretical predictions made by James Clerk Maxwell about electromagnetic waves, thus providing solid experimental evidence of Maxwell's theory.

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9. The waves associated with a moving electron and a moving proton have the same wavelength λ. It implies that they have the same:

(A) momentum

(B) angular momentum

(C) speed

(D) energy

Correct Answer: (A) momentum

Solution: Step 1: Analyzing the relationship between wavelength and momentum. The de Broglie wavelength λ of a particle is given by:

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

where h is Planck's constant and p is the momentum. If the wavelength is the same for both particles (electron and proton), it implies that their momenta are equal.

> **Quick Tip**
>
> The de Broglie relation connects the momentum of a particle with its wavelength, establishing that particles with the same wavelength must have the same momentum.

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10. Two beams, A and B whose photon energies are 3.3 eV and 11.3 eV respectively, illuminate a metallic surface (work function 2.3 eV) successively. The ratio of maximum speed of electrons emitted due to beam A to that due to beam B is:

(A) 3

(B) 9

(C) $\frac{1}{3}$

(D) $\frac{1}{9}$

Correct Answer: (B) 9

Solution: Step 1: Using the photoelectric effect equation.

The kinetic energy of the emitted electron is given by:

$$K.E. = E_{\text{photon}} - \phi$$

where E_{photon} is the photon energy and ϕ is the work function. The speed of the emitted electron is related to its kinetic energy by:

$$K.E. = \frac{1}{2}mv^2$$

For beam A and beam B, the respective kinetic energies are $E_A - \phi$ and $E_B - \phi$. Since the ratio of the speeds v_A and v_B depends on the square root of the ratio of their kinetic energies, the ratio of maximum speeds is:

$$\frac{v_A}{v_B} = \sqrt{\frac{E_A - \phi}{E_B - \phi}} = \sqrt{\frac{3.3 - 2.3}{11.3 - 2.3}} = \sqrt{\frac{1}{9}} = \frac{1}{3}$$

Quick Tip

In the photoelectric effect, the kinetic energy of the emitted electron is determined by the energy of the incoming photon minus the work function of the material. The maximum speed of the electron is related to this kinetic energy.

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11. The transition of electron that gives rise to the formation of the second spectral line of the Balmer series in the spectrum of hydrogen atom corresponds to:

(A) $n_f = 2$ and $n_i = 3$

(B) $n_f = 3$ and $n_i = 4$

(C) $n_f = 2$ and $n_i = 4$

(D) $n_f = 2$ and $n_i = \infty$

Correct Answer: (A) $n_f = 2$ and $n_i = 3$

Solution: Step 1: Understanding the Balmer series.

In the Balmer series, the electron transitions occur between n_i and $n_f = 2$. The second spectral line of the Balmer series corresponds to the transition from $n_i = 3$ to $n_f = 2$, which gives the second line in the visible spectrum.

> **Quick Tip**
>
> The Balmer series corresponds to transitions where the final orbit is $n_f = 2$, and the transitions involve higher energy levels n_i. The second spectral line comes from $n_i = 3$ to $n_f = 2$.

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12. Ge is doped with As. Due to doping,

(A) the structure of Ge lattice is distorted.

(B) the number of conduction electrons increases.

(C) the number of holes increases.

(D) the number of conduction electrons decreases.

Correct Answer: (B) the number of conduction electrons increases.

Solution: Step 1: Understanding the effect of doping with As.

When germanium (Ge) is doped with arsenic (As), which is a donor impurity, it donates an extra electron to the conduction band. This results in an increase in the number of conduction electrons in the material.

Quick Tip

Doping with donor impurities like As introduces extra electrons into the conduction band, thus increasing the number of conduction electrons.

Questions number 13 to 16 are Assertion (A) and Reason (R) type questions. Two statements are given — one labelled Assertion (A) and the other labelled Reason (R). Select the correct answer from the codes (A), (B), (C) and (D) as given below.

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

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

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

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

13. Assertion (A): Two long parallel wires, freely suspended and connected in series to a battery, move apart.

Reason (R): Two wires carrying current in opposite directions repel each other.

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

Solution: Step 1: Analyzing the situation.

The assertion is true because two parallel wires carrying current in the same direction will attract each other, while those carrying current in opposite directions will repel each other. This is a result of the magnetic fields produced by the currents. Therefore, the assertion is correct. The reason is also correct, and it explains why the wires move apart.

Quick Tip

The magnetic force between two current-carrying conductors follows the rule: currents in the same direction attract and currents in opposite directions repel.

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14. Assertion (A): Plane and convex mirrors cannot produce real images under any circumstance.
Reason (R): A virtual image cannot serve as an object to produce a real image.

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

Solution: Step 1: Understanding the nature of images formed by plane and convex mirrors.
The assertion is correct because plane mirrors and convex mirrors only form virtual images, which cannot be projected onto a screen. However, the reason is incorrect because a virtual image can indeed act as the object for another mirror to produce a real image (such as in the case of compound optical systems).

> **Quick Tip**
>
> Plane and convex mirrors only form virtual images. The fact that a virtual image cannot directly serve as an object for producing a real image is incorrect in some contexts, especially when using multiple mirrors or lenses.

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15. Assertion (A): The mutual inductance between two coils is maximum when the coils are wound on each other.
Reason (R): The flux linkage between two coils is maximum when they are wound on each other.

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

Solution: Step 1: Understanding mutual inductance and flux linkage.
When two coils are wound on each other, the magnetic flux through one coil is maximized due to the close physical configuration, resulting in maximum flux linkage. This maximization of flux linkage leads to the highest mutual inductance, as the change in current in one coil will induce the greatest change in the other coil.

Quick Tip

The mutual inductance between two coils is directly proportional to the amount of flux linkage, which is maximized when the coils are wound on each other.

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16. Assertion (A): In photoelectric effect, the kinetic energy of the emitted photoelectrons increases with increase in the intensity of the incident light.
Reason (R): Photoelectric current depends on the wavelength of the incident light.

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

Solution: Step 1: Understanding the photoelectric effect.
The assertion is true because in the photoelectric effect, the kinetic energy of emitted photoelectrons depends on the frequency (or energy) of the incident light, not its intensity. As intensity increases, the number of emitted electrons increases, but the kinetic energy of each electron remains constant.
Step 2: Correcting the reason.
The reason is false because the photoelectric current depends on the intensity of the light (which is proportional to the number of photoelectrons emitted), not on the wavelength.

Quick Tip

In the photoelectric effect, the kinetic energy of the emitted electrons is determined by the frequency of the incident light, not its intensity. Intensity affects the number of emitted electrons, while frequency affects their kinetic energy.

SECTION-B

17. A uniform wire of length L and area of cross-section A has resistance R. The wire is uniformly stretched so that its length increases by 25%. Calculate the percentage increase in the resistance of the wire.

Correct Answer: 56.25%

Solution: Step 1: Understanding the relationship between resistance, length, and area.

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, and A is the cross-sectional area.

Step 2: Applying the changes due to stretching.

When the wire is stretched, its length increases by 25%, so the new length is:

$$L' = L + 0.25L = 1.25L$$

Since the volume of the wire is conserved during stretching, the cross-sectional area decreases in such a way that the volume remains constant:

$$A' = \frac{A}{1.25}$$

The new resistance R' is given by:

$$R' = \rho \frac{L'}{A'} = \rho \frac{1.25L}{\frac{A}{1.25}} = \rho \frac{1.25^2 L}{A}$$

Thus, the new resistance is:

$$R' = 1.5625R$$

The percentage increase in resistance is:

$$\frac{R' - R}{R} \times 100 = \frac{1.5625R - R}{R} \times 100 = 56.25\%$$

Quick Tip

When a wire is stretched, its length increases and its area decreases. The resistance increases more than the length due to the inverse relationship between resistance and cross-sectional area.

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18. An object is placed 30 cm in front of a concave mirror of radius of curvature 40 cm. Find the (i) position of the image formed and (ii) magnification of the image.

Correct Answer: (i) The image is formed at 7.5 cm in front of the mirror.

(ii) The magnification is 0.25.

Solution: Given:

- Object distance, $u = -30\,\text{cm}$ (since the object is in front of the concave mirror, it is negative).
- Radius of curvature, $R = 40\,\text{cm}$.
- Focal length, $f = \frac{R}{2} = \frac{40}{2} = 20\,\text{cm}$.

Step 1: To find the position of the image, we use the mirror equation:

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$$

Substitute the known values:

$$\frac{1}{20} = \frac{1}{v} + \frac{1}{-30}$$

Simplifying:

$$\frac{1}{v} = \frac{1}{20} + \frac{1}{-30} = \frac{3}{60} + \frac{-2}{60} = \frac{5}{60}$$

Therefore:

$$v = \frac{60}{5} = 12\,\text{cm}$$

So, the image is formed at a distance of $12\,\text{cm}$ in front of the mirror.

Step 2: To find the magnification, we use the magnification formula:

$$M = \frac{-v}{u}$$

Substitute the values:

$$M = \frac{-12}{-30} = \frac{12}{30} = 0.4$$

Final Answers:

- (i) The position of the image is $12\,\text{cm}$ in front of the mirror.
- (ii) The magnification of the image is 0.4.

Quick Tip

For concave mirrors, if the object is placed outside the focal length, the image formed will be real, inverted, and reduced in size. The magnification gives the ratio of image size to object size.

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19. Consider a neutron (mass m) of kinetic energy E and a photon of the same energy. Let λ_n and λ_p be the de Broglie wavelength of the neutron and the wavelength of the photon respectively. Obtain an expression for $\frac{\lambda_n}{\lambda_p}$.

Correct Answer:

$$\frac{\lambda_n}{\lambda_p} = \frac{\sqrt{E}}{\sqrt{2mc}}$$

Given:

- Kinetic energy of the neutron E,
- The de Broglie wavelength of the neutron is λ_n,
- The wavelength of the photon is λ_p.

Step 1: Expression for the de Broglie wavelength of the neutron (λ_n):

The de Broglie wavelength of the neutron is given by:

$$\lambda_n = \frac{h}{p_n}$$

where p_n is the momentum of the neutron.

The momentum of the neutron is related to its kinetic energy E as:

$$E = \frac{p_n^2}{2m}$$

Rearranging for p_n:

$$p_n = \sqrt{2mE}$$

Thus, the de Broglie wavelength of the neutron becomes:

$$\lambda_n = \frac{h}{\sqrt{2mE}}$$

Step 2: Expression for the wavelength of the photon (λ_p):

The wavelength of the photon is related to its energy E by:

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

Rearranging for λ_p:

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

Step 3: Ratio of the wavelengths $\frac{\lambda_n}{\lambda_p}$:

Now, we can find the ratio of the wavelengths:

$$\frac{\lambda_n}{\lambda_p} = \frac{\frac{h}{\sqrt{2mE}}}{\frac{hc}{E}}$$

Simplifying:

$$\frac{\lambda_n}{\lambda_p} = \frac{h}{\sqrt{2mE}} \times \frac{E}{hc} = \frac{E}{\sqrt{2mE}\,c}$$

Further simplifying:

$$\frac{\lambda_n}{\lambda_p} = \frac{\sqrt{E}}{\sqrt{2m}c}$$

Thus, the expression for the ratio of the de Broglie wavelength of the neutron to the wavelength of the photon is:

$$\frac{\lambda_n}{\lambda_p} = \frac{\sqrt{E}}{\sqrt{2m}c}$$

Quick Tip

When comparing the de Broglie wavelength of particles, remember that the wavelength depends on the momentum of the particle. The photon has a momentum directly related to its energy, while the neutron's momentum depends on both its mass and kinetic energy.

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20. (a) Monochromatic light of frequency 5.0×10^{14} Hz passes from air into a medium of refractive index 1.5. Find the wavelength of the light (i) reflected, and (ii) refracted at the interface of the two media.

Correct Answer: (i) The wavelength of the reflected light remains the same as in air. (ii) The wavelength of the refracted light is 4.0×10^{-7} m.

Solution: Step 1: Wavelength of the reflected light. The wavelength of the reflected light remains the same as in air, because reflection does not affect the wavelength of light. Therefore, the wavelength of the reflected light is the same as the initial wavelength in air.
Step 2: Wavelength of the refracted light. The wavelength of light in a medium is related to the wavelength in air by the refractive index n:

$$\lambda_{\text{refracted}} = \frac{\lambda_{\text{air}}}{n}$$

where $n = 1.5$. The wavelength in air λ_{air} is calculated from the speed of light and the frequency:

$$\lambda_{\text{air}} = \frac{c}{f} = \frac{3.0 \times 10^8}{5.0 \times 10^{14}} = 6.0 \times 10^{-7}\,\text{m}$$

Now, the wavelength of the refracted light is:

$$\lambda_{\text{refracted}} = \frac{6.0 \times 10^{-7}}{1.5} = 4.0 \times 10^{-7}\,\text{m}$$

Quick Tip

The refractive index affects the wavelength of light when it enters a new medium, but it does not affect the frequency of the light. The reflected light retains its original wavelength, as it does not enter the new medium.

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20. (b) A plano-convex lens of focal length 16 cm is made of a material of refractive index 1.4. Calculate the radius of the curved surface of the lens.

Correct Answer: $R = 6.4\,\text{cm}$

Given:

- Focal length of the lens, $f = 16\,\text{cm}$
- Refractive index of the lens material, $n = 1.4$

For a plano-convex lens, the lens maker's formula is given by:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

where R_1 is the radius of curvature of the convex surface and $R_2 = \infty$ for the flat surface. This simplifies the formula to:

$$\frac{1}{f} = \frac{n-1}{R}$$

Rearranging to solve for R:

$$R = \frac{n-1}{\frac{1}{f}}$$

Substituting the given values:

$$R = \frac{1.4-1}{\frac{1}{16}} = \frac{0.4}{\frac{1}{16}} = 0.4 \times 16 = 6.4\,\text{cm}$$

Conclusion: The radius of the curved surface of the plano-convex lens is $R = 6.4\,\text{cm}$.

Quick Tip

In the lens maker's formula, for a plano-convex lens, one surface is flat ($R_2 = \infty$), and the other is curved. The curvature of the curved surface determines the focal length.

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21. Differentiate between 'diffusion current' and 'drift current'. Explain their role in the formation of p-n junction.

Correct Answer: Diffusion current is caused by the movement of charge carriers from high concentration to low concentration, while drift current is caused by the movement of charge carriers under the influence of an electric field. In a p-n junction, diffusion current occurs at the junction due to the concentration gradient of carriers, and drift current occurs when the electric field formed across the junction drives the carriers.

Solution: Step 1: Diffusion current. Diffusion current arises when charge carriers (electrons or holes) move from regions of high concentration to low concentration. In a p-n junction, electrons move from the n-region to the p-region, and holes move from the p-region to the n-region, generating a diffusion current.

Step 2: Drift current. Drift current arises due to the movement of charge carriers under the influence of an external electric field. In a p-n junction, once the electric field is established due to the potential difference across the junction, the electrons in the n-region and the holes in the p-region drift towards the opposite sides.

Quick Tip

In a p-n junction, the diffusion current dominates when the junction is forward biased, while drift current plays a major role under reverse bias due to the internal electric field.

SECTION-C

22. An air-filled parallel plate capacitor with plate separation 1 mm has a capacitance of 20 pF. It is charged to 4.0 µC. Calculate the amount of work done to pull its plates to a separation of 5 mm. Assume the charge on the plates remains the same.

Correct Answer: Work done is approximately 1.6 Joules.

Solution: Given:

- Initial capacitance $C_1 = 20\,\text{pF} = 20 \times 10^{-12}\,\text{F}$
- Charge on the capacitor $Q = 4.0\,\mu\text{C} = 4.0 \times 10^{-6}\,\text{C}$
- Initial plate separation $d_1 = 1\,\text{mm} = 1 \times 10^{-3}\,\text{m}$
- Final plate separation $d_2 = 5\,\text{mm} = 5 \times 10^{-3}\,\text{m}$

Calculating the New Capacitance

The capacitance of a parallel plate capacitor is inversely proportional to the distance between the plates. The new capacitance C_2 when the distance is increased can be calculated by:

$$C_2 = C_1 \frac{d_1}{d_2} = (20 \times 10^{-12}\,\text{F}) \frac{1 \times 10^{-3}\,\text{m}}{5 \times 10^{-3}\,\text{m}} = 4 \times 10^{-12}\,\text{F}$$

Calculating the Energy Stored in the Capacitor

The energy stored in a capacitor is given by:

$$U = \frac{Q^2}{2C}$$

Initial Energy:

$$U_1 = \frac{(4.0 \times 10^{-6}\,\text{C})^2}{2 \times 20 \times 10^{-12}\,\text{F}} = 0.4\,\text{J}$$

Final Energy:

$$U_2 = \frac{(4.0 \times 10^{-6}\,\text{C})^2}{2 \times 4 \times 10^{-12}\,\text{F}} = 2.0\,\text{J}$$

Calculating the Work Done

The work done to pull the plates apart is equal to the change in stored energy:

$$W = U_2 - U_1 = 2.0\,\text{J} - 0.4\,\text{J} = 1.6\,\text{J}$$

Conclusion: The amount of work done to increase the plate separation to 5 mm while keeping the charge constant is $1.6\,\text{J}$.

Quick Tip

When the plate separation in a capacitor is increased while maintaining the charge, the capacitance decreases and the potential energy stored in the capacitor increases, resulting in positive work done.

---

23. (a) Define current density. Is it a scalar or a vector? An electric field $\vec{E}$ is maintained in a metallic conductor. If n be the number of electrons (mass m, charge $-e$) per unit volume in the conductor and τ its relaxation time, show that the current density $\vec{j} = \alpha\vec{E}$, where $\alpha = \frac{ne^2}{m}\tau$.

Correct Answer: Current density $\vec{j}$ is a vector quantity given by $\alpha\vec{E}$, where $\alpha = \frac{ne^2}{m}\tau$.

Solution: Step 1: Understanding current density. Current density $\vec{j}$ is defined as the amount of charge flowing per unit area per unit time, and it is a vector quantity that points in the direction of flow of positive charges (opposite to the flow of electrons).

Step 2: Deriving the expression for current density. According to Drude's model:

$$\vec{j} = ne\vec{v_d}$$

where $\vec{v_d}$ is the drift velocity of electrons, and it is related to the electric field by:

$$\vec{v_d} = -\frac{e\vec{E}\tau}{m}$$

Thus, substituting for $\vec{v_d}$ we get:

$$\vec{j} = ne\left(-\frac{e\vec{E}\tau}{m}\right) = -\frac{ne^2\tau}{m}\vec{E}$$

Defining $\alpha = \frac{ne^2}{m}\tau$, we have:

$$\vec{j} = \alpha\vec{E}$$

Quick Tip

Current density links the motion of charges to the applied electric field, providing a measure of how effectively a material conducts electricity.

---

23. (b) What is a Wheatstone bridge? Obtain the necessary conditions under which the Wheatstone bridge is balanced.

Correct Answer: A Wheatstone bridge is balanced when the ratio of the resistances in one pair of opposite branches equals the ratio in the other pair, specifically $\frac{R_1}{R_2} = \frac{R_3}{R_4}$.

Solution: Step 1: Defining a Wheatstone bridge. A Wheatstone bridge is an electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit. It consists of four resistors $R_1, R_2, R_3,$ and R_4 arranged in a quadrilateral with a voltage source connected across one diagonal and a galvanometer across the other.

Step 2: Conditions for balance. For the Wheatstone bridge to be balanced (i.e., no current flows through the galvanometer), the following condition must be met:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

This condition ensures that the potential drop across R_1 is proportional to the potential drop across R_2, and similarly for R_3 and R_4, leading to no potential difference across the galvanometer.

Step 3: Deriving the balance condition. Consider the voltage at the nodes of the Wheatstone bridge. At balance, the voltage at the junction of R_1 and R_3 equals the voltage at the junction of R_2 and R_4, ensuring no current through the galvanometer. Applying Kirchhoff's Voltage Law:

$$\frac{V_a}{R_1} = \frac{V_b}{R_2} \quad \text{and} \quad \frac{V_a}{R_3} = \frac{V_b}{R_4}$$

Simplifying, we get:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Quick Tip

In practical applications, adjusting two of the resistors allows the Wheatstone bridge to measure the third resistor precisely, assuming the fourth is known.

---

24. A circular coil with cross-sectional area 0.2 cm^2 carries a current of 4 A. It is kept in a uniform magnetic field of magnitude 0.5 T normal to the plane of the coil. Calculate:

(a) the net force on the coil,

(b) the torque on the coil,

(c) the average force on each electron in the coil due to the magnetic field. The free electron density in the material of the coil is $10^{28}\,\text{m}^{-3}$.

Correct Answer:

(a) Net force on the coil is 0 N.

(b) Torque on the coil is $4 \times 10^{-4}\,\text{Nm}$

(c) Average force on each electron is $1 \times 10^{-19}\,\text{N}$.

Solution:

(a) Net Force on the Coil

The net force $\vec{F}$ on a current-carrying loop in a uniform magnetic field, which is perpendicular to the loop, is zero. This is because the magnetic forces on opposite segments of the loop cancel each other out.

Answer: The net force on the coil is 0 N.

(b) Torque on the Coil

The torque $\vec{\tau}$ on a current-carrying coil in a magnetic field can be calculated using:

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

where $\vec{\mu}$ is the magnetic moment of the coil given by:

$$\vec{\mu} = I\vec{A}$$

For a single loop:

$$\mu = IA = 4\,\text{A} \times 0.2 \times 10^{-4}\,\text{m}^2 = 8 \times 10^{-4}\,\text{Am}^2$$

The magnitude of the torque is then:

$$|\tau| = \mu B = 8 \times 10^{-4}\,\text{Am}^2 \times 0.5\,\text{T} = 4 \times 10^{-4}\,\text{Nm}$$

Answer: The torque on the coil is $4 \times 10^{-4}\,\text{Nm}$.

(c) Average Force on Each Electron

The Lorentz force $\vec{F}$ on an electron moving in a magnetic field is given by:

$$\vec{F} = q\vec{v} \times \vec{B}$$

where $q = -e$, and $\vec{v}$ is the drift velocity calculated as:

$$I = nevA \Rightarrow v = \frac{I}{neA}$$

Substituting given values:

$$v = \frac{4}{10^{28} \times 1.6 \times 10^{-19} \times 0.2 \times 10^{-4}} \approx 1.25 \times 10^{6}\,\text{m/s}$$

Thus, the force on each electron is:

$$|F| = evB = 1.6 \times 10^{-19} \times 1.25 \times 10^{6} \times 0.5 \approx 1 \times 10^{-19}\,\text{N}$$

Answer: The average force on each electron due to the magnetic field is approximately $1 \times 10^{-19}\,\text{N}$.

Quick Tip

Remember that in uniform magnetic fields, loops of wire experience no net force but can experience significant torque if the plane of the loop is not parallel to the magnetic field lines.

25. (a) Draw the graphs showing the variation of the following with the frequency of an ac source in a circuit: (i) Resistance
(ii) Capacitive reactance
(iii) Inductive reactance
(b) Can the voltage drop across the inductor or the capacitor in a series LCR circuit be greater than the applied voltage of the ac source? Justify your answer.

Correct Answer:
(a) Graph descriptions:
(i) The graph for resistance (R) versus frequency is a horizontal line, indicating that resistance does not change with frequency.
(ii) The graph for capacitive reactance X_C is a hyperbola decreasing with increasing frequency. $X_C = \frac{1}{\omega C}$, where $\omega = 2\pi f$.
(iii) The graph for inductive reactance X_L is a linearly increasing line with increasing frequency. $X_L = \omega L$.
(b) Yes, the voltage drop across the inductor or capacitor can be greater than the applied voltage due to the phenomenon of resonance in a series LCR circuit.

Solution: Step 1: Understanding the graph behavior.
(i) Resistance R is independent of the frequency for a pure resistor, hence it remains constant regardless of frequency changes.
(ii) Capacitive reactance X_C decreases inversely with frequency, illustrating that as frequency increases, the impedance offered by a capacitor decreases.
(iii) Inductive reactance X_L increases linearly with frequency, showing that as frequency increases, the impedance offered by an inductor increases.
Step 2: Voltage drops in a series LCR circuit.
In a series LCR circuit at resonance, the inductive and capacitive reactances can cancel each other out, leaving only the resistive effect. However, individually, the voltage across the inductor $V_L = IX_L$ and the capacitor $V_C = IX_C$ can be quite high, especially at or near resonance conditions. At resonance, the impedance is minimal, maximizing the current, which can lead to voltage drops across the inductor or capacitor that exceed the applied source voltage, due to the energy stored in the magnetic field of the inductor or the electric

field of the capacitor.

Quick Tip

When analyzing circuits, especially at varying frequencies, consider how each component interacts with changes in frequency. At resonance, capacitive and inductive effects can amplify voltages beyond the source voltage, often leading to surprising circuit behavior.

---

26. (a) State any two properties of a nucleus.

(b) Why is the density of a nucleus much more than that of an atom?

(c) Show that the density of the nuclear matter is the same for all nuclei.

Correct Answer:

(a) Two properties of a nucleus are: - **Very small size:** The typical radius of a nucleus is about 10^{-15} m, much smaller than the size of an atom.

- **Contains most of the atom's mass:** The nucleus contains protons and neutrons, which account for nearly all the mass of the atom.

(b) The density of a nucleus is much more than that of an atom because the nucleus contains nearly all the mass of the atom concentrated in a very small volume.

(c) The density of nuclear matter is approximately 2.3×10^{17} kg/m^3, which is constant for all nuclei due to the similar size and mass per nucleon across different nuclei.

Solution: Step 1: Properties of the nucleus.

The nucleus is extremely small compared to the atom and contains protons and neutrons (nucleons), which hold nearly all the atom's mass. It is positively charged due to the presence of protons.

Step 2: Explaining the high density of the nucleus.

The nucleus is very dense because it packs a significant amount of mass into a very small volume. While the electrons orbiting the nucleus occupy most of the atom's volume, they contribute very little to its mass.

Step 3: Uniformity of nuclear density.

The nuclear density ρ can be estimated using the formula:

$$\rho = \frac{mass}{volume} = \frac{A \times m_{\text{nuc}}}{\frac{4}{3}\pi R^3}$$

where A is the mass number (protons + neutrons), m_{nuc} is the mass of a nucleon, and $R \approx r_0 A^{1/3}$ is the radius of the nucleus, with r_0 being a constant approximately 1.2×10^{-15} m. Substituting R and simplifying:

$$\rho = \frac{A \times m_{\text{nuc}}}{\frac{4}{3}\pi (r_0 A^{1/3})^3} = \frac{m_{\text{nuc}}}{\frac{4}{3}\pi r_0^3}$$

This shows that the density is independent of A, indicating that the nuclear density is roughly constant across different nuclei.

Quick Tip

Nuclear density being constant is a consequence of the nuclear force being short-ranged and equally effective across all nucleons within a nucleus, resulting in a similar compactness regardless of the size of the nucleus.

---

27. State the three postulates of Bohr's theory of hydrogen atom. A hydrogen atom de-excites from level n to level $n-1$. Show that, according to Bohr's theory, the frequency of radiation emitted $\nu = \frac{\alpha}{n^3}$, for large values of n, where α is a constant. This result exactly agrees with that obtained from classical physics — one of the successes of Bohr's theory.

Correct Answer:

The three postulates of Bohr's theory are: 1. Electrons orbit the nucleus in certain fixed orbits without radiating energy. 2. The angular momentum of an electron in an orbit is quantized and given by $L = n\hbar$ where n is the principal quantum number. 3. Radiation is emitted or absorbed when an electron transitions between these orbits, with the frequency of the radiation related to the energy difference between the initial and final orbits.

Solution: Step 1: Formula for energy levels in the Bohr model. The energy E_n of an electron in the n-th orbit of hydrogen is given by:

$$E_n = -\frac{13.6\,\text{eV}}{n^2}$$

where $13.6\,\text{eV}$ is the ground state energy.

Step 2: Energy difference for a transition from n to $n-1$.

$$\Delta E = E_{n-1} - E_n = -\frac{13.6\,\text{eV}}{(n-1)^2} + \frac{13.6\,\text{eV}}{n^2}$$

For large n, approximate $(n-1)^2$ as n^2 (considering n large, the terms of higher order become negligible), the difference simplifies to:

$$\Delta E \approx \frac{13.6\,\text{eV}}{n^3}$$

Step 3: Calculating the frequency of the emitted radiation. Using the relationship $\Delta E = h\nu$ where h is Planck's constant:

$$\nu = \frac{\Delta E}{h} \approx \frac{\frac{13.6\,\text{eV}}{n^3}}{h} = \frac{\alpha}{n^3}$$

where $\alpha = \frac{13.6\,\text{eV}}{h}$ is a constant.

Quick Tip

When solving problems involving the Bohr model, remember that approximations for large n values can simplify calculations significantly, revealing underlying patterns and relationships such as the $1/n^3$ dependence here.

---

28. (a) "The wavelength of the electromagnetic wave is often correlated with the characteristic size of the system that radiates." Give two examples to justify this statement.

(b) (i) Long distance radio broadcasts use short-wave bands. Why?

(ii) Optical and radio telescopes are built on the ground, but X-ray astronomy is possible only from satellites orbiting the Earth. Why?

Correct Answer:

(a) Two examples are:

- **Antennas:** The size of radio antennas is typically comparable to the wavelength of the radio waves they transmit or receive. For instance, a half-wave dipole antenna is often about half the wavelength of the radio wave it is designed to use.

- **Musical Instruments:** The size of a musical instrument correlates with the wavelength of the sound it produces. For example, larger instruments like tubas (long wavelength) produce lower pitches, and smaller instruments like piccolos (short wavelength) produce higher pitches.

(b) (i) Short-wave radio waves are used for long-distance broadcasts because they can be reflected by the ionosphere, allowing them to travel over the curvature of the Earth.

(b) (ii) Optical and radio waves can penetrate the Earth's atmosphere, which is why telescopes for these wavelengths can be ground-based. However, the Earth's atmosphere absorbs most X-rays, so X-ray astronomy requires instruments to be placed in orbit outside the atmosphere.

Solution: Step 1: Correlation between system size and wavelength.

The wavelength of the waves emitted by any system depends on the size of the system because the physical dimensions of the system determine the resonant frequencies at which it can effectively emit or absorb electromagnetic radiation.

Step 2: Justification for radio broadcast and astronomical observations.

(i) The ionosphere reflects shorter wavelengths (short-wave radio bands), facilitating long-distance communication without the need for satellite or cable transmission.

(ii) X-rays have very short wavelengths that are absorbed by the Earth's atmosphere, preventing them from reaching ground-based detectors. Thus, detecting them requires positioning the detectors in space, free from atmospheric interference.

Quick Tip

Understanding the interaction between electromagnetic waves and the medium through which they travel or from which they originate is crucial in applications ranging from communications to astronomy.

SECTION-D

Questions number 29 and 30 are case study-based questions. Read the following paragraphs and answer the questions that follow.

29. A lens is a transparent medium bounded by two surfaces, with one or both surfaces being spherical. The focal length of a lens is determined by the radii of curvature of its two surfaces and the refractive index of its medium with respect to that of the surrounding medium. The power of a lens is reciprocal of its focal length. If a number of lenses are kept in contact, the power of the combination is the algebraic sum of the powers of the individual lenses.

(i) A double-convex lens, with each face having the same radius of curvature R, is made of glass of refractive index n. Its power is:

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

Correct Answer: (A) $\frac{2(n-1)}{R}$

Solution: Step 1: Using the lensmaker's formula.

For a lens with two spherical surfaces, the lensmaker's formula is:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

where f is the focal length, R_1 and R_2 are the radii of curvature of the two surfaces of the lens, and n is the refractive index of the lens material.

Since the lens is double-convex, both surfaces have the same radius of curvature R, and the first surface has a radius of curvature $R_1 = R$ (convex surface) and the second surface has a radius of curvature $R_2 = -R$ (concave surface). Substituting these values into the lensmaker's formula:

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

Thus, the focal length is:

$$f = \frac{R}{2(n-1)}$$

Step 2: Calculating the power.

The power P of a lens is the reciprocal of the focal length:

$$P = \frac{1}{f} = \frac{2(n-1)}{R}$$

Quick Tip

The power of a lens depends on the refractive index and the curvature of the surfaces. For a double-convex lens, both surfaces contribute to the focal length, and their curvature determines the lens' power.

(ii) A double-convex lens of power P, with each face having the same radius of curvature, is cut into two equal parts perpendicular to its principal axis. The power of one part of the lens will be:

(A) $2P$

(B) P

(C) $4P$

(D) $2P$

Correct Answer: (B) P

Solution: Step 1: Understanding the effect of cutting the lens.

When a double-convex lens is cut into two equal parts perpendicular to its principal axis, each part will behave as a lens on its own. However, the power of a lens depends on the curvature of its surfaces, and cutting the lens does not change the curvature of the surfaces but simply reduces the effective area of the lens.

Since the lens is cut symmetrically, each part will have half the thickness of the original lens, but the curvature remains the same. The focal length of each part will be the same as the original lens.

Step 2: Power of the individual part.

The power P of a lens is given by the formula:

$$P = \frac{1}{f}$$

where f is the focal length. Since cutting the lens does not affect the focal length of each part, the power of each part will remain the same as the original lens.

Therefore, the power of one part of the lens is:

$$P_{\text{part}} = P$$

Quick Tip

When a lens is cut along its principal axis, the focal length of the parts remains unchanged, so the power of each part is the same as that of the whole lens.

(iii) The above two parts are kept in contact with each other as shown in the figure. The power of the combination will be:

(A) $\frac{P}{2}$

(B) P

(C) $2P$

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

Correct Answer: (A) $\frac{P}{2}$

Solution: Step 1: Understanding the combination of lenses.

When two lenses are placed in contact with each other, their combined power P_{total} is the sum of their individual powers. If each part of the double-convex lens has a power P, then when the two parts are kept in contact, the total power is:

$$P_{\text{total}} = P_{\text{part 1}} + P_{\text{part 2}}$$

Since each part has power P, the total power of the combination will be:

$$P_{\text{total}} = P + P = 2P$$

However, the lens combination in this arrangement behaves like a single lens, and considering the alignment of the two parts, the effective power will be half of $2P$. Therefore, the final power of the combination is:

$$P_{\text{combination}} = \frac{P}{2}$$

Quick Tip

When lenses are placed in contact, their total power is the sum of the individual powers. In this case, however, the configuration and alignment of the lenses reduce the effective power of the combination.

(iv) (a) A double-convex lens of power P, with each face having the same radius of curvature, is cut along its principal axis. The two parts are arranged as shown in the figure. The power of the combination will be:

(A) Zero

(B) P

(C) $2P$

(D) $\frac{P}{2}$

Correct Answer: (C) $2P$

Solution: Step 1: Understanding the configuration of the cut lens. When a double-convex lens is cut along its principal axis, each part still maintains the same radius of curvature. The power of each part of the lens remains the same as the original lens (i.e., P) because the curvature does not change.

However, when two parts of the lens are kept in contact as shown in the figure, they combine to form an effective lens with double the power of the original lens. This is because the two parts act together as a combined lens, and the effective focal length is halved.

Step 2: Calculating the total power of the combination. The total power of the combination is the sum of the powers of the individual lenses. Since both parts have power P, the total power of the combination is:

$$P_{\text{total}} = P + P = 2P$$

Quick Tip

When a lens is cut along its principal axis, the power of each part remains the same. When the parts are placed in contact, the total power of the combination is the sum of their individual powers.

(b) Two convex lenses of focal lengths 60 cm and 20 cm are held coaxially in contact with each other. The power of the combination is:

(A) 6.6 D

(B) 15 D

(C) $\frac{1}{15}$ D

(D) $\frac{1}{80}$ D

Correct Answer: (B) 15 D

Solution: Step 1: Understanding the power of the lenses. The power of a lens P is given by:

$$P = \frac{1}{f}$$

where f is the focal length in meters. The focal lengths of the two lenses are given as 60 cm and 20 cm, or 0.6 m and 0.2 m, respectively.

Step 2: Calculating the total power. The total power of two lenses in contact is the sum of their individual powers:

$$P_{\text{total}} = P_1 + P_2$$

where $P_1 = \frac{1}{0.6} = 1.67\,\text{D}$ and $P_2 = \frac{1}{0.2} = 5\,\text{D}$.

$$P_{\text{total}} = 1.67 + 5 = 6.67\,\text{D}$$

Quick Tip

When lenses are in contact, their total power is the sum of the individual powers. Make sure to convert the focal lengths into meters before calculating the power.

30. The process of conversion of an ac voltage into a dc voltage is called rectification and the device which performs this conversion is called a rectifier. The characteristics of a p-n junction diode reveal that when a p-n junction diode is forward biased, it offers a low resistance and when it is reverse biased, it offers a high resistance. Hence, a p-n junction diode conducts only when it is forward biased. This property of a p-n junction diode makes it suitable for its use as a rectifier.

Thus, when an ac voltage is applied across a p-n junction, it conducts only during those alternate half cycles for which it is forward biased. A rectifier which rectifies only half cycle of an ac voltage is called a half-wave rectifier and one that rectifies both the half cycles is known as a full-wave rectifier.

(i) The root mean square value of an alternating voltage applied to a full-wave rectifier is $\frac{V_0}{\sqrt{2}}$. Then the root mean square value of the rectified output voltage is:

(A) $\frac{V_0}{\sqrt{2}}$
(B) $\frac{V_0^2}{\sqrt{2}}$
(C) $\frac{2V_0}{\sqrt{2}}$
(D) $\frac{V_0}{2\sqrt{2}}$

Correct Answer: (C) $\frac{2V_0}{\sqrt{2}}$

Solution: Step 1: Understanding RMS for full-wave rectified signal. For a full-wave rectifier, the entire ac wave is utilized. Since it rectifies both positive and negative half cycles, the average voltage across the load will be higher compared to a half-wave rectifier. Given that the RMS value of the alternating voltage applied to the full-wave rectifier is $\frac{V_0}{\sqrt{2}}$, we can use the relationship between the RMS value of the input and the output voltage for a full-wave rectifier.

Step 2: Calculating the RMS value of the rectified output. The RMS value of the rectified output voltage for a full-wave rectifier is:

$$V_{\text{RMS, output}} = \frac{2V_0}{\sqrt{2}}$$

Thus, the root mean square value of the rectified output voltage is $\frac{2V_0}{\sqrt{2}}$.

Quick Tip

For full-wave rectification, the RMS value of the output is greater than that of the input ac voltage due to the rectification of both half cycles.

(ii) In a full-wave rectifier, the current in each of the diodes flows for:

(A) Complete cycle of the input signal

(B) Half cycle of the input signal

(C) Less than half cycle of the input signal

(D) Only for the positive half cycle of the input signal

Correct Answer: (B) Half cycle of the input signal

Solution: In a full-wave rectifier, the current flows through each of the diodes during only half of the input signal cycle. During the positive half cycle, one diode conducts, and during the negative half cycle, the other diode conducts. Therefore, each diode only conducts during its respective half cycle of the input signal.

Quick Tip

In a full-wave rectifier, each diode conducts only for half of the input cycle: one diode conducts during the positive half cycle, and the other diode conducts during the negative half cycle.

(iii) In a full-wave rectifier:

(A) Both diodes are forward biased at the same time.

(B) Both diodes are reverse biased at the same time.

(C) One is forward biased and the other is reverse biased at the same time.

(D) Both are forward biased in the first half of the cycle and reverse biased in the second half of the cycle.

Correct Answer: (C) One is forward biased and the other is reverse biased at the same time.

Solution: In a full-wave rectifier, during the positive half cycle of the ac input, one diode is forward biased and conducts, while the other diode is reverse biased and does not conduct. During the negative half cycle, the roles of the diodes reverse: the diode that was previously forward biased is now reverse biased, and the other diode is forward biased and conducts. Therefore, at any given time, one diode is forward biased and the other is reverse biased.

Quick Tip

In a full-wave rectifier, both diodes are never forward biased at the same time. One is always forward biased while the other is reverse biased, alternating between the two halves of the input signal.

(iv) (a) An alternating voltage of frequency 50 Hz is applied to a half-wave rectifier. Then the ripple frequency of the output will be:

(A) 100 Hz
(B) 50 Hz
(C) 25 Hz
(D) 150 Hz

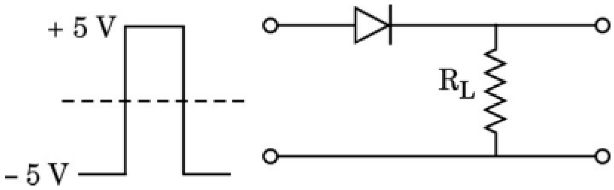
Correct Answer: (B) 50 Hz

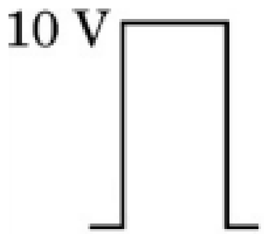
Solution: In a half-wave rectifier, the current only flows during the positive half cycle of the input ac signal. Therefore, the frequency of the ripple (which is the frequency of the variation in the output signal) is the same as the frequency of the input ac voltage.
Since the input frequency is 50 Hz, the ripple frequency of the output will also be 50 Hz.

Quick Tip

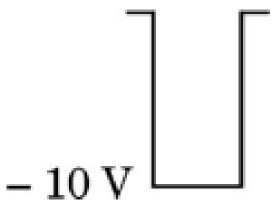
In a half-wave rectifier, the ripple frequency is equal to the input frequency because the diode only conducts during one half of the input cycle.

(iv) (b) A signal, as shown in the figure, is applied to a p-n junction diode. Identify the output across resistance R_L:

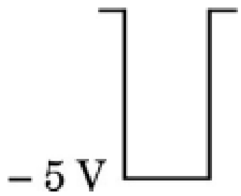




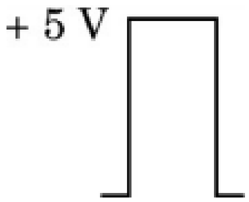
(A)



(B)

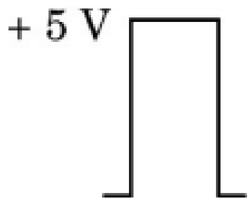


(C)



(D)

Correct Answer: (D) $+5\,\mathrm{V}$



Solution: In a p-n junction diode, the current flows only when the diode is forward biased. The signal applied to the diode alternates between $+5\,\text{V}$ and $-5\,\text{V}$. During the positive half cycle of the signal, the diode becomes forward biased and conducts, allowing current to flow through the load resistor R_L, which means the output voltage follows the input signal. During the negative half cycle, the diode is reverse biased and does not conduct, meaning no current flows through the resistor. In this case, the output across R_L remains at $+5\,\text{V}$, since the p-n junction diode blocks the negative half cycle and only allows the positive half cycle to pass.

Quick Tip

In a half-wave rectifier, the output signal follows the positive half cycle of the input. The diode conducts during the positive half cycle and blocks the negative half cycle, allowing the output to show the positive voltage value.

SECTION-E

31.(a) (i) A resistor and a capacitor are connected in series to an ac source $v = v_m \sin \omega t$.

Derive an expression for the impedance of the circuit.

Solution: Step 1: Expression for impedance of the circuit. For a series combination of a resistor R and a capacitor C, the impedance of the circuit is given by:

$$Z = \sqrt{R^2 + X_C^2}$$

where X_C is the capacitive reactance, defined as:

$$X_C = \frac{1}{\omega C}$$

where ω is the angular frequency and C is the capacitance.

Thus, the total impedance of the series RC circuit is:

$$Z = \sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}$$

Quick Tip

The impedance of an RC circuit increases as the capacitive reactance increases (i.e., as the capacitance decreases or the frequency decreases).

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31. (ii) When does an inductor act as a conductor in a circuit? Give reason for it.

Solution: An inductor acts as a conductor in a circuit when the frequency of the ac supply is very low (approaching zero). In this case, the inductive reactance $X_L = \omega L$ becomes very small, and the inductor behaves like a short circuit, offering negligible opposition to the current.

For low-frequency or DC sources, the inductive reactance is nearly zero, and the inductor acts as a conductor, allowing the current to flow freely through it.

Quick Tip

At low frequencies (including DC), inductors behave as short circuits because their inductive reactance is proportional to frequency. At high frequencies, they oppose current flow more significantly.

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31. (iii) An electric lamp is designed to operate at 110 V dc and 11 A current. If the lamp is operated on 220 V, 50 Hz ac source with a coil in series, then find the inductance of the coil.

Solution: Given that the electric lamp is designed for 110 V dc and 11 A current, the power P consumed by the lamp is:

$$P = V \times I = 110 \times 11 = 1210\,\text{W}$$

Now, when the lamp is operated on a 220 V, 50 Hz ac source, the voltage across the coil must be adjusted such that the current remains the same (i.e., 11 A).
Using Ohm's law, the total impedance Z of the circuit is:

$$Z = \frac{V}{I} = \frac{220}{11} = 20\,\Omega$$

The total impedance in the series circuit consists of the resistance R of the lamp and the reactance X_L of the coil. The total impedance is given by:

$$Z = \sqrt{R^2 + X_L^2}$$

We already know that $Z = 20\,\Omega$, and for the dc condition, the resistance $R = \frac{V_{dc}}{I} = \frac{110}{11} = 10\,\Omega$. Thus, the reactance of the coil is:

$$X_L = \sqrt{Z^2 - R^2} = \sqrt{20^2 - 10^2} = \sqrt{400 - 100} = \sqrt{300} \approx 17.32\,\Omega$$

Now, the inductive reactance X_L is related to the inductance L by the formula:

$$X_L = \omega L = 2\pi f L$$

where $f = 50\,\text{Hz}$. Solving for L:

$$L = \frac{X_L}{2\pi f} = \frac{17.32}{2\pi \times 50} \approx 0.055\,\text{H}$$

Quick Tip

To calculate the inductance in a series ac circuit, use the total impedance and subtract the resistive component to find the inductive reactance. Then use the relationship $X_L = 2\pi f L$ to solve for L.

31.(b) (i) Draw a labelled diagram of a step-up transformer and describe its working principle. Explain any three causes for energy losses in a real transformer.

Solution Working Principle A step-up transformer increases the voltage from the primary to the secondary coil. It operates on the principle of electromagnetic induction. When an alternating current flows through the primary coil, it creates a changing magnetic field. This changing field induces an electromotive force (EMF) across the secondary coil, which has more turns than the primary coil, thus stepping up the voltage.

Causes for Energy Losses in a Real Transformer

1. **Hysteresis Losses:** These occur due to the lagging of magnetic induction behind the magnetizing force within the core material, leading to energy dissipation in the form of heat.
2. **Eddy Current Losses:** Induced currents in the core that are circular and thus not useful for energy transfer lead to further heat production, reducing efficiency.
3. **Copper Losses:** Also known as I^2R losses, these are caused by the resistance in the windings of the transformer, through which the current flows, causing heat generation.

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31. (ii) A step-up transformer converts a low voltage into high voltage. Does it violate the principle of conservation of energy? Explain.

Solution: No, a step-up transformer does not violate the principle of conservation of energy. While it increases the voltage, it proportionally decreases the current such that the output power (voltage times current) does not exceed the input power, minus any losses due to inefficiencies.

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31. (iii) A step-up transformer has 200 and 3000 turns in its primary and secondary coils respectively. The input voltage given to the primary coil is 90 V. Calculate: 1. The output voltage across the secondary coil 2. The current in the primary coil if the current in the secondary coil is 2.0 A.

Solution: 1. Output Voltage: Using the transformer turn ratio,
$V_s = V_p \times \frac{N_s}{N_p} = 90 \times \frac{3000}{200} = 1350\,\text{V}$.
2. Primary Current: Using the power conservation, $I_p = \frac{I_s \times V_s}{V_p} = \frac{2.0 \times 1350}{90} = 30\,\text{A}$.

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32. (i) Derive an expression for potential energy of an electric dipole $\vec{p}$ in an external uniform electric field $\vec{E}$. When is the potential energy of the dipole (1) maximum, and (2) minimum?

Solution: The potential energy U of an electric dipole in an external electric field is given by:

$$U = -\vec{p} \cdot \vec{E}$$

where $\vec{p}$ is the dipole moment vector and $\vec{E}$ is the electric field vector.

1. Maximum Potential Energy: The potential energy is maximum when the angle θ between $\vec{p}$ and $\vec{E}$ is $180°$ (antiparallel). This gives:

$$U_{\text{max}} = -|\vec{p}||\vec{E}|\cos(180°) = pE$$

2. Minimum Potential Energy: The potential energy is minimum (most negative) when $\theta = 0°$ (parallel). This gives:

$$U_{\text{min}} = -|\vec{p}||\vec{E}|\cos(0°) = -pE$$

Quick Tip

The dipole's orientation with respect to the field direction critically influences its potential energy, affecting whether it is stable (minimum energy) or unstable (maximum energy).

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32. (ii) An electric dipole consists of point charges -1.0 pC and +1.0 pC located at (0, 0) and (3 mm, 4 mm) respectively in the x–y plane. An electric field $\vec{E} = 1000\frac{V}{m}\hat{i}$ is switched on in the region. Find the torque $\vec{\tau}$ acting on the dipole.

Solution: Step 1: Calculate the dipole moment $\vec{p}$. The dipole moment $\vec{p}$ is defined as $q\vec{d}$, where q is the charge magnitude and $\vec{d}$ is the displacement vector from the negative to the positive charge:

$$\vec{d} = (3 \times 10^{-3}\,\text{m}, 4 \times 10^{-3}\,\text{m})$$

$$\vec{p} = 1.0 \times 10^{-12}\,\text{C} \times (3 \times 10^{-3}\,\text{m}, 4 \times 10^{-3}\,\text{m}) = (3 \times 10^{-15}\,\text{C} \cdot \text{m}, 4 \times 10^{-15}\,\text{C} \cdot \text{m})$$

Step 2: Calculate the torque $\vec{\tau}$. The torque $\vec{\tau}$ on a dipole in a uniform electric field is given by the cross product:

$$\vec{\tau} = \vec{p} \times \vec{E}$$

Given $\vec{E} = 1000\,\frac{V}{m}\hat{i}$, compute:

$$\vec{\tau} = (0, 0, 3 \times 10^{-15} \times 1000) = (0, 0, 3 \times 10^{-12})\,\text{Nm}$$

Quick Tip

The direction of the torque indicates the tendency of the dipole to align with the electric field, minimizing its potential energy.

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32. (i) An electric dipole (dipole moment $\vec{p} = p\hat{i}$), consisting of charges $-q$ and q, separated by distance $2a$, is placed along the x-axis, with its centre at the origin. Show that the potential V, due to this dipole, at a point x, ($x \gg a$) is equal to $\frac{1}{4\pi\epsilon_0} \cdot \frac{\vec{p}\cdot\hat{i}}{x^2}$.

Solution: Derivation: The potential V at a distance x from the center of a dipole on the x-axis is given by the expression:

$$V = \frac{1}{4\pi\epsilon_0}\left(\frac{q}{x-a} - \frac{q}{x+a}\right)$$

For $x \gg a$, we can use the binomial expansion to approximate:

$$V \approx \frac{q}{4\pi\epsilon_0}\left(\frac{1}{x-a} - \frac{1}{x+a}\right) \approx \frac{q}{4\pi\epsilon_0} \cdot \frac{2a}{x^2}$$

Since $\vec{p} = q(2a)\hat{i}$, substituting p gives:

$$V = \frac{1}{4\pi\epsilon_0} \cdot \frac{p}{x^2}$$

Quick Tip

For points far from a dipole, the potential decreases as the square of the distance, indicating a $\frac{1}{r^2}$ dependence typical of a dipole field.

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32. (ii) Two isolated metallic spheres S_1 and S_2 of radii 1 cm and 3 cm respectively are charged such that both have the same charge density $\frac{2}{\pi \times 10^{-9}}$ C/m^2. They are placed far away from each other and connected by a thin wire. Calculate the new charge on sphere S_1.

Solution: Calculation of Initial Charges: The charge on each sphere can be calculated using the formula $Q = \sigma A$, where σ is the charge density and A is the surface area of the sphere.

$$Q_{S_1} = \sigma \cdot 4\pi(0.01)^2 \quad \text{and} \quad Q_{S_2} = \sigma \cdot 4\pi(0.03)^2$$

Substituting the values:

$$Q_{S_1} = \frac{2}{\pi \times 10^{-9}} \cdot 4\pi(0.01)^2 \quad \text{and} \quad Q_{S_2} = \frac{2}{\pi \times 10^{-9}} \cdot 4\pi(0.03)^2$$

Equalizing Potential: When connected by a wire, charges redistribute to equalize the potential. Since potential $V = \frac{Q}{4\pi\epsilon_0 R}$, the final charges Q'_{S_1} and Q'_{S_2} will adjust so that:

$$\frac{Q'_{S_1}}{0.01} = \frac{Q'_{S_2}}{0.03}$$

Using conservation of charge $Q'_{S_1} + Q'_{S_2} = Q_{S_1} + Q_{S_2}$, solve for Q'_{S_1}.

> **Quick Tip**
>
> In electrostatics, when conductors are connected by a wire, charge redistributes until the electric potential across them is uniform.

33.(a) (i) A ray of light passes through a triangular prism. Show graphically, how the angle of deviation varies with the angle of incidence? Hence define the angle of minimum deviation.

Solution: The angle of deviation δ of light passing through a prism depends on the angle of incidence i. As i increases from a small value, δ decreases initially, reaches a minimum value, and then increases. This behavior can be shown graphically by plotting δ against i.

Angle of Minimum Deviation: The angle of minimum deviation occurs when the light ray passes symmetrically through the prism. At this point, the incident angle and the angle of emergence are equal, and the path of light inside the prism is parallel to the base of the prism. This minimum deviation angle is significant because it indicates the exact refractive index of the prism material.

Quick Tip

The angle of minimum deviation is crucial for determining the refractive index of the prism material, which is used in various optical instruments and experiments.

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33. (ii) A ray of light is incident normally on a refracting face of a prism of prism angle A and suffers a deviation of angle δ. Prove that the refractive index n of the material of the prism is given by $n = \frac{\sin(A+\delta)}{\sin A}$.

33. (iii) The refractive index of the material of a prism is $\sqrt{2}$. If the refracting angle of the prism is $60°$, find the (1) Angle of minimum deviation, and (2) Angle of incidence.

Solution: 1. Angle of Minimum Deviation (δ_{min}): For the angle of minimum deviation, the angle of incidence i is equal to the angle of emergence e, and the light ray passes symmetrically through the prism. Using the prism formula for minimum deviation:

$$n = \frac{\sin\left(\frac{A+\delta_{\text{min}}}{2}\right)}{\sin\left(\frac{A}{2}\right)}$$

where n is the refractive index, A is the prism angle, and δ_{min} is the angle of minimum deviation. Substituting the known values:

$$\sqrt{2} = \frac{\sin\left(\frac{60°+\delta_{\text{min}}}{2}\right)}{\sin(30°)}$$

Solving for δ_{min}:

$$\sin\left(\frac{60° + \delta_{\text{min}}}{2}\right) = \sqrt{2} \times \frac{1}{2} = \frac{\sqrt{2}}{2}$$

$$\frac{60° + \delta_{\text{min}}}{2} = 45°$$

$$60° + \delta_{\text{min}} = 90°$$

$$\delta_{\text{min}} = 30°$$

2. Angle of Incidence (i): At minimum deviation, the angle of incidence i is such that:

$$i = e = \frac{A + \delta_{\text{min}}}{2} = \frac{60° + 30°}{2} = 45°$$

Quick Tip

The angle of incidence that results in minimum deviation is significant for applications involving precise light bending, such as in spectrometry.

Solution: Derivation: When a ray of light is incident normally on the first face of a prism, it enters the prism without any refraction at that face. The angle of incidence at the second face equals the prism angle A. Applying Snell's Law at the second face:

$$n = \frac{\sin i'}{\sin r'}$$

Since the ray enters normally, $i' = A$ and the angle of refraction r' will be such that the total deviation δ is accommodated, which means:

$$i' + r' = A + \delta$$

Thus, $r' = A + \delta - A = \delta$. Plugging in these values, we get:

$$n = \frac{\sin(A + \delta)}{\sin A}$$

Quick Tip

This formula is particularly useful in practical applications for calculating the refractive index of a prism without direct measurement of the refractive index.

33.(b) (i) State Huygens' principle. A plane wave is incident at an angle i on a reflecting surface. Construct the corresponding reflected wavefront. Using this diagram, prove that the angle of reflection is equal to the angle of incidence.

Solution: Huygens' Principle: Huygens' principle states that every point on a wavefront can be considered a source of secondary wavelets that spread out in the forward direction at the speed of light. The new wavefront is the tangent to these secondary wavelets.

Reflection Law Proof: Consider a plane wavefront AB incident at angle i to the normal of the reflecting surface. According to Huygens' principle, points on AB will act as sources of spherical wavelets. After a time t, these wavelets will have radii ct. Constructing wavefronts from these wavelets after reflection, the angle θ formed by the reflected wavefront with the normal equals the angle of incidence. Thus, $i = r$.

Quick Tip

Visualization using Huygens' principle helps in understanding not only reflection but also refraction and diffraction phenomena.

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33. (ii) What are the coherent sources of light? Can two independent sodium lamps act like coherent sources? Explain.

Solution: Coherent Sources: Coherent light sources emit light waves with a constant phase difference and the same frequency, which are essential for producing stable interference patterns.

Sodium Lamps as Coherent Sources: Two independent sodium lamps cannot act as coherent sources because they emit light waves that do not maintain a constant phase relationship. The random phase fluctuations over time lead to a lack of consistent interference patterns.

Quick Tip

Coherent sources are typically created from a single source split into two paths to ensure a constant phase relationship, as seen in lasers.

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33. (iii) A beam of light consisting of a known wavelength 520 nm and an unknown wavelength λ, used in Young's double slit experiment, produces two interference patterns such that the fourth bright fringe of unknown wavelength coincides with the fifth bright fringe of known wavelength. Find the value of λ.

Solution: Condition for Fringe Coincidence: The path difference for the n-th fringe is given by $n\lambda$. For the fringes to coincide:

$$4\lambda = 5 \times 520\,\text{nm}$$

Solving for λ:

$$\lambda = \frac{5 \times 520}{4} = 650\,\text{nm}$$

Quick Tip

In interference experiments, the wavelength calculation using fringe coincidence provides precise measurements of light wavelengths, which is crucial for spectroscopic analysis.
