

CBSE Class 12 Physics Question Paper 2026 with Solution PDF-Set 55/5/2



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **33** questions. **All** questions are **compulsory**.
- (ii) This question paper is divided into **five** sections – **Sections A, B, C, D and E**.
- (iii) In **Section A** – Questions no. **1 to 16** are Multiple Choice type questions. Each question carries **1** mark.
- (iv) In **Section B** – Questions no. **17 to 21** are Very Short Answer type questions. Each question carries **2** marks.
- (v) In **Section C** – Questions no. **22 to 28** are Short Answer type questions. Each question carries **3** marks.
- (vi) In **Section D** – Questions no. **29 and 30** are Case Study-based questions. Each question carries **4** marks.
- (vii) In **Section E** – Questions no. **31 to 33** are Long Answer type questions. Each question carries **5** marks.
- (viii) 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.
- (ix) Kindly note that there is a separate question paper for Visually Impaired candidates.
- (x) Use of calculators is not allowed.

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. The energy of an electron in an orbit in hydrogen atom is -3.4 eV. Its angular momentum in the orbit will be: [1 mark]

- (A) $\frac{3h}{2\pi}$
(B) $\frac{2h}{\pi}$
(C) $\frac{h}{\pi}$
(D) $\frac{h}{2\pi}$

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

Solution:

Concept:

- For hydrogen, the energy in the orbit with principal quantum number n is $E_n = -13.6/n^2$ eV, where $n = 1, 2, 3, \dots$
- Bohr's angular-momentum quantisation gives $L_n = nh/(2\pi)$, where h is Planck's constant.

Step 1: Identify the orbit from its energy Equate the given negative energy to the hydrogen energy formula. The minus signs cancel:

$$-\frac{13.6}{n^2} = -3.4 \Rightarrow n^2 = \frac{13.6}{3.4} = 4.$$

The allowed positive quantum number is therefore $n = 2$.

Step 2: Apply angular-momentum quantisation Substitute the orbit number into Bohr's condition:

$$L_2 = \frac{2h}{2\pi} = \frac{h}{\pi}.$$

Option (A) corresponds to $n = 3$, option (B) to $n = 4$, and option (D) to $n = 1$; none gives the stated energy. In particular, the factor 2 in 2π must not be dropped before substitution.

Step 3: Conclusion The angular momentum is $\boxed{h/\pi}$. Hence, the correct option is (C).

Quick Tip to Solve: First calculate $n = \sqrt{13.6/|E_n|}$, with energy in eV; then use $L = nh/(2\pi)$.

2. The momentum of a photon associated with a microwave of wavelength 4.00 cm is:

[1 mark]

- (A) $1.66 \times 10^{-32} \text{ kg ms}^{-1}$
- (B) $1.83 \times 10^{-34} \text{ kg ms}^{-1}$
- (C) $2.05 \times 10^{-34} \text{ kg ms}^{-1}$
- (D) $1.66 \times 10^{-34} \text{ kg ms}^{-1}$

Correct Answer: (A) $1.66 \times 10^{-32} \text{ kg ms}^{-1}$

Solution:

Concept:

- A photon has momentum $p = E/c = h/\lambda$, where E is its energy, c the speed of light, and λ its wavelength.
- Use SI units with Planck's constant $h = 6.63 \times 10^{-34} \text{ J s}$; the wavelength must be in metres to obtain momentum in kg m s^{-1} .

Step 1: Convert the wavelength to metres Since $1 \text{ cm} = 10^{-2} \text{ m}$, the given microwave wavelength becomes

$$\lambda = 4.00 \text{ cm} = 4.00 \times 10^{-2} \text{ m}.$$

The photon relation applies to microwaves just as it does to visible light.

Step 2: Substitute into the photon-momentum relation Dividing Planck's constant by the wavelength gives

$$p = \frac{6.63 \times 10^{-34}}{4.00 \times 10^{-2}} = 1.6575 \times 10^{-32} \text{ kg m s}^{-1}.$$

To three significant figures this is $1.66 \times 10^{-32} \text{ kg m s}^{-1}$. Option (D) results from treating 4.00 cm as 4.00 m. Options (B) and (C) also have the wrong power of ten and do not follow from h/λ .

Step 3: Conclusion The photon momentum is $1.66 \times 10^{-32} \text{ kg m s}^{-1}$. Hence, the correct option is (A).

Quick Tip to Solve: Convert centimetres to metres before dividing by wavelength; dividing by 10^{-2} raises the exponent by two.

3. The radius of a nucleus of mass number 125 is:

[1 mark]

- (A) 6.0 fm
- (B) 30 fm
- (C) 72 fm
- (D) 150 fm

Correct Answer: (A) 6.0 fm

Solution:

Concept:

- The empirical nuclear-radius law is $R = R_0 A^{1/3}$, where A is the mass number and $R_0 \simeq 1.2 \text{ fm}$.
- Since nuclear density is approximately constant, nuclear volume is proportional to A , so radius grows as its cube root; $1 \text{ fm} = 10^{-15} \text{ m}$.

Step 1: Evaluate the cube root of the mass number For the given nucleus, $A = 125$. As $125 = 5^3$,

$$A^{1/3} = 125^{1/3} = 5.$$

This is the factor by which the nuclear radius exceeds R_0 ; the mass number itself is not the radius multiplier.

Step 2: Calculate and compare the radii Apply the empirical law with the standard nuclear-radius constant:

$$R = (1.2 \text{ fm})(5) = 6.0 \text{ fm}.$$

The printed values 30 fm and 72 fm in options (B) and (C) do not satisfy the cube-root law. Option (D), 150 fm, comes from the incorrect linear expression $R = R_0 A = 1.2 \times 125 \text{ fm}$.

Step 3: Conclusion The nuclear radius is 6.0 fm, or $6.0 \times 10^{-15} \text{ m}$. Hence, the correct option is (A).

Quick Tip to Solve: Recognise $125 = 5^3$ immediately and multiply 5 by 1.2 fm; never multiply the mass number directly by R_0 .

4. The rms and the average value of an ac voltage $V = V_0 \sin \omega t$ volt over a cycle respectively will be: [1 mark]

- (A) $\frac{V_0}{2}, \frac{V_0}{\sqrt{2}}$
(B) $\frac{V_0}{\pi}, \frac{V_0}{2}$
(C) $\frac{V_0}{\sqrt{2}}, 0$
(D) $V_0, \frac{V_0}{\sqrt{2}}$

Correct Answer: (C) $\frac{V_0}{\sqrt{2}}, 0$

Solution:

Concept:

- The root-mean-square voltage is $V_{\text{rms}} = \sqrt{\langle V^2 \rangle}$, where angle brackets denote the time average over one full cycle.
- For a sinusoid, $\langle \sin^2 \omega t \rangle = 1/2$ and $\langle \sin \omega t \rangle = 0$. The signed average voltage differs from the rms value.

Step 1: Calculate the rms voltage Square the given voltage before taking its cycle average, and then take the positive square root:

$$V_{\text{rms}} = \sqrt{V_0^2 \langle \sin^2 \omega t \rangle} = \sqrt{\frac{V_0^2}{2}} = \frac{V_0}{\sqrt{2}}.$$

Here V_0 is the positive amplitude. Squaring makes both half-cycles contribute positively.

Step 2: Find the signed average over the complete cycle For a period $T = 2\pi/\omega$, the equal positive

and negative half-cycles cancel:

$$V_{av} = \frac{1}{T} \int_0^T V_0 \sin \omega t \, dt = 0.$$

Every other printed option gives a nonzero full-cycle average, and its first value also differs from the rms result. A half-cycle or rectified average is a different quantity and must not be used here.

Step 3: Conclusion The rms and full-cycle average values are respectively $V_0/\sqrt{2}$, 0. Hence, the correct option is (C).

Quick Tip to Solve: For a full sine-wave cycle, the signed average is zero while the rms value is the peak divided by $\sqrt{2}$.

5. A good diode checked by a multimeter should indicate:

[1 mark]

- (A) high resistance in reverse bias and a low resistance in forward bias
- (B) high resistance in both forward bias and reverse bias
- (C) low resistance in both reverse bias and forward bias
- (D) high resistance in forward bias and low resistance in reverse bias

Correct Answer: (A) high resistance in reverse bias and a low resistance in forward bias

Solution:

Concept:

- A p-n junction diode conducts readily in forward bias because the applied voltage lowers the junction barrier and narrows the depletion region.
- Reverse bias raises the barrier and widens the depletion region. Below breakdown, only a very small reverse current flows, corresponding to a high resistance.

Step 1: Compare the two bias conditions When the multimeter forward-biases a working diode, appreciable current can pass, so the indicated resistance is low. Reversing the connections reverse-biases the diode and suppresses the current; the indicated resistance is high. These readings refer to ordinary testing below the reverse-breakdown voltage.

Step 2: Check the alternatives against normal diode behaviour High resistance in both directions, as in (B), suggests an open diode. Low resistance in both directions, as in (C), suggests a shorted diode. Option (D) interchanges the defining forward- and reverse-bias behaviours, so it cannot describe a good p-n junction diode.

Step 3: Conclusion A good diode indicates high resistance in reverse bias and low resistance in forward bias. Hence, the correct option is (A).

Quick Tip to Solve: Reverse the meter leads: a healthy diode should conduct readily in one bias direction and strongly oppose current in the other.

6. Two point charges $-Q$ and Q are located at points $(d, 0)$ and $(0, d)$ respectively, in the x - y plane. The electric field $\vec{E}$ at the origin will be: [1 mark]

- (A) $\frac{1}{4\pi\epsilon_0} \frac{\sqrt{2}Q}{d^2} (\hat{i} - \hat{j})$
(B) $\frac{1}{4\pi\epsilon_0} \frac{\sqrt{2}Q}{d^2} (-\hat{i} - \hat{j})$
(C) $\frac{1}{4\pi\epsilon_0} \frac{Q}{d^2} (\hat{i} - \hat{j})$
(D) $\frac{1}{4\pi\epsilon_0} \frac{Q}{d^2} (-\hat{i} - \hat{j})$

Correct Answer: (C) $\frac{1}{4\pi\epsilon_0} \frac{Q}{d^2} (\hat{i} - \hat{j})$

Solution:

Concept:

- A point charge of magnitude Q produces a field of magnitude kQ/r^2 , where $k = 1/(4\pi\epsilon_0)$ and r is the distance from the charge.
- Electric fields add vectorially. The field points towards a negative charge and away from a positive charge; $\hat{i}$ and $\hat{j}$ are the positive coordinate unit vectors.

Step 1: Determine each field at the origin The negative charge at $(d, 0)$ attracts a positive test charge at the origin towards the positive x -axis. The positive charge at $(0, d)$ repels it towards the negative y -axis. Both distances are d , so

$$\vec{E}_{-Q} = \frac{kQ}{d^2} \hat{i}, \quad \vec{E}_{+Q} = -\frac{kQ}{d^2} \hat{j}.$$

Step 2: Add the perpendicular components Superposition gives

$$\vec{E} = \vec{E}_{-Q} + \vec{E}_{+Q} = \frac{kQ}{d^2} (\hat{i} - \hat{j}).$$

The magnitude is $\sqrt{2}kQ/d^2$, but the vector $\hat{i} - \hat{j}$ already has magnitude $\sqrt{2}$. Thus (A) includes an extra factor of $\sqrt{2}$; (B) also has this error and reverses the x -component. Option (D) has an incorrect negative x -component.

Step 3: Conclusion The field is $\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{Q}{d^2} (\hat{i} - \hat{j})$, towards positive x and negative y . Hence, the correct option is (C).

Quick Tip to Solve: Find the sign of each component first. Do not multiply a component vector by the magnitude's extra $\sqrt{2}$ factor.

7. An electron is moving with velocity $v_0\hat{i}$. If a uniform electric field $\vec{E} = E_0\hat{j}$ is set up in the region, the electron will: [1 mark]

- (A) describe a circular path
- (B) describe a helical path
- (C) describe a parabolic path
- (D) continue moving without any deviation

Correct Answer: (C) describe a parabolic path

Solution:

Concept:

- An electron has charge $-e$, so a uniform field $\vec{E} = E_0\hat{j}$ produces the constant force $\vec{F} = -eE_0\hat{j}$ and acceleration $\vec{a} = -(eE_0/m_e)\hat{j}$, where m_e is the electron mass.
- With no force along x , the horizontal velocity remains v_0 . Uniform horizontal motion combined with constant transverse acceleration gives a parabolic trajectory in the standard nonrelativistic treatment.

Step 1: Write the component motions Choose the entry point as the origin and $t = 0$ when the electron enters the field. The initial transverse velocity is zero, so

$$x = v_0t, \quad y = -\frac{eE_0}{2m_e}t^2.$$

The negative sign shows that the electron deflects opposite to the electric field, towards negative y .

Step 2: Eliminate time and identify the trajectory Substitute $t = x/v_0$ into the transverse displacement:

$$y = -\frac{eE_0}{2m_ev_0^2}x^2.$$

This has the form $y = -ax^2$, a parabola. A constant electric force does not supply the continuously changing inward force required for circular or helical motion, ruling out (A) and (B). The nonzero transverse force also rules out the undeflected motion in (D).

Step 3: Conclusion The electron describes a parabolic path, bending opposite to $\vec{E}$. Hence, the correct option is (C).

Quick Tip to Solve: For a uniform electric field perpendicular to the initial velocity, combine $x \propto t$ and $y \propto t^2$ to recognise a parabola.

8. A charged particle of mass m having kinetic energy K passes undeflected through a region with electric field $\vec{E}$ and magnetic field $\vec{B}$ acting perpendicular to each other. The mass m of the particle will be: [1 mark]

- (A) $\frac{KB^2}{2E^2}$
(B) $\frac{2KB^2}{E^2}$
(C) $\frac{2KE^2}{B^2}$
(D) $\frac{KE^2}{2B^2}$

Correct Answer: (B) $\frac{2KB^2}{E^2}$

Solution:

Concept:

- In a velocity selector, the electric force and magnetic force oppose each other. An undeflected particle satisfies $qE = qvB$, where v is its speed.
- The non-relativistic kinetic energy is $K = \frac{1}{2}mv^2$, where m is the particle mass.

Step 1: Balance the two forces For the particle to move straight through the crossed fields, the electric and magnetic forces must cancel. Equating their magnitudes and cancelling the nonzero charge gives

$$v = \frac{E}{B}.$$

Thus the selected speed is independent of the magnitude and sign of the charge.

Step 2: Substitute the selected speed Rearrange the kinetic-energy expression to isolate the mass, and then use the field ratio:

$$m = \frac{2K}{v^2} = \frac{2K}{(E/B)^2} = \frac{2KB^2}{E^2}.$$

Option (A) has an incorrect factor of $1/2$ instead of 2. Options (C) and (D) invert the squared field ratio; mass must be energy divided by speed squared, not multiplied by it.

Step 3: Conclusion The particle's mass is $m = \frac{2KB^2}{E^2}$. Hence, the correct option is (B).

Quick Tip to Solve: First find the selector speed E/B , then put its square in the denominator of $m = 2K/v^2$.

9. A rectangular loop of size $5\text{ cm} \times 8\text{ cm}$ is lying in the x - y plane in a uniform magnetic field $\vec{B} = (2.0\text{ T})\hat{k}$. The total magnetic flux linked with the loop is: [1 mark]

- (A) 80 Wb
(B) 16 Wb
(C) 8×10^{-2} Wb
(D) 8×10^{-3} Wb

Correct Answer: (D) 8×10^{-3} Wb

Solution:

Concept:

- Magnetic flux through a plane loop is $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos \theta$, where θ is the angle between the field and the area normal.
- For a rectangular loop, $A = lb$. Convert both side lengths to metres before calculating flux in webers.

Step 1: Find the area and its orientation The loop lies in the x - y plane, so its positive area normal points along $+\hat{k}$. The field also points along $+\hat{k}$; hence $\theta = 0^\circ$. Its area is

$$A = (5 \times 10^{-2})(8 \times 10^{-2}) = 4.0 \times 10^{-3} \text{ m}^2.$$

Step 2: Calculate the linked flux The field is uniform and perpendicular to the loop plane, so the flux magnitude is maximum:

$$\Phi_B = 2.0 \times 4.0 \times 10^{-3} \times \cos 0^\circ = 8.0 \times 10^{-3} \text{ Wb}.$$

Option (A) incorrectly uses the area in square centimetres as though it were in square metres. Option (C) has the wrong power of ten, while option (B) does not equal the field times the correctly converted area.

Step 3: Conclusion The total flux linked with the loop is $8 \times 10^{-3} \text{ Wb}$. Hence, the correct option is (D).

Quick Tip to Solve: A field along $\hat{k}$ is normal to the x - y plane; use BA , with $1 \text{ cm}^2 = 10^{-4} \text{ m}^2$.

10. Which of the following statements is *not* true for electric energy in ac form compared to that in dc form? [1 mark]

- (A) Production of ac is economical.
- (B) ac can be easily and efficiently converted from one voltage to the other.
- (C) ac can be transmitted economically over long distances.
- (D) ac is less dangerous.

Correct Answer: (D) ac is less dangerous.

Solution:

Concept:

- Alternating current changes with time and can produce the changing magnetic flux required for transformer action.
- Transmission losses are $P_{\text{loss}} = I^2 R$. Raising the transmission voltage reduces the current needed to transfer a given power and therefore reduces these losses.

Step 1: Check the stated advantages of ac Alternators allow economical generation of ac, so statement (A) is true. Transformers efficiently step ac voltage up or down, making statement (B) true. In the usual ac power system, stepping up the voltage before transmission lowers the current and line losses, which is the economic advantage described by statement (C).

Step 2: Assess the safety statement Alternation of the current does not make electrical contact safe. Both ac and dc can cause dangerous currents through the body; the effect depends on the voltage, current, duration and path. Thus the blanket assertion that ac is less dangerous is not a valid advantage of ac. The question asks for the statement that is *not* true, so the three established generation, conversion and transmission advantages are excluded.

Step 3: Conclusion The statement “ac is less dangerous” is not true as a general comparison. Hence, the correct option is (D).

Quick Tip to Solve: In ac-versus-dc advantage questions, connect economical transmission to transformers and reduced $I^2 R$ loss; do not infer greater safety.

11. The magnetic field in a plane electromagnetic wave travelling in glass ($n = 1.5$) is given by

$$B_y = (2 \times 10^{-7} \text{ T}) \sin(\alpha x + 1.5 \times 10^{11} t)$$

where x is in metres and t is in seconds. The value of α is:

[1 mark]

- (A) $0.5 \times 10^3 \text{ m}^{-1}$
- (B) $6.0 \times 10^2 \text{ m}^{-1}$
- (C) $7.5 \times 10^2 \text{ m}^{-1}$
- (D) $1.5 \times 10^3 \text{ m}^{-1}$

Correct Answer: (C) $7.5 \times 10^2 \text{ m}^{-1}$

Solution:

Concept:

- The phase speed of light in a medium of refractive index n is $v = c/n$, where $c = 3.0 \times 10^8 \text{ m s}^{-1}$.
- For a wave with phase $kx + \omega t$, the wave-number magnitude is $k = \omega/v$. The coefficient of time is angular frequency ω , not ordinary frequency.

Step 1: Identify the speed and angular frequency Comparing the given phase with $kx + \omega t$ gives $k = \alpha$ and $\omega = 1.5 \times 10^{11} \text{ rad s}^{-1}$. The wave speed in glass is

$$v = \frac{3.0 \times 10^8}{1.5} = 2.0 \times 10^8 \text{ m s}^{-1}.$$

Step 2: Calculate the spatial coefficient Use the phase-speed relation to obtain

$$\alpha = \frac{\omega}{v} = \frac{1.5 \times 10^{11}}{2.0 \times 10^8} = 7.5 \times 10^2 \text{ m}^{-1}.$$

The plus sign in the phase indicates propagation along negative x ; it does not make α negative. Option (A) results from using the vacuum speed instead of the glass speed. Options (B) and (D) do not satisfy $v = \omega/\alpha$ with the stated refractive index.

Step 3: Conclusion The required coefficient is $\alpha = 7.5 \times 10^2 \text{ m}^{-1}$. Hence, the correct option is (C).

Quick Tip to Solve: Read ω directly from the coefficient of t , then use $\alpha = n\omega/c$; no extra factor of 2π is needed.

12. The energy of an electron revolving in the n^{th} orbit in Bohr model of hydrogen atom is proportional to: [1 mark]

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

Correct Answer: (D) $\frac{1}{n^2}$

Solution:

Concept:

- In the Bohr model of hydrogen, the allowed orbit radius is $r_n = a_0 n^2$, where a_0 is the ground-state radius and n is the principal quantum number.
- The electron's total energy is $E_n = -e^2/(8\pi\epsilon_0 r_n)$. Its negative sign indicates a bound state relative to a free electron at infinity.

Step 1: Relate energy to orbit number The Coulomb attraction supplies the centripetal force, giving kinetic energy $e^2/(8\pi\epsilon_0 r_n)$. Adding the potential energy $-e^2/(4\pi\epsilon_0 r_n)$ yields the total energy in the concept formula. Substituting $r_n = a_0 n^2$ therefore gives

$$E_n = -\frac{e^2}{8\pi\epsilon_0 a_0} \frac{1}{n^2} = -\frac{13.6}{n^2} \text{ eV}.$$

Step 2: Compare the powers of the quantum number The constant of proportionality is negative, but the dependence on n is still inverse square. As n increases, the energy becomes less negative and approaches zero. The n^2 dependence in option (A) belongs to the radius. Neither the linear dependence in (B) nor the inverse-first-power dependence in (C) agrees with the Bohr energy expression.

Step 3: Conclusion The electron energy is proportional to $\frac{1}{n^2}$, with a negative proportionality constant. Hence, the correct option is (D).

Quick Tip to Solve: Keep the Bohr dependences distinct: radius varies as n^2 , whereas total energy is $-13.6/n^2$ eV.

13. Assertion (A): Energy is released when heavy nuclei undergo fission or light nuclei undergo fusion.
Reason (R): For heavy nuclei, binding energy per nucleon increases with increasing Z while for light nuclei, it decreases with increasing Z .

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- Binding energy is the energy needed to separate a nucleus into its nucleons. Larger binding energy per nucleon generally means greater nuclear stability.
- Nuclear reactions release energy when the total binding energy of the products exceeds that of the reactants: $Q = B_{\text{products}} - B_{\text{reactants}} > 0$.

Step 1: Evaluate the assertion Heavy nuclei can split into medium-mass nuclei with greater binding energy per nucleon. Light nuclei can combine to form a more tightly bound nucleus. In these energy-releasing fission and fusion reactions, the increase in total binding energy appears as released energy. Hence Assertion (A) is true.

Step 2: Evaluate the reason The broad binding-energy-per-nucleon curve rises through the light nuclei towards the iron region and then decreases gradually for heavier nuclei. Thus, across light nuclei it generally increases as nuclear size and Z increase; in the heavy region the broad trend is decreasing binding energy per nucleon. The reason states the opposite trends, so Reason (R) is false.

Step 3: Test the explanatory link The release of energy is explained by movement towards more tightly bound products, near the maximum of the binding-energy-per-nucleon curve. Since the printed reason reverses both trends, it cannot explain the assertion. Codes (A) and (B) require a true reason, while code (D) incorrectly declares the assertion false.

Step 4: Conclusion The assertion is true, but the reason is false. Hence, the correct option is (C).

Quick Tip to Solve: Picture the binding-energy peak near iron: light nuclei gain stability by fusing and heavy nuclei by splitting towards the peak.

14. Assertion (A): Photoelectric effect is a spontaneous phenomenon.

Reason (R): According to the wave picture of radiation, an electron would take hours/days to absorb sufficient energy to overcome the work function and come out from a metal surface.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- Photoemission starts without an appreciable delay when radiation of frequency at least the threshold frequency illuminates a suitable metal. A photon transfers its energy $h\nu$ to an electron in one interaction.
- The classical wave picture distributes energy continuously over the wavefront. At low intensity it predicts that an electron must accumulate energy for a long time before overcoming the work function ϕ .

Step 1: Evaluate the assertion Here the printed word “spontaneous” describes the prompt, effectively instantaneous onset of photoemission after suitable light falls on the metal. It does not mean emission without incident radiation. There is no appreciable accumulation time before emission when $h\nu \geq \phi$, so the assertion is true in this intended sense.

Step 2: Evaluate the reason In the classical wave model, an electron intercepts only a small part of the continuously distributed light energy. For sufficiently weak illumination, the predicted time to collect the work-function energy can be hours or days. Thus the reason correctly states a prediction of the wave picture, although that prediction disagrees with the observed prompt emission.

Step 3: Test the explanatory link A theory that predicts a long delay cannot explain an observation of negligible delay. Prompt emission is instead explained by the transfer of one photon’s energy to one electron. Therefore both statements are true in context, but the reason does not explain the assertion. Code (A) incorrectly claims an explanatory link, while (C) and (D) incorrectly classify the reason as false.

Step 4: Conclusion Both the assertion and the reason are true, but the reason is not the correct explanation of the assertion. Hence, the correct option is (B).

Quick Tip to Solve: Separate a true statement about a theory’s prediction from experimental truth: the wave model’s delay is precisely what it fails to explain.

15. Assertion (A): Induced emf produced in a coil will be more when the magnetic flux linked with the coil is more.

Reason (R): Induced emf produced is directly proportional to the magnetic flux.

Select the correct answer from the codes given below:

[1 mark]

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

Correct Answer: (D) Both Assertion (A) and Reason (R) are false.

Solution:

Concept:

- Faraday's law gives the induced emf in a coil of N turns as $\varepsilon = -N d\Phi/dt$, where Φ is the magnetic flux through each turn.
- The magnitude of emf depends on the rate of change of flux linkage, not on the instantaneous value of the flux. The negative sign expresses Lenz's law.

Step 1: Evaluate the assertion A larger magnetic flux does not necessarily produce a larger induced emf. For example, a coil linked with a large but constant flux has $d\Phi/dt = 0$, so its induced emf is zero. A smaller flux changing rapidly can produce a nonzero emf. Therefore Assertion (A) is false.

Step 2: Evaluate the reason Reason (R) states proportionality to magnetic flux itself. Faraday's law instead requires

$$|\varepsilon| = N \left| \frac{d\Phi}{dt} \right|.$$

Thus Reason (R) is also false: the time dependence of the flux must be known before the emf can be determined.

Step 3: Check the proposed explanation Since both statements confuse flux with its rate of change, the reason cannot explain a true assertion. Options (A) and (B) require both statements to be true, while option (C) requires a true assertion; all three are excluded.

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

Quick Tip to Solve: Test any claim about induced emf using a large constant flux: its time derivative and hence its induced emf are zero.

16. Assertion (A): In Young's double-slit experiment, the fringe width for dark and bright fringes is the same.

Reason (R): Fringe width is given by $\beta = \frac{\lambda D}{d}$, where symbols have their usual meanings.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- In Young's double-slit experiment, fringe width is the distance between two successive bright fringes or two successive dark fringes.
- For wavelength λ , slit separation d , and screen distance D , the small-angle result is $\beta = \lambda D/d$.

Step 1: Evaluate the assertion Bright fringes occur at $y_n = n\lambda D/d$, whereas dark fringes occur at $y_n = (n + \frac{1}{2})\lambda D/d$. In either sequence, increasing the integer n by one changes the position by $\lambda D/d$. Thus the bright and dark fringe widths are equal, so Assertion (A) is true.

Step 2: Evaluate the reason Reason (R) correctly states the common fringe-width formula:

$$\beta_{\text{bright}} = \beta_{\text{dark}} = \frac{\lambda D}{d}.$$

The quantities λ , D , and d are the same for both fringe sequences in the same experiment, so the reason is true.

Step 3: Check the explanatory link The stated formula applies to both bright and dark fringes and has the same value for each. It therefore directly explains their equal widths. Option (B) misses this explanatory link, while options (C) and (D) incorrectly treat at least one true statement as false.

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

Quick Tip to Solve: Measure fringe width between consecutive fringes of the same kind; a bright fringe and its nearest dark fringe are separated by $\beta/2$.

Section B (10 marks)

17. Suppose a pure Si crystal has 5×10^{28} atoms per m^3 . It is doped with 5×10^{22} atoms per m^3 of Arsenic. Calculate the majority and minority carrier concentration in the doped silicon. (Given: $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$) [2 marks]

Solution:

Concept:

- Arsenic is a pentavalent donor impurity in silicon. Each ionised donor supplies one conduction electron, producing an n-type semiconductor with electrons as majority carriers.
- At thermal equilibrium, the electron concentration n and hole concentration p obey the mass-action law $np = n_i^2$, where n_i is the intrinsic carrier concentration at the same temperature.

Step 1: Find the majority-carrier concentration Assume the arsenic donors are fully ionised. Their concentration is $N_D = 5 \times 10^{22} \text{ m}^{-3}$, much greater than $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$. Charge neutrality gives $n = N_D + p$; since the minority-hole concentration is very small, we use

$$n \simeq N_D = 5 \times 10^{22} \text{ m}^{-3}.$$

The given silicon atom density is the host-atom density, not the number of free carriers. The donor fraction is only 10^{-6} , so the doping is dilute even though it dominates the intrinsic carrier population.

Step 2: Calculate the minority-carrier concentration Use the mass-action law for holes in the doped crystal:

$$\begin{aligned} p &= \frac{n_i^2}{n} = \frac{(1.5 \times 10^{16})^2}{5 \times 10^{22}} \\ &= \frac{2.25 \times 10^{32}}{5 \times 10^{22}} = 4.5 \times 10^9 \text{ m}^{-3}. \end{aligned}$$

This is negligible compared with N_D , confirming the approximation used for n . Doping increases the electron population while reducing the equilibrium hole population.

Step 3: Conclusion The majority carriers are electrons, with $n \simeq 5 \times 10^{22} \text{ m}^{-3}$. The minority carriers are holes, with $p \simeq 4.5 \times 10^9 \text{ m}^{-3}$.

Quick Tip to Solve: For a pentavalent dopant with $N_D \gg n_i$, first set $n \simeq N_D$, then obtain holes from $p = n_i^2/n$; do not use the host-atom density as n .

18. In a Young's double-slit experiment, two waves each of intensity I superpose each other and produce an interference pattern. Prove that the resultant intensities at maxima and minima are $4I$ and zero respectively. [2 marks]

Solution:

Concept:

- Coherent waves superpose with a stable phase difference. For waves of intensities I_1 and I_2 and phase difference ϕ , the resultant intensity is $I_R = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$.
- Constructive interference occurs when $\phi = 2m\pi$, and destructive interference occurs when $\phi = (2m + 1)\pi$, where m is an integer. Intensity is proportional to the square of wave amplitude.

Step 1: Substitute the equal incident intensities In this experiment each wave has intensity I , so

$I_1 = I_2 = I$. Substitution into the interference formula gives

$$\begin{aligned} I_R &= I + I + 2\sqrt{I \cdot I} \cos \phi \\ &= 2I(1 + \cos \phi) = 4I \cos^2 \left(\frac{\phi}{2} \right). \end{aligned}$$

The phase-dependent term describes the reinforcement or cancellation of the waves at different screen positions.

Step 2: Evaluate the intensity at a maximum At a bright fringe the waves arrive in phase, so $\cos \phi = 1$. Hence

$$I_{\max} = 2I(1 + 1) = 4I.$$

Equivalently, two equal amplitudes add to twice the individual amplitude; squaring gives four times the individual intensity.

Step 3: Evaluate the intensity at a minimum At a dark fringe the waves have opposite phases, so $\cos \phi = -1$. Therefore

$$I_{\min} = 2I(1 - 1) = 0.$$

Because the amplitudes are equal, cancellation is complete. The bright and dark regions represent redistribution of energy across the interference pattern.

Step 4: Conclusion The resultant intensity is $I_{\max} = 4I$ at maxima and $I_{\min} = 0$ at minima, as required.

Quick Tip to Solve: For equal interfering waves, add or subtract amplitudes before squaring: doubled amplitude gives $4I$, while complete cancellation gives zero.

19(a). An electric iron rated 2.2 kW, 220 V is operated at 110 V supply. Find:

(i) its resistance, and

(ii) heat produced by it in 10 minutes.

[2 marks]

Solution:

Concept:

- For a resistive appliance, electrical power is $P = V^2/R$, where V is the potential difference and R is its resistance. The rated power applies at the rated voltage.
- Joule's law gives heat produced in time t as $H = Pt = V^2t/R$. Treat the heating element's resistance as constant, as in the usual rated-appliance calculation.

Step 1: Calculate the resistance from the rating The iron's rating means that it consumes $P_r = 2.2 \text{ kW} = 2200 \text{ W}$ when connected to $V_r = 220 \text{ V}$. Therefore its resistance is

$$R = \frac{V_r^2}{P_r} = \frac{220^2}{2200} = 22 \Omega.$$

The resistance must be determined using the rated voltage and rated power together.

Step 2: Find the power at the actual supply voltage The operating voltage is $V = 110 \text{ V}$. Using the

same resistance, the actual power is

$$P = \frac{V^2}{R} = \frac{110^2}{22} = 550 \text{ W}.$$

Halving the voltage reduces power to one quarter because power depends on the square of voltage at fixed resistance.

Step 3: Calculate the heat produced in ten minutes Convert the operating time to seconds: $t = 10 \times 60 = 600 \text{ s}$. The electrical energy converted into heat is

$$H = Pt = 550 \times 600 = 3.3 \times 10^5 \text{ J}.$$

Use the actual power of 550 W in this calculation, since the iron is operating below its rated voltage.

Step 4: Conclusion (i) The iron's resistance is 22Ω . (ii) The heat produced in ten minutes at 110 V is $3.3 \times 10^5 \text{ J}$, or 330 kJ.

Quick Tip to Solve: At fixed resistance, half the rated voltage gives one quarter of the rated power; multiply that reduced power by time in seconds.

OR

19(b). A current of 4.0 A flows through a wire of length 1 m and cross-sectional area 1.0 mm^2 , when potential difference of 2 V is applied across its ends. Calculate the resistivity of the material of the wire. [2 marks]

Solution:

Concept:

- Ohm's law gives the resistance of the wire as $R = V/I$, where V is the potential difference and I is the current.
- For a uniform wire, $R = \rho l/A$, where ρ is the material's resistivity, l its length and A its cross-sectional area. Thus $\rho = RA/l$.

Step 1: Express the area in SI units The given area is already a cross-sectional area, so no radius or diameter calculation is needed. Since $1 \text{ mm} = 10^{-3} \text{ m}$, the conversion factor must be squared:

$$A = 1.0 \text{ mm}^2 = 1.0 \times 10^{-6} \text{ m}^2, \quad l = 1 \text{ m}.$$

Step 2: Calculate the resistance and substitute First use the measured voltage and current to obtain the resistance of this particular wire. Then remove the dependence on its dimensions using $\rho = RA/l$:

$$R = \frac{2}{4.0} = 0.50 \Omega,$$
$$\rho = \frac{0.50 \times 1.0 \times 10^{-6}}{1} = 5.0 \times 10^{-7} \Omega \text{ m}.$$

The unit is $\Omega \text{ m}^2/\text{m} = \Omega \text{ m}$, as required for resistivity.

Step 3: Conclusion The resistivity of the material of the wire is $\rho = 5.0 \times 10^{-7} \Omega \text{ m}$.

Quick Tip to Solve: Use $\rho = VA/(Il)$ directly, but first convert mm^2 to m^2 with the factor 10^{-6} , not 10^{-3} .

20. A square loop of side 10 cm, free to rotate about a vertical axis coinciding with its one arm, is initially held perpendicular to a uniform horizontal magnetic field of 0.2 T. If it is rotated at the uniform speed of 60 rpm, find the emf induced in the loop. [2 marks]

Solution:

Concept:

- Magnetic flux through a single planar loop is $\Phi = BA \cos \theta$, where θ is the angle between the magnetic field and the loop's area normal.
- Faraday's law gives $\varepsilon = -d\Phi/dt$. For uniform rotation at angular speed ω , the peak emf is $\varepsilon_0 = BA\omega$.

Step 1: Find the area and angular speed The square has side $a = 10 \text{ cm} = 0.10 \text{ m}$. Convert revolutions per minute into revolutions per second before calculating the angular speed:

$$A = a^2 = (0.10)^2 = 1.0 \times 10^{-2} \text{ m}^2,$$
$$f = \frac{60}{60} = 1 \text{ Hz}, \quad \omega = 2\pi f = 2\pi \text{ rad s}^{-1}.$$

Step 2: Differentiate the time-dependent flux Initially the plane of the loop is perpendicular to the field, so its area normal is parallel to the field and the flux is maximum. Taking this instant as $t = 0$, and choosing the initial area normal along the field, gives

$$\Phi(t) = BA \cos(\omega t), \quad \varepsilon(t) = BA\omega \sin(\omega t).$$

Rotation about an edge changes the orientation of the whole area just as rotation about a parallel central axis would. Thus the emf amplitude is

$$\varepsilon_0 = (0.2)(1.0 \times 10^{-2})(2\pi) = 4\pi \times 10^{-3} \text{ V}.$$

The emf is zero initially because the flux has an extremum then; it is not a constant emf during rotation.

Step 3: Conclusion With t in seconds, $\varepsilon(t) = 4\pi \times 10^{-3} \sin(2\pi t) \text{ V}$. Its maximum magnitude is $\varepsilon_0 \simeq 1.26 \times 10^{-2} \text{ V} = 12.6 \text{ mV}$. Reversing the chosen loop polarity reverses the sign of the emf.

Quick Tip to Solve: When the loop starts perpendicular to the field, write flux as a cosine and emf as a sine: maximum initial flux means zero initial emf.

21. A point source, in air, is placed at a distance of 6 cm in front of a convex spherical surface ($n = 1.5$ and radius of curvature = 24 cm). Find the position and nature of the image formed. [2 marks]

Solution:

Concept:

- For paraxial refraction at a spherical surface, $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$. Here u , v and R are measured from the pole of the surface.
- In the Cartesian sign convention, distances along the incident light are positive. A negative image distance places the image on the incident side; for the refracted rays this is a virtual image.

Step 1: Assign the signs of the distances Take light to travel from the source in air towards the refracting medium. The object is before the pole, so $u = -6$ cm. The surface is convex towards the source, placing its centre of curvature inside the medium on the positive side:

$$n_1 = 1, \quad n_2 = 1.5, \quad R = +24 \text{ cm.}$$

All distances may be kept in centimetres because the same unit is used throughout the refraction formula.

Step 2: Solve the spherical-refraction equation Substitute the signed distances rather than their unsigned magnitudes:

$$\begin{aligned} \frac{1.5}{v} - \frac{1}{-6} &= \frac{1.5 - 1}{24}, \\ \frac{1.5}{v} &= \frac{1}{48} - \frac{1}{6} = -\frac{7}{48}, \\ v &= -\frac{72}{7} \text{ cm} \simeq -10.3 \text{ cm.} \end{aligned}$$

The negative result means that the emergent rays remain divergent; their backward extensions meet on the air side of the surface. They do not actually meet at that point.

Step 3: Conclusion The image is 10.3 cm in front of the spherical surface, on the same side as the source. It is virtual, with signed image distance $v = -10.3$ cm.

Quick Tip to Solve: For a convex surface viewed from air, use $u < 0$ and $R > 0$; decide whether the image is real or virtual from the calculated sign of v .

Section C (21 marks)

22. (a) Differentiate between inductive reactance, capacitive reactance and impedance of an ac circuit.
(b) An ideal inductor and an ideal capacitor are connected in series across an ac voltage. Plot a graph showing variation of net reactance of the circuit with frequency of the applied ac voltage. [3 marks]

Solution:

Concept:

- Reactance is opposition to alternating current caused by energy storage in an inductor or capacitor. For angular frequency $\omega = 2\pi f$, its magnitudes are $X_L = \omega L$ and $X_C = 1/(\omega C)$, where L is inductance and C is capacitance.
- Impedance $Z = V_{\text{rms}}/I_{\text{rms}}$ describes the total opposition to ac. For a series RLC circuit, $Z = \sqrt{R^2 + (X_L - X_C)^2}$; resistance, reactance and impedance all have SI unit ohm (Ω).

Step 1: Compare inductive reactance, capacitive reactance and impedance (a) Inductive reactance: $X_L = 2\pi fL$ is the opposition due to an inductor. It increases linearly with frequency. In an ideal inductor, current lags voltage by $\pi/2$, and energy is stored in its magnetic field.

Capacitive reactance: $X_C = 1/(2\pi fC)$ is the opposition due to a capacitor. It decreases as frequency increases. In an ideal capacitor, current leads voltage by $\pi/2$, and energy is stored in its electric field.

Impedance: Unlike either individual reactance, impedance accounts for the combined effect of resistance and net reactance. For series elements its magnitude is $\sqrt{R^2 + (X_L - X_C)^2}$, not the arithmetic sum $R + X_L + X_C$, because the corresponding voltages differ in phase. Ideal reactances do not dissipate average power; a resistance does.

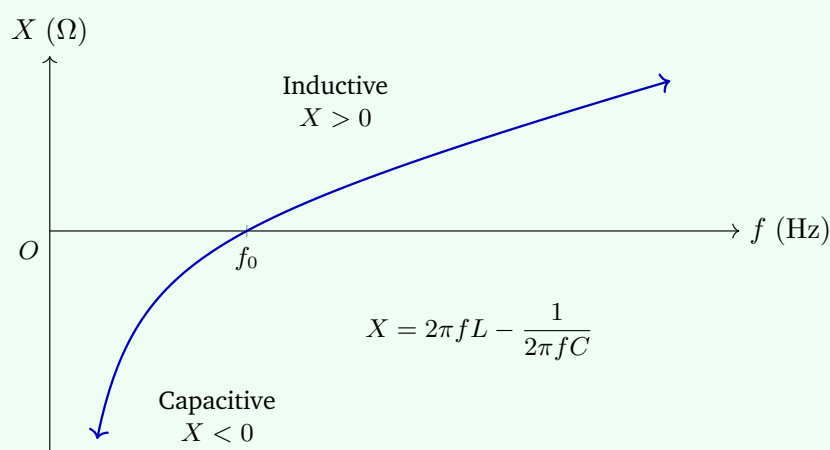
Step 2: Establish the signed net reactance and its graph (b) In the ideal series LC circuit, inductive and capacitive contributions have opposite signs. Taking inductive reactance as positive,

$$X(f) = X_L - X_C = 2\pi fL - \frac{1}{2\pi fC}.$$

At low positive frequency the capacitive term dominates, so $X \rightarrow -\infty$ as $f \rightarrow 0^+$. At high frequency the inductive term dominates and X grows positively. The zero crossing occurs when

$$2\pi f_0 L = \frac{1}{2\pi f_0 C} \Rightarrow f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

The slope $dX/df = 2\pi L + 1/(2\pi C f^2)$ is positive throughout: the curve rises continuously through f_0 . It approaches the straight line $X = 2\pi Lf$ at high frequency. The sketch shows signed reactance; the impedance magnitude of this ideal circuit is $Z = |X|$.



Signed net reactance of a series LC circuit; $f_0 = 1/(2\pi\sqrt{LC})$.

Step 3: Conclusion X_L increases with frequency, X_C decreases with frequency, and impedance gives the total ac opposition. For the series LC circuit, the net reactance is negative for $f < f_0$, zero at $f_0 = 1/(2\pi\sqrt{LC})$, and positive for $f > f_0$, as plotted.

Quick Tip to Solve: Plot $X_L - X_C$ with its sign: start below the frequency axis, cross at resonance, and rise above it. Taking an absolute value would instead plot impedance.

23. Two parallel plate capacitors X and Y are connected in series to a 6 V battery. They have the same plate area and same plate separation but capacitor X has air between its plates, whereas capacitor Y contains a material of dielectric constant 4.

(a) Calculate the capacitances of X and Y , if the equivalent capacitance of the combination of X and Y is $4\ \mu\text{F}$.

(b) Calculate the potential difference across the plates of X and Y .

[3 marks]

Solution:

Concept:

- For a parallel plate capacitor, $C = K\epsilon_0 A/d$, where K is the dielectric constant, A is the plate area and d is the separation. Identical geometry makes capacitance proportional to K .
- Capacitors in series carry the same charge magnitude Q . Their equivalent capacitance satisfies $1/C_{\text{eq}} = 1/C_X + 1/C_Y$, and each voltage is $V = Q/C$.

Step 1: Relate the two capacitances Air has dielectric constant approximately 1, whereas the dielectric in Y has dielectric constant 4. Since the two capacitors have equal plate areas and separations,

$$C_X = \frac{\epsilon_0 A}{d}, \quad C_Y = \frac{4\epsilon_0 A}{d} = 4C_X.$$

Thus the dielectric increases the capacitance of Y to four times that of X ; it does not change the series connection into a parallel one.

Step 2: Calculate the capacitances for part (a) Substitute this relation into the series formula, using

the stated equivalent capacitance:

$$C_{\text{eq}} = \frac{C_X C_Y}{C_X + C_Y} = \frac{C_X (4C_X)}{5C_X} = \frac{4}{5} C_X,$$

$$C_X = \frac{5}{4} (4 \mu\text{F}) = 5 \mu\text{F},$$

$$C_Y = 4(5 \mu\text{F}) = 20 \mu\text{F}.$$

As a check, the equivalent capacitance $4 \mu\text{F}$ is smaller than either individual capacitance, as required for series capacitors.

Step 3: Find the common charge and voltages for part (b) The battery places 6 V across the combination, so the charge magnitude on each capacitor is

$$Q = C_{\text{eq}} V = (4 \mu\text{F})(6 \text{ V}) = 24 \mu\text{C}.$$

Divide this same charge by each capacitance:

$$V_X = \frac{24 \mu\text{C}}{5 \mu\text{F}} = 4.8 \text{ V},$$

$$V_Y = \frac{24 \mu\text{C}}{20 \mu\text{F}} = 1.2 \text{ V}.$$

Their sum is $4.8 + 1.2 = 6.0 \text{ V}$, equal to the battery voltage. The smaller capacitor has the larger voltage because the series charge is common.

Step 4: Conclusion (a) $C_X = 5 \mu\text{F}$ and $C_Y = 20 \mu\text{F}$. (b) The potential differences are $V_X = 4.8 \text{ V}$ and $V_Y = 1.2 \text{ V}$.

Quick Tip to Solve: For identical capacitor geometry, first use $C_Y/C_X = K$. In series the voltage ratio is the inverse capacitance ratio, so $V_X : V_Y = 4 : 1$.

24(a). (i) Write any two features of nuclear forces.

(ii) If both the number of protons and the neutrons are conserved in each nuclear reaction, in what way is mass converted into energy (or vice versa) in a nuclear reaction? Explain. [3 marks]

Solution:

Concept:

- Nuclear forces bind protons and neutrons into nuclei. They are very strong over nuclear distances but have a very short range.
- The binding energy B is the energy required to separate a nucleus into free nucleons. Its rest mass is $M = Zm_p + Nm_n - B/c^2$, where Z and N count protons and neutrons, and m_p , m_n are their free rest masses.
- A reaction conserves total energy, including rest energy. Its energy release is $Q = (M_{\text{initial}} - M_{\text{final}})c^2$, using the total rest masses of all initial and final particles.

Step 1: State two features of nuclear forces for part (i) **Short range:** Nuclear forces act effectively only across distances of a few femtometres, where $1 \text{ fm} = 10^{-15} \text{ m}$; they become negligible at larger separations. Their attractive part holds neighbouring nucleons together.

Approximate charge independence: The nuclear interaction between two protons, two neutrons, or

a proton and a neutron is approximately the same for comparable states. This statement concerns the nuclear interaction itself; protons additionally experience electrostatic repulsion.

Step 2: Identify the changing quantity in part (ii) Conservation of the numbers of protons and neutrons fixes the sum of their *free* rest masses. It does not fix the rest mass of each bound nuclear system, because that mass also includes its negative binding contribution. Nucleons are rearranged into nuclei with different binding energies during a reaction.

Let B_i and B_f be the total binding energies before and after the reaction. Under the stated conservation of both nucleon counts, the free-nucleon mass terms cancel, giving

$$M_i - M_f = \frac{B_f - B_i}{c^2},$$

$$Q = (M_i - M_f)c^2 = B_f - B_i.$$

Thus an increase in total binding energy means a decrease in total rest mass.

Step 3: Explain energy release and energy absorption If the products are more tightly bound in total, $B_f > B_i$, then $Q > 0$. The decrease in rest energy appears as kinetic energy of the products and/or emitted radiation. No nucleon has to disappear.

Conversely, producing a system with smaller total binding energy requires energy input: $B_f < B_i$ and $Q < 0$. Part of the supplied energy becomes increased rest energy of the products. Total mass-energy is conserved in both directions, although the sum of rest masses need not be conserved.

Step 4: Conclusion Nuclear forces are short-ranged and approximately charge-independent. Even with unchanged proton and neutron counts, changes in nuclear binding energy alter the total rest mass; the corresponding energy transfer is $Q = (M_i - M_f)c^2$.

Quick Tip to Solve: Keep nucleon count separate from bound nuclear mass: $M = \text{free-nucleon mass} - B/c^2$. Greater total binding energy means smaller rest mass and positive energy release.

OR

24(b). (i) Draw the number of scattered particles versus the scattering angle graph for scattering of alpha particles by a thin foil. Write two important conclusions that can be drawn from this plot.

(ii) If Bohr's quantization postulate (angular momentum $= \frac{nh}{2\pi}$) is a basic law of nature, it should be equally valid for the case of planetary motion also. Why, then, do we never speak of quantization of orbits of planets around the Sun? Explain. [3 marks]

Solution:

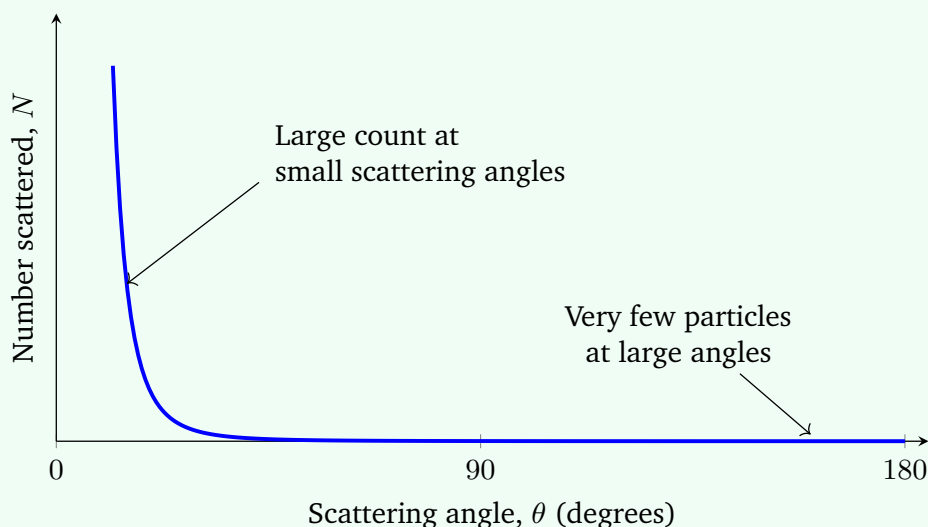
Concept:

- In Rutherford scattering, most incident α -particles pass through a thin metal foil with little deflection, while very few scatter through large angles. For equal detector solid angles, the scattered count follows $N(\theta) \propto 1/\sin^4(\theta/2)$.
- Bohr's postulate gives $L = n\hbar$, where L is orbital angular momentum, n is a positive integer and $\hbar = h/(2\pi)$. Adjacent allowed values differ by the extremely small quantity $\hbar$.

Step 1: Sketch the scattering distribution for part (i) Plot the number N of scattered α -particles vertically and scattering angle θ horizontally. The curve is very high near the forward direction and decreases rapidly as θ increases. A small nonzero number is scattered even through very large angles,

including backward directions near 180° .

The figure shows the qualitative variation; the vertical scale is arbitrary. Only the measurable angular range away from 0° is drawn, since the ideal Rutherford expression diverges at exactly zero angle.



Number of scattered α -particles versus scattering angle (arbitrary vertical scale).

Step 2: State two conclusions from the plot **Most of an atom is empty space.** The large number of particles that pass nearly straight through shows that most trajectories encounter little deflecting force.

Positive charge and almost all atomic mass occupy a very small, dense nucleus. The rare large-angle and backward deflections require a strong repulsive force concentrated in a tiny region. Their rarity shows that this region occupies only a very small fraction of the atom's volume.

Step 3: Compare planetary angular momentum with the quantum spacing for part (ii) For a planet, the large mass and orbital dimensions make its angular momentum L enormously greater than $\hbar$. If the stated quantization rule is applied, then

$$n = \frac{L}{\hbar} \gg 1, \quad \frac{\Delta L}{L} = \frac{\hbar}{L} = \frac{1}{n} \ll 1.$$

Therefore successive allowed angular momenta are indistinguishably close on a planetary scale. For circular gravitational orbits, $L = m\sqrt{GMr}$; combining this with $L = n\hbar$ gives $r \propto n^2$, and hence

$$\frac{r_{n+1} - r_n}{r_n} = \frac{2n + 1}{n^2} \approx \frac{2}{n}.$$

The relative spacing of planetary orbital radii would thus be far too small to resolve. The allowed orbits appear continuous, so classical mechanics successfully describes the observed motion.

Step 4: Conclusion The scattering curve falls steeply with angle: it indicates a mostly empty atom with a tiny, dense, positively charged nucleus. Quantization of planetary motion is unobservable because the quantum spacing is negligible compared with planetary angular momenta and orbital dimensions.

Quick Tip to Solve: Link the many small deflections to empty space and the rare backward deflections to a compact nucleus. For macroscopic quantization, compare $\hbar$ with L , using $\Delta L/L = 1/n$.

25. Photoemission of electrons occurs from a metal ($\phi_0 = 1.96$ eV) when light of frequency 6.4×10^{14} Hz is incident on it. Calculate:

- (a) Energy of a photon in the incident light,
- (b) The maximum kinetic energy of the emitted electrons, and
- (c) The stopping potential.

[3 marks]

Solution:

Concept:

- A photon of frequency ν has energy $E_\gamma = h\nu$, where h is Planck's constant. Here $h = 6.63 \times 10^{-34}$ J s.
- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi_0$, where ϕ_0 is the minimum energy needed to remove an electron from the metal surface.
- The stopping potential magnitude V_s satisfies $eV_s = K_{\max}$. Use $e = 1.6 \times 10^{-19}$ C and $1 \text{ eV} = 1.6 \times 10^{-19}$ J.

Step 1: Calculate the incident photon energy For part (a), multiply the given frequency by Planck's constant. This gives the energy carried by each photon, rather than the total energy in the incident beam:

$$\begin{aligned} E_\gamma &= (6.63 \times 10^{-34})(6.4 \times 10^{14}) \\ &= 4.2432 \times 10^{-19} \text{ J.} \end{aligned}$$

To compare this with the work function stated in electron-volts, convert the photon energy:

$$E_\gamma = \frac{4.2432 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.652 \text{ eV.}$$

Step 2: Apply energy conservation to the emitted electron For part (b), the photon first supplies the work function 1.96 eV; the remaining energy is the greatest kinetic energy an emitted electron can have. Since $2.652 > 1.96$, emission is energetically possible. Thus

$$\begin{aligned} K_{\max} &= 2.652 - 1.96 = 0.692 \text{ eV} \\ &= 0.692(1.6 \times 10^{-19}) \\ &= 1.1072 \times 10^{-19} \text{ J.} \end{aligned}$$

Step 3: Find the retarding potential needed to stop the fastest electrons For part (c), the electric field must remove the entire maximum kinetic energy. The positive magnitude of the stopping potential is

$$V_s = \frac{K_{\max}}{e} = \frac{1.1072 \times 10^{-19}}{1.6 \times 10^{-19}} = 0.692 \text{ V.}$$

The collector is maintained negative relative to the emitting surface so that this potential retards the photoelectrons.

Step 4: Conclusion (a) $E_\gamma \approx 4.24 \times 10^{-19}$ J (2.65 eV); (b) $K_{\max} \approx 0.69 \text{ eV} = 1.11 \times 10^{-19}$ J; (c) the stopping potential magnitude is $V_s \approx 0.69$ V.

Quick Tip to Solve: Subtract the work function only after expressing both energies in the same unit. The numerical value of $K_{\max}$ in eV directly gives the stopping potential in volts.

26. Write the expression for the magnetic field due to a current element in vector form. Consider a 1 cm segment of a wire, centered at the origin, carrying a current of 10 A in positive x -direction. Calculate the magnetic field $\vec{B}$ at a point (1 m, 1 m, 0). [3 marks]

Solution:

Concept:

- The vector form of the Biot–Savart law is $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \vec{r}}{r^3}$. Here $d\vec{\ell}$ points along the current and $\vec{r}$ points from the current element to the observation point.
- For a sufficiently short wire segment, its field is approximately $\vec{B} = \frac{\mu_0}{4\pi} \frac{I \Delta\vec{\ell} \times \vec{r}}{r^3}$, using the displacement from its centre. In free space, $\mu_0/(4\pi) = 10^{-7} \text{ T m A}^{-1}$.

Step 1: Express the wire length and displacement as vectors Convert the wire length into SI units: 1 cm = 10^{-2} m. Since the current flows along the positive x -axis, the directed segment length is

$$\Delta\vec{\ell} = 10^{-2}\hat{i} \text{ m}.$$

The segment is centred at the origin, while the observation point is (1 m, 1 m, 0). Therefore

$$\vec{r} = (\hat{i} + \hat{j}) \text{ m}, \quad r = \sqrt{1^2 + 1^2} = \sqrt{2} \text{ m}.$$

The length 0.01 m is much smaller than this distance, so the short-current-element approximation is appropriate.

Step 2: Evaluate the cross product and identify the direction The part of $\vec{r}$ parallel to the wire contributes nothing to the cross product. Using $\hat{i} \times \hat{j} = \hat{k}$,

$$\Delta\vec{\ell} \times \vec{r} = 10^{-2}\hat{i} \times (\hat{i} + \hat{j}) = 10^{-2}\hat{k} \text{ m}^2.$$

Thus the field is perpendicular to the xy -plane, along the positive z -axis, consistent with the right-hand rule for current in the positive x -direction.

Step 3: Substitute in the Biot–Savart expression Insert $I = 10 \text{ A}$ and $r^3 = (\sqrt{2})^3 = 2\sqrt{2} \text{ m}^3$:

$$\begin{aligned} \vec{B} &\simeq 10^{-7} \frac{10 \times 10^{-2}}{2\sqrt{2}} \hat{k} \text{ T} \\ &= \frac{10^{-8}}{2\sqrt{2}} \hat{k} \text{ T}. \end{aligned}$$

Both the distance factor and the cross product are needed; replacing the latter by the product of magnitudes would omit the angle between the wire and $\vec{r}$.

Step 4: Conclusion The magnetic field is $\boxed{\vec{B} \simeq 3.54 \times 10^{-9} \hat{k} \text{ T}}$, directed along the positive z -axis.

The required vector law is $d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{\ell} \times \vec{r}}{r^3}$.

Quick Tip to Solve: Use $\Delta\vec{\ell} \times \vec{r}$ to obtain the direction first. With this form the denominator is r^3 ; use r^2 only when the numerator contains the unit vector $\hat{r}$.

27. Differentiate between conduction current and displacement current. A capacitor is connected across a source providing time-dependent current. Explain how the total current at an instant is the sum of conduction current and displacement current in the circuit at that instant. [3 marks]

Solution:

Concept:

- Conduction current $i_c = dQ/dt$ is the rate of free-charge transport through a surface.
- Displacement current in vacuum is $i_d = \epsilon_0 d\Phi_E/dt$, where Φ_E is electric flux and ϵ_0 is the permittivity of free space.
- Maxwell's law, $\oint \vec{B} \cdot d\vec{\ell} = \mu_0(i_c + i_d)$, includes both currents through the same surface.

Step 1: Distinguish the two kinds of current Conduction current requires mobile charges crossing a surface, as in metallic wires. Displacement current requires changing electric flux and can occur in vacuum or an insulating gap without free charges crossing it. Both produce magnetic fields. Conduction current can persist under a constant electric field; displacement current vanishes when the flux is constant.

Step 2: Relate the charging current to the changing field between the plates Consider an ideal parallel-plate capacitor with plate area A , charge magnitude $Q(t)$, and vacuum between its plates. Neglect edge effects. The conduction current in a connecting wire is $i_c(t) = dQ/dt$. Charge accumulating on the plates changes the field and flux in the gap:

$$E(t) = \frac{Q(t)}{\epsilon_0 A}, \quad \Phi_E(t) = E(t)A = \frac{Q(t)}{\epsilon_0}.$$

Hence the displacement current through a surface between the plates is

$$i_d(t) = \epsilon_0 \frac{d\Phi_E}{dt} = \epsilon_0 \frac{d}{dt} \left(\frac{Q(t)}{\epsilon_0} \right) = \frac{dQ}{dt}.$$

It therefore has the same instantaneous value as the conduction current supplying the capacitor, even when that current varies with time.

Step 3: Apply the total-current relation consistently Maxwell's law counts both contributions through one surface spanning the chosen Amperian loop:

$$i_{\text{total}}(t) = i_c(t) + i_d(t).$$

In the ideal circuit approximation, a surface cutting the wire has conduction current with negligible displacement contribution. A surface through the capacitor gap has zero conduction current and the equal displacement current. Both give the same total current and magnetic circulation. These equal wire and gap currents refer to different surfaces, so they must not be added to obtain twice the circuit current.

Step 4: Conclusion Thus $i_{\text{total}} = i_c + i_d$ through a given surface. In a charging ideal capacitor, $i_d = dQ/dt$ in the gap equals the conduction current in the wire, preserving current continuity.

Quick Tip to Solve: Specify the surface before using $i_c + i_d$: the wire carries conduction current, while the capacitor gap carries the corresponding displacement current. Do not add currents evaluated on these two different surfaces.

28. What are de Broglie waves? Show that the wavelength of the electromagnetic radiation is equal to the de Broglie wavelength of its quantum (photon). [3 marks]

Solution:

Concept:

- De Broglie's hypothesis associates a wave with every moving material particle. Its wavelength is $\lambda_{\text{dB}} = h/p$, where h is Planck's constant and p is the magnitude of the particle's momentum.
- A photon of frequency ν has energy $E = h\nu$ and momentum $p = E/c$. For electromagnetic radiation in vacuum, $c = \nu\lambda$, where c is the speed of light and λ is its wavelength.

Step 1: Define de Broglie waves The waves associated with moving material particles are called de Broglie waves or matter waves. They express the wave nature of matter and account for phenomena such as electron diffraction. For a particle moving slowly compared with the speed of light, $p = mv$, so

$$\lambda_{\text{dB}} = \frac{h}{p} = \frac{h}{mv}.$$

Here m is the particle's mass and v its speed. Matter waves are not electromagnetic waves; the relation h/p describes the wavelength associated with a particle's momentum.

Step 2: Express the photon's momentum using its frequency A photon has zero rest mass but nonzero energy and momentum. Thus the nonrelativistic formula $p = mv$ must not be applied to it. Use the energy-momentum relation for a photon instead:

$$E = pc, \quad E = h\nu \quad \Rightarrow \quad p = \frac{h\nu}{c}.$$

Step 3: Apply the de Broglie relation to the photon Substituting the photon's momentum in $\lambda_{\text{dB}} = h/p$ gives

$$\lambda_{\text{dB}} = \frac{h}{h\nu/c} = \frac{c}{\nu}.$$

Independently, the wave relation for the electromagnetic radiation gives

$$c = \nu\lambda \quad \Rightarrow \quad \lambda = \frac{c}{\nu}.$$

Both expressions therefore have the same value for the same frequency.

Step 4: Conclusion De Broglie waves are the matter waves associated with moving material particles. For a photon, $\lambda_{\text{dB}} = h/p = c/\nu = \lambda$; its de Broglie wavelength equals the wavelength of the electromagnetic radiation of which it is a quantum.

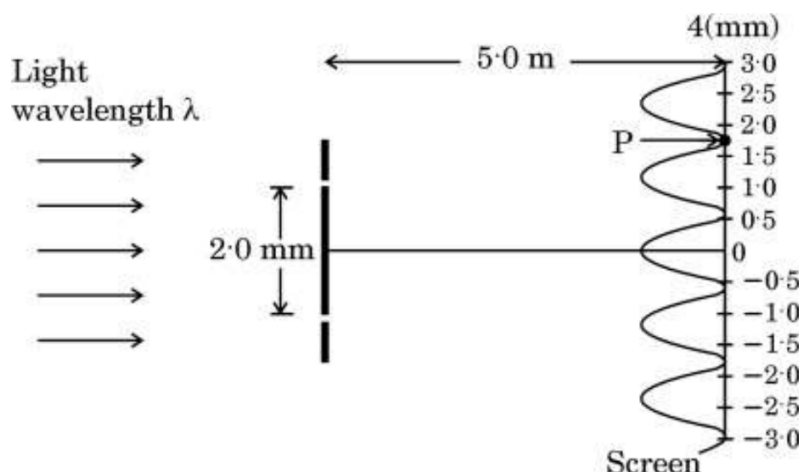
Quick Tip to Solve: For a photon, start with $p = E/c$ and $E = h\nu$; do not substitute zero rest mass into $p = mv$.

Section D (8 marks)

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

29. In a Young's double-slit experiment, the two slits behave as coherent sources. When coherent light waves superpose over each other they create an interference pattern of successive bright and dark regions due to constructive and destructive interference.

Two slits 2 mm apart are illuminated by a source of monochromatic light and the interference pattern is observed on a screen 5.0 m away from the slits as shown in the figure. [4 marks]



29(i). What property of light does this interference experiment demonstrate? [1 mark]

- (A) Wave nature of light
- (B) Particle nature of light
- (C) Transverse nature of light
- (D) Both wave nature and transverse nature of light

Correct Answer: (A) Wave nature of light

Solution:

Concept:

- Interference is the redistribution of intensity produced by the superposition of coherent waves, which have the same frequency and a constant phase difference.
- Constructive and destructive superposition produce bright and dark fringes. Polarisation, rather than interference alone, establishes the transverse nature of a wave.

Step 1: Identify the evidence in the experiment The two slits produce alternate bright and dark regions. At a bright fringe the wave amplitudes reinforce, while at a dark fringe they cancel. This dependence on the relative phase is a characteristic wave phenomenon, so Young's experiment demonstrates the wave nature of light.

Step 2: Compare the other alternatives Option (B) refers to particle behaviour, which does not

account for these alternating interference fringes in a classical particle picture. Both longitudinal and transverse waves can interfere, so interference alone does not establish transverse nature. Hence (C) is unsupported, and (D) adds a claim that this experiment does not demonstrate.

Step 3: Conclusion Young's double-slit interference experiment demonstrates the wave nature of light. Hence, the correct option is (A).

Quick Tip to Solve: Associate interference with wave nature and polarisation with transverse nature when distinguishing these options.

29(ii)(a). The wavelength of light used in this experiment is:

[1 mark]

- (A) 720 nm
- (B) 590 nm
- (C) 480 nm
- (D) 364 nm

Correct Answer: (C) 480 nm

Solution:

Concept:

- In Young's double-slit experiment the fringe width is $\beta = \lambda D/d$, where d is slit separation, D is screen distance and λ is wavelength.
- Fringe width is the spacing between successive bright fringes or successive dark fringes; it is not the spacing from a bright fringe to its adjacent dark fringe.

Step 1: Read the fringe width from the plot The central bright fringe is at zero displacement. The next bright fringe is at approximately 1.2 mm; equivalently, the dark fringes occur at approximately 0.6 mm and 1.8 mm. Thus the common spacing is $\beta = 1.2$ mm. The given separations are $d = 2.0$ mm and $D = 5.0$ m.

Step 2: Calculate the wavelength and compare the choices Convert both millimetre lengths to metres before substitution:

$$\lambda = \frac{\beta d}{D} = \frac{(1.2 \times 10^{-3})(2.0 \times 10^{-3})}{5.0} = 4.8 \times 10^{-7} \text{ m.}$$

This is 480 nm. The other wavelengths, 720, 590 and 364 nm, would give fringe widths 1.80, 1.475 and 0.910 mm, respectively, inconsistent with the plotted spacing.

Step 3: Conclusion The wavelength is 480 nm. Hence, the correct option is (C).

Quick Tip to Solve: Read the spacing between two successive peaks before using $\lambda = \beta d/D$; a peak-to-trough spacing is only half a fringe width.

29(ii)(b). The fringe width in the interference pattern formed on the screen is:

[1 mark]

- (A) 1.2 mm
- (B) 0.2 mm
- (C) 4.2 mm
- (D) 6.8 mm

Correct Answer: (A) 1.2 mm

Solution:

Concept:

- The fringe width β is the distance between two consecutive bright fringes or two consecutive dark fringes in an interference pattern.
- For equally spaced slits in Young's experiment, $\beta = \lambda D/d$. A bright fringe and the adjacent dark fringe are separated by $\beta/2$, not β .

Step 1: Identify equivalent points of the pattern The plot has a central intensity maximum at zero displacement and the next maximum at approximately 1.2 mm. Alternatively, its first and second dark fringes above the centre lie at approximately 0.6 mm and 1.8 mm. Their separation gives the same fringe width:

$$\beta = (1.8 - 0.6) \text{ mm} = 1.2 \text{ mm}.$$

Step 2: Check the competing distances Option (B), 0.2 mm, is much smaller than the separation of consecutive peaks. Options (C) and (D), 4.2 mm and 6.8 mm, are also inconsistent with the several regularly spaced fringes visible over the plotted screen interval. Only 1.2 mm matches the repeated spacing.

Step 3: Conclusion The fringe width is 1.2 mm. Hence, the correct option is (A).

Quick Tip to Solve: Choose two consecutive maxima or two consecutive minima on the graph and subtract their screen coordinates.

29(iii). The path difference between the two waves meeting at point P, where there is a minimum in the interference pattern is:

[1 mark]

- (A) $8.1 \times 10^{-7} \text{ m}$
- (B) $7.2 \times 10^{-7} \text{ m}$
- (C) $6.5 \times 10^{-7} \text{ m}$
- (D) $6.0 \times 10^{-7} \text{ m}$

Correct Answer: (B) $7.2 \times 10^{-7} \text{ m}$

Solution:

Concept:

- For screen displacement y in Young's double-slit experiment, the magnitude of the path difference is $\Delta \simeq dy/D$, where d is slit separation and D is screen distance.
- Dark fringes occur at $\Delta = (n + \frac{1}{2})\lambda$, with $n = 0, 1, 2, \dots$. The second minimum on either side has $\Delta = 3\lambda/2$.

Step 1: Locate the marked minimum The central bright fringe is at zero displacement. Point P is the second minimum above it, at approximately $y_P = 1.8 \text{ mm}$. Use $d = 2.0 \times 10^{-3} \text{ m}$, $y_P = 1.8 \times 10^{-3} \text{ m}$ and $D = 5.0 \text{ m}$.

Step 2: Calculate and check the path difference Since D greatly exceeds both d and y_P , the small-angle relation applies:

$$\Delta = \frac{dy_P}{D} = \frac{(2.0 \times 10^{-3})(1.8 \times 10^{-3})}{5.0} = 7.2 \times 10^{-7} \text{ m}.$$

As a check, the graph gives $\lambda = 480 \text{ nm}$, and $3\lambda/2 = 720 \text{ nm}$, as required for this second minimum. Options (A), (C) and (D) give 810, 650 and 600 nm, respectively; none equals the required odd half-multiple at P.

Step 3: Conclusion The magnitude of the path difference at P is $7.2 \times 10^{-7} \text{ m}$. Hence, the correct option is (B).

Quick Tip to Solve: Count dark fringes from the central bright fringe: the first has path difference $\lambda/2$, and the second has $3\lambda/2$.

29(iv). When the experiment is performed in a liquid of refractive index greater than 1, then fringe pattern will: [1 mark]

- (A) disappear
- (B) become blurred
- (C) be widened
- (D) be compressed

Correct Answer: (D) be compressed

Solution:

Concept:

- In a uniform liquid of refractive index $\mu > 1$, light speed is $v = c/\mu$. Its frequency remains fixed by the source, so its wavelength becomes $\lambda' = \lambda/\mu$.
- Fringe width is $\beta = \lambda D/d$, where D is the screen distance and d is slit separation. With this geometry fixed, fringe width is proportional to wavelength.

Step 1: Determine the change in wavelength Performing the whole experiment in the liquid reduces the speed of light without changing the source frequency ν . Thus

$$\lambda' = \frac{v}{\nu} = \frac{c}{\mu\nu} = \frac{\lambda}{\mu}.$$

The wavelength is therefore smaller than it was in air.

Step 2: Relate this change to the fringe pattern Substitution in the fringe-width relation gives

$$\beta' = \frac{\lambda' D}{d} = \frac{\beta}{\mu} < \beta.$$

Adjacent fringes move closer together. In the ideal uniform medium, the two beams remain coherent, so the pattern neither disappears nor necessarily becomes blurred; this excludes (A) and (B). A wider pattern, as in (C), would require a larger wavelength, contrary to the change here.

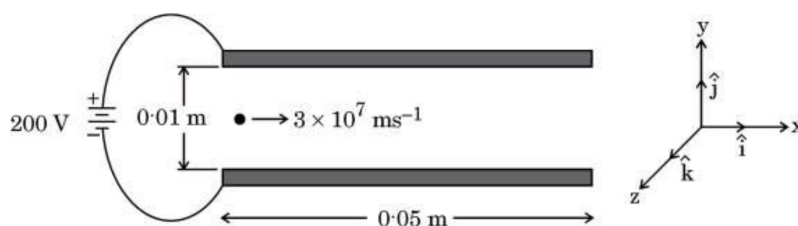
Step 3: Conclusion The fringe pattern is compressed, with fringe width $\beta' = \beta/\mu$. Hence, the correct

option is (D).

Quick Tip to Solve: When the entire setup is immersed, divide both the wavelength and the fringe width by the liquid's refractive index.

30. The electric potential V and electric field E are closely related concepts in electrostatics. The electric field is a vector quantity that represents the force per unit charge at a given point in space, whereas electric potential is a scalar quantity that represents the potential energy per unit charge at a given point in space. Electric field and electric potential are related by the equations $E_r = -\frac{dV}{dr}$ and $\vec{E} = E_r \hat{r}$, i.e., electric field is the negative gradient of the electric potential. This means that electric field points in the direction of decreasing potential and its magnitude is the rate of change of potential with distance. The electric field is the force that drives a unit charge to move from higher potential region to lower potential region and electric potential difference between the two points determines the work done in moving a unit charge from one point to the other point.

A pair of square conducting plates having sides of length 0.05 m are arranged parallel to each other in x - y plane. They are 0.01 m apart along z -axis and are connected to a 200 V power supply as shown in the figure. An electron enters with a speed of $3 \times 10^7 \text{ ms}^{-1}$ horizontally and symmetrically in the space between the two plates. Neglect the effect of gravity on the electron. [4 marks]



30(i). The electric field $\vec{E}$ in the region between the plates is:

[1 mark]

- (A) $\left(2 \times 10^2 \frac{\text{V}}{\text{m}}\right) \hat{k}$
(B) $-\left(2 \times 10^2 \frac{\text{V}}{\text{m}}\right) \hat{k}$
(C) $\left(2 \times 10^4 \frac{\text{V}}{\text{m}}\right) \hat{k}$
(D) $-\left(2 \times 10^4 \frac{\text{V}}{\text{m}}\right) \hat{k}$

Correct Answer: (C) $\left(2 \times 10^4 \frac{\text{V}}{\text{m}}\right) \hat{k}$

Solution:

Concept:

- Between parallel conducting plates, neglecting edge effects, the field magnitude is $E = \Delta V/d$, where ΔV is the potential difference and d is the plate separation.
- The electric field points from the positive plate towards the negative plate, in the direction of decreasing potential.

Step 1: Calculate the field magnitude The separation along the field is 0.01 m, whereas 0.05 m is the

plate length. Thus

$$E = \frac{200}{0.01} = 2.0 \times 10^4 \text{ V m}^{-1}.$$

Options (A) and (B) have the wrong magnitude: the applied voltage must be divided by the separation.

Step 2: Determine the field direction The upper plate is connected to the positive terminal and the lower plate to the negative terminal. The field therefore points from the upper plate towards the lower plate, along the positive z -direction used for the plate separation. Option (D) reverses this direction. The charge of the entering electron changes its force direction, but does not change the direction of the field produced by the plates.

Step 3: Conclusion $\vec{E} = (2 \times 10^4 \text{ V m}^{-1})\hat{k}$. Hence, the correct option is (C).

Quick Tip to Solve: Use the separation 0.01 m in $E = V/d$, then follow the field from the positive plate to the negative plate.

30(ii). In the region between the plates, the electron moves with an acceleration $\vec{a}$ given by: [1 mark]

(A) $-(3.5 \times 10^{15} \text{ ms}^{-2})\hat{k}$

(B) $(3.5 \times 10^{15} \text{ ms}^{-2})\hat{k}$

(C) $(3.5 \times 10^{13} \text{ ms}^{-2})\hat{i}$

(D) $-(3.5 \times 10^{13} \text{ ms}^{-2})\hat{i}$

Correct Answer: (A) $-(3.5 \times 10^{15} \text{ ms}^{-2})\hat{k}$

Solution:

Concept:

- The electric force on a charge is $\vec{F} = q\vec{E}$, and Newton's second law gives $\vec{a} = q\vec{E}/m$, where m is its mass.
- An electron has charge $-e$, so its acceleration is opposite to the electric field and towards the positive plate.

Step 1: Find the acceleration magnitude The uniform field has magnitude $E = 200/0.01 = 2 \times 10^4 \text{ V m}^{-1}$. With $e = 1.6 \times 10^{-19} \text{ C}$ and $m_e = 9.1 \times 10^{-31} \text{ kg}$,

$$a = \frac{eE}{m_e} = \frac{(1.6 \times 10^{-19})(2 \times 10^4)}{9.1 \times 10^{-31}} \simeq 3.5 \times 10^{15} \text{ m s}^{-2}.$$

Step 2: Apply the negative electron charge The field points from the positive upper plate to the negative lower plate, along $+\hat{k}$ for the stated plate separation. Hence the electron accelerates along $-\hat{k}$, towards the positive plate. Option (B) assigns the force direction of a positive charge. Options (C) and (D) give the wrong magnitude and incorrectly place the acceleration along the horizontal x -direction, where the electric force is zero.

Step 3: Conclusion $\vec{a} = -(3.5 \times 10^{15} \text{ m s}^{-2})\hat{k}$. Hence, the correct option is (A).

Quick Tip to Solve: First calculate $eV/(m_e d)$; then reverse the field direction because the moving particle is an electron.

30(iii)(a). Time interval during which an electron moves through the region between the plates is: [1 mark]

- (A) $9.0 \times 10^{-9} \text{ s}$
- (B) $1.67 \times 10^{-8} \text{ s}$
- (C) $1.67 \times 10^{-9} \text{ s}$
- (D) $2.17 \times 10^{-9} \text{ s}$

Correct Answer: (C) $1.67 \times 10^{-9} \text{ s}$

Solution:

Concept:

- Perpendicular components of motion are independent. The electric force is perpendicular to the initial horizontal velocity, so the horizontal speed u_x remains constant.
- For horizontal travel through a plate length L , the flight time is $t = L/u_x$, provided the electron does not strike a plate earlier.

Step 1: Use the horizontal distance The electron travels along the plates over $L = 0.05 \text{ m}$, with $u_x = 3 \times 10^7 \text{ m s}^{-1}$. Therefore

$$t = \frac{0.05}{3 \times 10^7} = 1.67 \times 10^{-9} \text{ s}.$$

The separation 0.01 m is perpendicular to this motion and must not replace the plate length.

Step 2: Check that the electron reaches the exit With transverse acceleration $a \simeq 3.52 \times 10^{15} \text{ m s}^{-2}$ and zero initial transverse velocity, the deflection during this interval is

$$|\Delta z| = \frac{1}{2}at^2 \simeq 4.88 \text{ mm} < \frac{d}{2} = 5.0 \text{ mm}.$$

The electron therefore leaves the plate region before hitting a plate. Option (B) has an extra factor of ten; neither (A) nor (D) equals the horizontal transit time.

Step 3: Conclusion The time spent between the plates is $1.67 \times 10^{-9} \text{ s}$. Hence, the correct option is (C).

Quick Tip to Solve: Find transit time from the unchanged horizontal speed, and compare the transverse deflection with half the plate separation.

30(iii)(b). The vertical displacement of the electron which travels through the region between the plates is: [1 mark]

- (A) 10 mm
- (B) 4.9 mm
- (C) 5.9 mm
- (D) 3.0 mm

Correct Answer: (B) 4.9 mm

Solution:

Concept:

- The electron has constant transverse acceleration of magnitude $a = eE/m_e$, where $E = V/d$, e is the elementary charge and m_e is the electron mass.
- Its initial transverse velocity is zero, so the displacement magnitude is $s = \frac{1}{2}at^2$. Its horizontal speed u is constant, giving $t = L/u$.

Step 1: Calculate the flight time and acceleration Use the plate length for the horizontal travel and the plate separation for the field:

$$t = \frac{0.05}{3 \times 10^7} = 1.667 \times 10^{-9} \text{ s},$$

$$a = \frac{(1.6 \times 10^{-19})(200/0.01)}{9.1 \times 10^{-31}} = 3.516 \times 10^{15} \text{ m s}^{-2}.$$

Step 2: Find the transverse displacement Since the electron enters horizontally at the mid-plane,

$$s = \frac{1}{2}(3.516 \times 10^{15})(1.667 \times 10^{-9})^2 = 4.88 \times 10^{-3} \text{ m} \simeq 4.9 \text{ mm}.$$

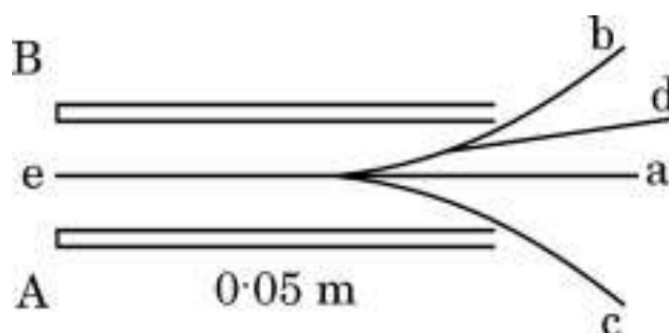
The displacement is towards the positive upper plate. It is just less than the available half-gap, 5.0 mm, so the electron exits without colliding. Option (A), 10 mm, is the full plate gap, and option (C) exceeds the half-gap. Option (D) does not follow from the uniformly accelerated motion.

Step 3: Conclusion The vertical displacement has magnitude 4.9 mm, towards the positive plate. Hence, the correct option is (B).

Quick Tip to Solve: Combine the two motions as $s = eVL^2/(2m_e u^2)$, and check that the result is smaller than $d/2$.

30(iv). Which one of the following is the path traced by the electron in between the two plates?

[1 mark]



- (A) a
- (B) b
- (C) c
- (D) d

Correct Answer: (B) b

Solution:

Concept:

- A negatively charged electron is attracted towards the positive plate. Its transverse acceleration is constant in the uniform electric field between parallel plates.
- Uniform horizontal motion together with uniform transverse acceleration produces a parabolic trajectory. The initial tangent is horizontal because the initial transverse velocity is zero.

Step 1: Determine the direction of bending The supply connects the upper plate to its positive terminal. The electron therefore bends upwards towards plate B. The downward curve c would describe bending towards the negative plate and has the wrong force direction. The straight path a would require zero transverse force, whereas the field here is non-zero.

Step 2: Identify the parabolic curve Let s denote displacement towards the upper plate and x horizontal distance from entry. For horizontal entry speed u and transverse acceleration magnitude a ,

$$x = ut, \quad s = \frac{1}{2}at^2 \quad \Rightarrow \quad s = \frac{a}{2u^2}x^2.$$

Thus the upward slope grows with horizontal distance. Curve b has this upward parabolic bending, whereas the straight inclined path d would require a constant transverse velocity and no transverse acceleration. Outside the plate region the field is neglected and the subsequent path follows the exit tangent.

Step 3: Conclusion The electron follows the upward parabolic path b between the plates. Hence, the correct option is (B).

Quick Tip to Solve: For horizontal electron entry, select the curve with a horizontal initial tangent that bends increasingly towards the positive plate.

Section E (15 marks)

31(a). (i) A rectangular loop of sides a and b carrying current I is placed in a magnetic field $\vec{B}$ such that its area vector $\vec{A}$ makes an angle θ with $\vec{B}$. With the help of a suitable diagram, show that the torque $\vec{\tau}$ acting on the loop is given by $\vec{\tau} = \vec{m} \times \vec{B}$, where $\vec{m}(= I\vec{A})$ is the magnetic dipole moment of the loop.

(ii) A circular coil of 100 turns and radius $\left(\frac{10}{\sqrt{\pi}}\right)$ cm carrying current of 5.0 A is suspended vertically in a uniform horizontal magnetic field of 2.0 T. The field makes an angle 30° with the normal to the coil. Calculate:

(I) the magnetic dipole moment of the coil, and

(II) the magnitude of the counter torque that must be applied to prevent the coil from turning.

[5 marks]

Solution:

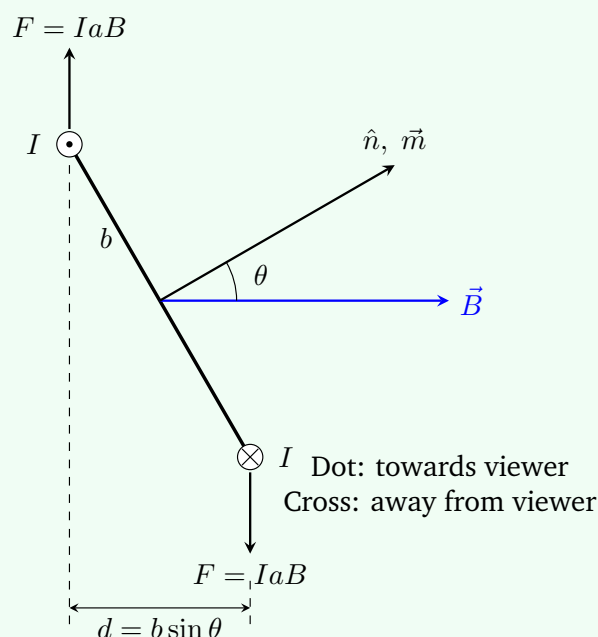
Concept:

- A straight current-carrying segment experiences magnetic force $\vec{F} = I\vec{\ell} \times \vec{B}$, where $\vec{\ell}$ points along the current.
- A couple consists of equal, opposite forces with different lines of action. Its torque magnitude is one force times the perpendicular separation of their lines of action.
- The area vector $\vec{A} = A\hat{n}$ follows the right-hand rule for the current. A coil of N turns has magnetic dipole moment $\vec{m} = NI\vec{A}$.

Step 1: (i) Identify the force pair on the loop Take the sides of length a perpendicular to the plane containing $\vec{B}$ and the area normal $\hat{n}$. The diagram is a view along these sides: a dot denotes current towards the viewer and a cross denotes current away. The line joining them represents a side of length b , and is perpendicular to $\hat{n}$. Each a -side is perpendicular to the field, so the two magnetic forces have magnitude

$$F = IaB.$$

Their directions are opposite, as given by $I\vec{\ell} \times \vec{B}$. The forces on the other two sides are also equal and opposite; they act along the same line through the midpoints of those sides, so their net torque is zero.



Edge view of the loop: the two sides of length a are seen end-on; their force lines are separated by $b \sin \theta$.

Step 2: (i) Evaluate the couple and its direction Since the normal makes angle θ with the field, the perpendicular separation of the force lines shown is $d = b \sin \theta$. Each of the two forces has lever arm $d/2$ about the centre. Adding their torques gives

$$\begin{aligned}\tau &= F \frac{d}{2} + F \frac{d}{2} = Fd \\ &= (IaB)(b \sin \theta) = IAB \sin \theta, \quad A = ab.\end{aligned}$$

With $m = IA$, this is $\tau = mB \sin \theta$. Applying the right-hand rule to the force couple gives the direction of $\hat{n} \times \vec{B}$. Therefore the magnitude and direction together yield

$$\vec{\tau} = I \vec{A} \times \vec{B} = \vec{m} \times \vec{B}.$$

This torque tends to align the magnetic moment with the field; the uniform field gives zero resultant force on the complete loop.

Step 3: (ii)(I) Calculate the coil area and magnetic moment Convert the radius to metres before calculating the area of one turn:

$$\begin{aligned}r &= \frac{10}{\sqrt{\pi}} \text{ cm} = \frac{0.10}{\sqrt{\pi}} \text{ m}, \\ A &= \pi r^2 = \pi \frac{(0.10)^2}{\pi} = 1.0 \times 10^{-2} \text{ m}^2.\end{aligned}$$

All 100 turns carry the same current and have the same area normal, so their moments add:

$$m = NIA = 100 \times 5.0 \times 1.0 \times 10^{-2} = 5.0 \text{ A m}^2.$$

The moment points along the normal to the coil, with its sense determined by the current.

Step 4: (ii)(II) Balance the magnetic torque The given 30° is the angle between the field and the

normal, so it is directly the angle in the torque formula:

$$\tau_{\text{mag}} = mB \sin 30^\circ = 5.0 \times 2.0 \times \frac{1}{2} = 5.0 \text{ N m}.$$

To hold the coil stationary, the applied counter torque must cancel this torque: $\vec{\tau}_{\text{counter}} = -\vec{\tau}_{\text{mag}}$. Its magnitude is consequently the same as the magnetic torque.

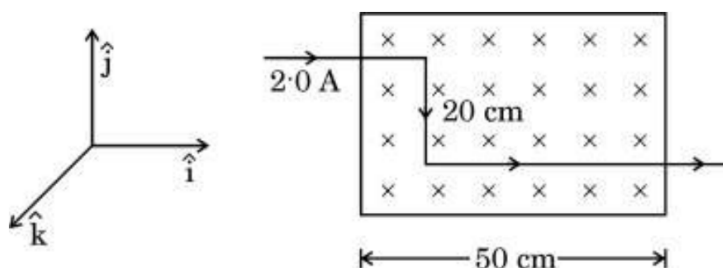
Step 5: Conclusion For the rectangular loop, $\vec{\tau} = \vec{m} \times \vec{B}$, where $\vec{m} = I\vec{A}$. The circular coil has magnetic moment 5.0 A m^2 and requires counter torque 5.0 N m , opposite to the magnetic torque.

Quick Tip to Solve: Use the angle with the normal in $NIAB \sin \theta$. Here squaring $10/\sqrt{\pi}$ cancels the π in the area, but first convert centimetres to metres.

OR

31(b). (i) Derive an expression for the force $\vec{F}$ acting on a conductor of length L and area of cross-section A carrying current I and placed in a magnetic field $\vec{B}$.

(ii) A part of a wire carrying 2.0 A current and bent at 90° at two points is placed in a region of uniform magnetic field $\vec{B} = -(0.50 \text{ T})\hat{k}$, as shown in the figure. Calculate the magnitude of the net force acting on the wire. [5 marks]



Solution:

Concept:

- A charge q moving with velocity $\vec{v}$ in a magnetic field experiences the magnetic Lorentz force $\vec{f} = q\vec{v} \times \vec{B}$.
- For a conductor with electron number density n , cross-sectional area A , electron charge magnitude e , and drift speed v_d , the current magnitude is $I = neAv_d$.
- Magnetic forces on successive wire segments add vectorially. In a uniform field, $\vec{F} = I \int d\vec{\ell} \times \vec{B} = I(\vec{r}_{\text{exit}} - \vec{r}_{\text{entry}}) \times \vec{B}$.

Step 1: (i) Sum the magnetic force on the charge carriers Let $\hat{\ell}$ point along the conventional current in a straight conductor of length L . There are $N_e = nAL$ conduction electrons in this length. Their mean drift velocity is opposite to the current, so $\vec{v}_d = -v_d\hat{\ell}$. An electron has charge $-e$; hence its mean magnetic force is

$$\vec{f} = (-e)(-v_d\hat{\ell}) \times \vec{B} = ev_d\hat{\ell} \times \vec{B}.$$

The random thermal velocities have zero mean and contribute no resultant force. Multiplying the drift-force contribution by the number of electrons gives the total magnetic force, transferred to the

conductor through interactions with its lattice:

$$\vec{F} = nALev_d\hat{\ell} \times \vec{B}.$$

Step 2: (i) Express the result in terms of current In time Δt , the magnitude of charge crossing a section is $\Delta Q = neAv_d\Delta t$. Thus $I = \Delta Q/\Delta t = neAv_d$. Substitution into the total-force expression gives

$$\vec{F} = IL\hat{\ell} \times \vec{B} = I\vec{L} \times \vec{B}, \quad \vec{L} = L\hat{\ell}.$$

If α is the angle between the current and field, the magnitude is $F = ILB \sin \alpha$; the force is perpendicular to both. The area A is absorbed into the specified current and therefore does not appear separately in the final expression.

Step 3: (ii) Resolve the lengths inside the magnetic field The field acts only on the portions inside the shaded rectangle. Both horizontal portions carry current in the $+\hat{i}$ direction, and their combined length is the full field-region width, $50 \text{ cm} = 0.50 \text{ m}$. The middle portion carries current downwards, with vector length $-0.20\hat{j} \text{ m}$. The entrance-to-exit displacement within the field is therefore

$$\vec{L}_{\text{eff}} = (0.50\hat{i} - 0.20\hat{j}) \text{ m}.$$

Horizontal parts outside the rectangle experience no force from this specified field. The detailed positions of the two bends do not affect the sum of the horizontal lengths inside it.

Step 4: (ii) Add the force components and find the magnitude Substitute $I = 2.0 \text{ A}$ and $\vec{B} = -0.50\hat{k} \text{ T}$. Using $\hat{i} \times \hat{k} = -\hat{j}$ and $\hat{j} \times \hat{k} = \hat{i}$,

$$\begin{aligned}\vec{F}_{\text{horizontal}} &= 2.0(0.50\hat{i}) \times (-0.50\hat{k}) = 0.50\hat{j} \text{ N}, \\ \vec{F}_{\text{vertical}} &= 2.0(-0.20\hat{j}) \times (-0.50\hat{k}) = 0.20\hat{i} \text{ N}.\end{aligned}$$

The two components are perpendicular, so their magnitudes cannot be added directly. Their vector sum and resultant magnitude are

$$\begin{aligned}\vec{F}_{\text{net}} &= (0.20\hat{i} + 0.50\hat{j}) \text{ N}, \\ |\vec{F}_{\text{net}}| &= \sqrt{(0.20)^2 + (0.50)^2} = \sqrt{0.29} \text{ N} = 0.5385 \dots \text{ N}.\end{aligned}$$

Step 5: Conclusion The force on a straight current-carrying conductor is $\vec{F} = I\vec{L} \times \vec{B}$, or $F = ILB \sin \alpha$. For the bent wire, $\vec{F}_{\text{net}} = (0.20\hat{i} + 0.50\hat{j}) \text{ N}$ and its magnitude is 0.54 N .

Quick Tip to Solve: In a uniform field, replace the bent part by its entrance-to-exit displacement: here $0.50\hat{i} - 0.20\hat{j}$ metres. Add perpendicular force components by Pythagoras, not by adding their magnitudes.

32(a). (i) A parallel beam of monochromatic light falls normally on a single slit of width ' a ' and a diffraction pattern is observed on a screen placed at distance D from the slits. Explain:

(I) the formation of maxima and minima in the diffraction pattern, and

(II) why the maxima go on becoming weaker and weaker with its increasing number (n).

(ii) Write any two points of difference between interference pattern due to double-slit and diffraction pattern due to single-slit.

[5 marks]

Solution:

Concept:

- By the Huygens–Fresnel principle, every point of the illuminated slit acts as a source of coherent secondary wavelets. Their superposition produces the diffraction pattern.
- For slit width a , wavelength λ and observation angle θ , the path difference between rays from the two edges is $a \sin \theta$. In the far-field, small-angle limit, the screen coordinate is $y \simeq D\theta$, where D is the slit-to-screen distance.
- The intensity distribution is $I(\theta) = I_0(\sin \beta / \beta)^2$, where $\beta = \pi a \sin \theta / \lambda$ and I_0 is the central-maximum intensity; the limiting value at $\beta = 0$ is I_0 .

Step 1: (i)(I) Explain the central maximum At the centre of the screen, $\theta = 0$. The secondary waves from all parts of the slit arrive in the same phase, so their amplitudes reinforce one another. The resultant amplitude, and hence the intensity, is greatest here. This produces the broad, bright central maximum. Away from the centre, the phase varies continuously across the slit, so some cancellation occurs.

Step 2: (i)(I) Obtain the condition for minima For $a \sin \theta = \lambda$, divide the slit into two equal halves. Each point in the upper half has a corresponding point a distance $a/2$ below it. The path difference of the corresponding wavelets is

$$\frac{a}{2} \sin \theta = \frac{\lambda}{2}.$$

Their phase difference is π ; with uniform illumination their amplitudes are equal, and every such pair cancels. Thus the first dark minimum is formed. More generally, if $a \sin \theta = m\lambda$, divide the slit into $2m$ equal strips and pair adjacent strips. Corresponding points again differ in path by $\lambda/2$, giving complete cancellation. Therefore the minima occur at

$$a \sin \theta_m = \pm m\lambda, \quad m = 1, 2, 3, \dots$$

For small angles their positions are $y_m \simeq \pm m\lambda D/a$. The first minima enclose the central maximum, whose width on the screen is therefore $2\lambda D/a$.

Step 3: (i)(I) Explain the secondary maxima Between two successive minima, cancellation is incomplete, so the resultant intensity rises from zero to a smaller maximum and then falls to zero again. These are the secondary maxima, on both sides of the central maximum. For example, near $a \sin \theta = 3\lambda/2$, the slit can be considered as three equal strips. The contributions from two adjacent strips cancel pairwise, while the remaining strip gives a nonzero resultant. The secondary maxima lie approximately at

$$a \sin \theta \simeq \pm \left(n + \frac{1}{2}\right) \lambda, \quad n = 1, 2, 3, \dots$$

This is an approximate position, not an exact condition. The exact secondary-maximum positions follow from $\tan \beta = \beta$, using the nonzero roots.

Step 4: (i)(II) Explain why successive maxima become weaker At larger angles the phase change

across the slit covers more cycles. More contributions oppose and cancel one another, leaving a smaller resultant amplitude. Quantitatively, in $I/I_0 = (\sin \beta / \beta)^2$, the numerator never exceeds unity while β^2 grows with order. At a secondary maximum, $\tan \beta = \beta$ gives

$$\frac{I_{\max}}{I_0} = \frac{\sin^2 \beta}{\beta^2} = \cos^2 \beta = \frac{1}{1 + \beta^2}.$$

The successive roots have increasing $|\beta|$, so the secondary-maximum intensities decrease with increasing n . The central maximum is consequently much brighter than the others.

Step 5: (ii) Compare the two patterns **1. Width:** In ideal Young's double-slit interference, adjacent bright fringes are equally spaced, with fringe width $\lambda D/d$, where d is the slit separation. In single-slit diffraction, the central bright band has width $2\lambda D/a$, twice the width $\lambda D/a$ of each neighbouring secondary bright band, measured between successive minima in the small-angle limit.

2. Intensity: For two equally illuminated, very narrow coherent slits, the ideal interference bright fringes have equal intensity. In single-slit diffraction the central maximum is the brightest, and the secondary maxima become progressively weaker away from the centre. If the two interference slits have appreciable width, their own diffraction envelope also modulates the interference intensities.

Step 6: Conclusion A single slit produces a central maximum by in-phase addition, minima at $a \sin \theta = \pm m\lambda$ by complete pairwise cancellation, and weaker secondary maxima by incomplete cancellation. Unlike the ideal double-slit pattern, its central bright band is twice as wide as the secondary bands and successive bright maxima decrease in intensity.

Quick Tip to Solve: Derive each minimum by dividing the slit into $2m$ strips and pairing adjacent strips. Remember that the half-integer formula for secondary maxima is approximate, whereas the integer condition for minima is exact in the far-field model.

OR

32(b). (i) With the help of a ray diagram, describe the construction and working of a compound microscope.

(ii) (I) The real image of an object placed between f and $2f$ from a convex lens can be seen on a screen placed at the image location. If the screen is removed, is the image still there? Explain.

(II) Plane and convex mirrors produce virtual images of objects. Can they produce real images under some circumstances? Explain.

[5 marks]

Solution:

Concept:

- A compound microscope combines the linear magnification of a convex objective with the angular magnification of a convex eyepiece. The objective makes a real, enlarged intermediate image; the eyepiece acts as a magnifying glass.
- A real image is formed where actual light rays converge. A virtual image is located where only their backward extensions meet. A screen detects a real image but is not responsible for forming it.
- For a spherical mirror, $\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$, where u , v and f are the signed object distance, image distance and focal length. An incident converging beam can provide a virtual object behind a mirror.

Step 1: (i) Describe the construction A compound microscope has two coaxial convex lenses mounted

at the ends of an adjustable tube. The objective O , close to the specimen, has a very short focal length and small aperture. The eyepiece E , close to the eye, has a focal length larger than that of the objective and a relatively larger aperture. A stage supports the illuminated specimen, and a focusing arrangement adjusts its distance from the objective or the lens separation.

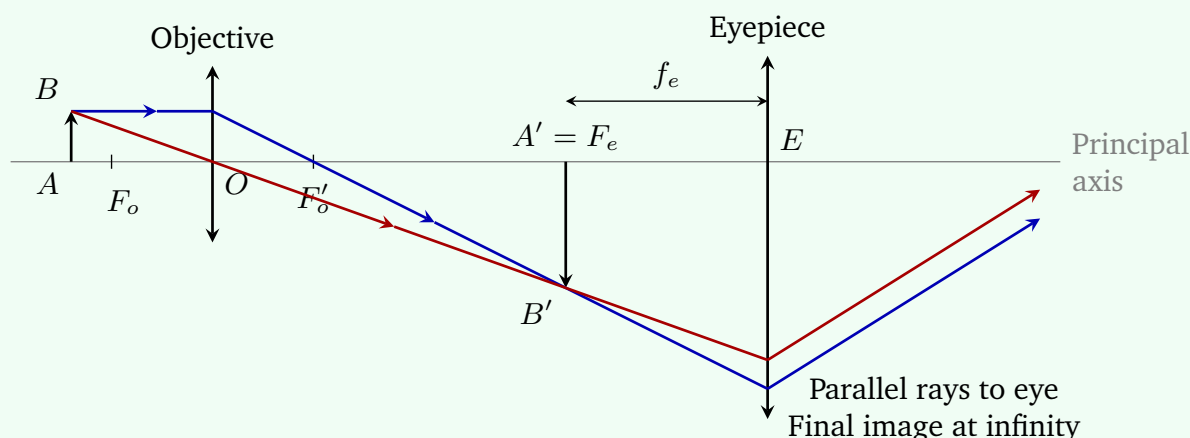
Step 2: (i) Trace the rays and explain the working Place the small object AB just beyond the first focal point F_o of the objective, between f_o and $2f_o$. The ray from B parallel to the principal axis refracts through F'_o ; the ray through the optical centre O proceeds undeviated. They meet at B' , forming a real, inverted and enlarged intermediate image $A'B'$.

For normal adjustment, adjust the lens separation so that $A'B'$ lies in the first focal plane of the eyepiece: A' coincides with F_e . Rays from B' then emerge parallel after refraction through the eyepiece. The eye receives these rays and sees a highly magnified virtual image at infinity, inverted relative to AB . The two emergent rays in the diagram are parallel to each other; they need not be parallel to the principal axis.

The magnitude of the angular magnifying power in this adjustment is

$$|M| = \frac{v_o}{|u_o|} \frac{D}{f_e},$$

where u_o and v_o are the objective's signed object and image distances, f_e is the eyepiece focal length and D is the least distance of distinct vision. Alternatively, placing $A'B'$ just within the eyepiece's focal length gives a magnified virtual final image at a finite viewing distance.



Compound microscope in normal adjustment: $A' = F_e$, and the final virtual image is at infinity. The ray diagram is schematic.

Step 3: (ii)(I) Examine the image after removing the screen Yes, the real image remains at the same position, provided the object and lens remain fixed and illuminated. For an object between f and $2f$, the convex lens makes the rays converge beyond $2f$. Removing the screen does not alter the paths of those rays or their point of convergence. The screen merely scatters the light so that the image is visible from different directions. Without it, an observer whose eye intercepts the rays after they cross the image plane can still see the image; it is no longer displayed on a scattering surface.

Step 4: (ii)(II) Supply a virtual object to the mirrors Yes. Their familiar virtual images refer to real objects in front of the mirror. Instead, send a converging beam towards the mirror, for example using a convex lens. The point behind the mirror towards which the incident rays would converge is a virtual object for the mirror.

Take the positive direction along the incident light, so a virtual object behind the mirror has $u > 0$,

while a real reflected image in front has $v < 0$. For a plane mirror, $1/f = 0$, and therefore

$$\frac{1}{v} = -\frac{1}{u}, \quad v = -u < 0.$$

Thus it reflects this converging beam to a real image equally far in front of the mirror.

For a convex mirror, $f > 0$. Its image distance is

$$v = \frac{fu}{u - f}.$$

If the virtual object is between the pole and the focus behind the mirror, $0 < u < f$, the denominator is negative and $v < 0$. The reflected rays then actually converge in front, producing a real image. At $u = f$ they emerge parallel; for $u > f$ the image is virtual.

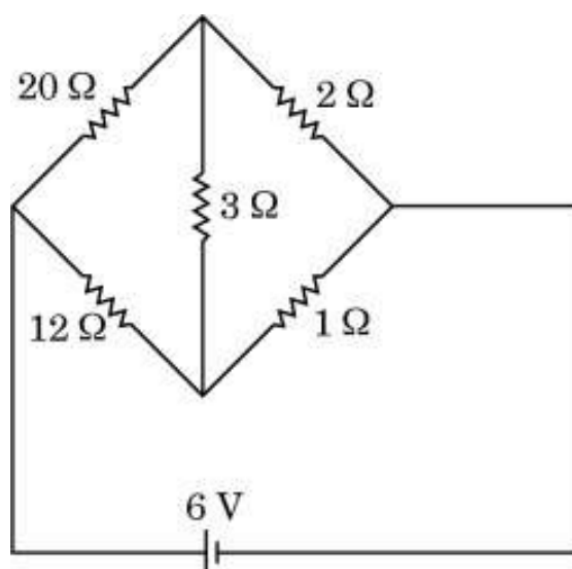
Step 5: Conclusion The compound microscope uses an objective to form an enlarged real intermediate image and an eyepiece to give a further magnified virtual final image. A real lens image persists after removing its screen. Both plane and convex mirrors can form real images from suitable converging incident beams; the convex mirror requires its virtual object to lie between its pole and focus.

Quick Tip to Solve: Draw the microscope's intermediate image first at the eyepiece's front focal plane for normal adjustment. For the mirror exception, test a virtual object with $u > 0$ and check whether the mirror equation gives $v < 0$.

33(a). (i) Derive the condition for which a Wheatstone Bridge is balanced.

(ii) Determine the current in 3Ω branch of a Wheatstone Bridge in the circuit shown in the figure.

[5 marks]



Solution:

Concept:

- A Wheatstone bridge is balanced when the two junctions joined by its central branch have equal potentials; hence no current flows through that branch.
- Ohm's law gives a branch current as the potential difference divided by its resistance. Kirchhoff's junction law states that the algebraic sum of currents leaving a junction is zero.

Step 1: (i) Define the four arms and impose balance Label the left, top, right and bottom junctions of a bridge as A, B, C, D , respectively. Let $AB = P$, $BC = Q$, $AD = R$ and $DC = S$, where these symbols denote the arm resistances. The battery is connected across A, C , and the galvanometer is connected across B, D . At balance, the galvanometer current is zero and $V_B = V_D$. Therefore, the current I_1 is the same in P, Q , and the current I_2 is the same in R, S .

Step 2: (i) Compare the potential drops and divide Since $V_B = V_D$, the drops from A to these junctions are equal. The drops from these junctions to C are also equal. Thus,

$$\begin{aligned} V_A - V_B &= V_A - V_D \Rightarrow I_1 P = I_2 R, \\ V_B - V_C &= V_D - V_C \Rightarrow I_1 Q = I_2 S. \end{aligned}$$

Dividing the equations eliminates both branch currents:

$$\frac{P}{Q} = \frac{R}{S}, \quad PS = QR.$$

Conversely, when this ratio holds, the two potential dividers give equal junction potentials, so the central branch carries no current. This establishes the balance condition.

Step 3: (ii) Check the actual bridge and choose node potentials In the given circuit, $P = 20 \Omega$, $Q = 2 \Omega$, $R = 12 \Omega$ and $S = 1 \Omega$. Since $20/2 = 10$, whereas $12/1 = 12$, this bridge is not balanced; the current in the 3Ω branch cannot be set to zero. The longer battery plate is connected to the left junction. Choose $V_C = 0$ and $V_A = 6 \text{ V}$. Write the unknown top and bottom potentials as $V_B = x$ and $V_D = y$, in volts. Retain the central branch when applying the junction law.

Step 4: (ii) Apply Kirchhoff's law at the two junctions The currents leaving B and D , respectively, give

$$\begin{aligned} \frac{x-6}{20} + \frac{x}{2} + \frac{x-y}{3} &= 0, \\ \frac{y-6}{12} + y + \frac{y-x}{3} &= 0. \end{aligned}$$

Multiplying the first equation by 60 and the second by 12 gives

$$53x - 20y = 18, \quad -4x + 17y = 6.$$

Multiply these equations by 17 and 20, respectively, and add to eliminate y :

$$821x = 426, \quad x = \frac{426}{821}, \quad y = \frac{390}{821}.$$

Hence $V_B > V_D$. The current from the top junction towards the bottom junction is

$$I_{BD} = \frac{V_B - V_D}{3 \Omega} = \frac{36}{821 \times 3} \text{ A} = \frac{12}{821} \text{ A}.$$

Step 5: Conclusion (i) The balance condition is $\boxed{P/Q = R/S}$, with no current in the central branch. (ii) In the printed circuit, $\boxed{I_{3\Omega} \approx 1.46 \times 10^{-2} \text{ A} = 14.6 \text{ mA}}$, flowing downwards from the junction of $20 \Omega, 2 \Omega$ to the junction of $12 \Omega, 1 \Omega$.

Quick Tip to Solve: Test the two arm ratios before removing a bridge branch. Here they are 10 and 12, so retain the 3Ω resistor and solve for the two junction potentials.

- 33(b).** (i) Consider a cylindrical conductor of length l and area of cross-section A . Current I is maintained in the conductor and electrons drift with velocity $\vec{v}_d$ $\left(|\vec{v}_d| = \frac{e|\vec{E}|}{m}\tau\right)$, (where symbols have their usual meanings). Show that the conductivity σ of the material of the conductor is given by $\sigma = \frac{ne^2\tau}{m}$.
- (ii) The resistance of a metal wire at 20°C is $1.05\ \Omega$ and at 100°C is $1.38\ \Omega$. Determine the temperature coefficient of resistivity of this metal. [5 marks]

Solution:**Concept:**

- For an electron number density n , charge magnitude e , conductor area A and drift speed v_d , the current magnitude is $I = neAv_d$. Conventional current is opposite to electron drift.
- The microscopic form of Ohm's law is $\vec{J} = \sigma\vec{E}$, where $J = I/A$ is current density and σ is conductivity. The mean relaxation time is τ , and m is the electron mass.
- Over a range where the temperature dependence is linear, $\rho(T) = \rho(T_0)[1 + \alpha_{T_0}(T - T_0)]$. Neglecting thermal expansion, resistance obeys the same relation because $R = \rho l/A$.

Step 1: (i) Relate the drift speed to current In time Δt , the electrons within a length $v_d\Delta t$ cross any chosen cross-section. The corresponding volume is $Av_d\Delta t$, containing $nAv_d\Delta t$ free electrons. Therefore, the magnitude of charge crossing is

$$\Delta Q = neAv_d\Delta t, \quad I = \frac{\Delta Q}{\Delta t} = neAv_d.$$

The random thermal motion alone gives no net current; this expression concerns the directed drift produced by the electric field.

Step 2: (i) Substitute the given drift law Using the given magnitude $v_d = eE\tau/m$, we obtain

$$I = neA \frac{eE\tau}{m}, \quad J = \frac{I}{A} = \frac{ne^2\tau}{m}E.$$

Since electrons have negative charge, their drift velocity is opposite to $\vec{E}$; multiplying by their negative charge makes $\vec{J}$ parallel to $\vec{E}$. Thus, the vector relation is

$$\vec{J} = \frac{ne^2\tau}{m}\vec{E}.$$

Comparing with $\vec{J} = \sigma\vec{E}$ identifies the required material coefficient. Equivalently, $E = V/l$ gives $I = (ne^2\tau/m)(A/l)V$, which agrees with $I = \sigma AV/l$.

Step 3: (ii) Use the initial temperature as the reference Take $T_0 = 20^\circ\text{C}$, with $R_{20} = 1.05\ \Omega$ and $R_{100} = 1.38\ \Omega$. The temperature rise is $100 - 20 = 80\ \text{K}$. Assuming the wire dimensions remain

effectively unchanged, the coefficient of resistance equals that of resistivity. Hence,

$$\begin{aligned} R_{100} &= R_{20}[1 + \alpha_{20}(100 - 20)], \\ \alpha_{20} &= \frac{R_{100} - R_{20}}{R_{20}(100 - 20)} \\ &= \frac{1.38 - 1.05}{1.05 \times 80} \text{ K}^{-1} \\ &= 3.93 \times 10^{-3} \text{ K}^{-1}. \end{aligned}$$

The positive sign is consistent with the increase of a metal's resistance on heating.

Step 4: (ii) State the reference-temperature convention The numerical temperature coefficient refers to the resistivity at the chosen reference temperature. The result above uses the given initial temperature, 20°C. If the coefficient is instead defined relative to 0°C, write $R_t = R_0(1 + \alpha_0 t)$. Eliminating R_0 between the two measurements gives

$$\begin{aligned} \alpha_0 &= \frac{R_{100} - R_{20}}{100R_{20} - 20R_{100}} \\ &= \frac{0.33}{105 - 27.6} \text{ K}^{-1} = 4.26 \times 10^{-3} \text{ K}^{-1}. \end{aligned}$$

Both definitions describe the same straight-line resistance variation; stating the reference removes any convention dependence in this numerical answer.

Step 5: Conclusion (i) $\sigma = ne^2\tau/m$. (ii) Taking the given initial temperature 20°C as reference, $\alpha_{20} = 3.93 \times 10^{-3} \text{ K}^{-1}$. With a 0°C reference instead, $\alpha_0 = 4.26 \times 10^{-3} \text{ K}^{-1}$.

Quick Tip to Solve: Derive conductivity by dividing $I = neAv_d$ by A . For the temperature coefficient, use the resistance at the stated reference temperature in the denominator, and explicitly name that reference.