

CBSE Class 12 Physics Question Paper 2022 with Solution PDF-Set 55/3/2

Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)



Time Allowed: 2 hours

Maximum Marks: 35

General Instructions

- (i) This question paper contains **12** questions. **All** questions are compulsory.
- (ii) This question paper is divided into three sections – Section A, B and C.
- (iii) **Section A** : Q. Nos. **1** to **3** are of **2** marks each.
- (iv) **Section B** : Q. Nos. **4** to **11** are of **3** marks each.
- (v) **Section C** : Q. No. **12** is a case study based questions of **5** marks.
- (vi) There is no overall choice in the question paper. However, internal choice has been provided in some of the questions. Attempt any one of the alternatives in such questions.
- (vii) Use of log tables is permitted, if necessary, but use of calculator is not permitted.

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

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

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

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

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

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

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

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

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

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

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

Section A (6 marks)

1. Explain the formation of the barrier potential in a p-n junction.

[2 marks]

Solution:

Concept:

- Diffusion carries majority carriers from a region of higher concentration to one of lower concentration: electrons from the n side to the p side and holes in the opposite direction.
- Immobile ionised dopants near the junction form a depletion region and an electric field. The resulting potential difference is the barrier potential.

Step 1: Follow diffusion and recombination On joining p-type and n-type regions, electrons diffuse from n to p and recombine with holes. Holes diffuse from p to n and recombine with electrons. Near the junction this removes mobile majority carriers, leaving uncovered positive donor ions on the n side and negative acceptor ions on the p side. These ions remain fixed in the crystal lattice; the region depleted of mobile carriers is called the depletion layer.

Step 2: Establish the opposing electric field The positive space charge on the n side and negative space charge on the p side produce an electric field directed from n to p. It opposes further diffusion of majority carriers and produces a drift current opposite to the diffusion current. The electrostatic potential is higher on the n side. As charge separation increases, the barrier grows until the drift and diffusion currents balance at thermal equilibrium, so the net current is zero without an external bias.

Step 3: Conclusion The barrier potential is the built-in potential difference across the depletion layer, produced by the fixed space charges left by diffusion and recombination. It opposes further majority-carrier diffusion across the p-n junction.

Quick Tip to Solve: Trace diffusion first, then label the remaining ions: n side positive, p side negative, and electric field from n to p.

2(a). Draw the circuit diagram of an illuminated photodiode and its I-V characteristics.

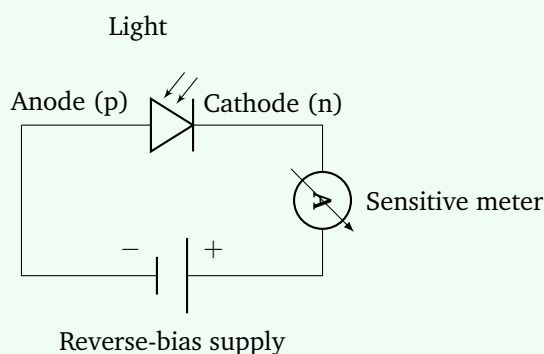
[1 mark]

Solution:

Concept:

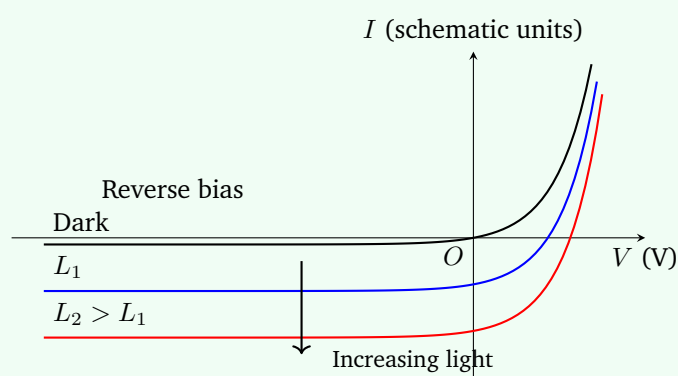
- An illuminated photodiode is operated in reverse bias: its cathode (n side) connects to the positive terminal and its anode (p side) to the negative terminal.
- Taking forward current as positive, illumination shifts the I-V curve towards more negative current. Greater light intensity gives a greater reverse photocurrent.

Step 1: Connect the reverse-biased photodiode The circuit shows a photodiode with incident-light arrows directed towards the junction, a reverse-bias supply, and a sensitive current meter in series. The cathode is connected to the positive supply terminal; this allows the depletion-layer field to collect the light-generated carriers.



Illuminated photodiode under reverse bias

Step 2: Draw the characteristic curves Plot signed diode current against signed diode voltage, with reverse bias to the left of the origin. In the reverse-bias region before breakdown, the current is nearly independent of voltage but its magnitude increases with illumination. The dark curve has only a small reverse saturation current; the curves for intensities $L_2 > L_1 > 0$ lie successively lower. The sketch also indicates the rising forward-bias branch.



Schematic I-V characteristics before reverse breakdown

Step 3: Conclusion The circuit reverse biases the photodiode. Its I-V curves show increasing magnitude of reverse current as the incident light intensity increases.

Quick Tip to Solve: Check the cathode is connected to positive supply and draw stronger illumination farther below the voltage axis on a signed I-V plot.

2(b). How can a photodiode be used to measure the light intensity?

[1 mark]

Solution:

Concept:

- A photodiode is operated in reverse bias so that light-generated electron-hole pairs produce a measurable reverse photocurrent.
- At a fixed reverse bias and fixed wavelength, the photocurrent is proportional to incident light intensity over the linear operating range.

Step 1: Illuminate the reverse-biased junction Connect the photodiode in reverse bias with a sensitive current meter in series. Incident photons of sufficient energy create electron-hole pairs near the depletion region, and the junction field separates them to produce reverse current.

Step 2: Calibrate the current reading First measure the dark current with no illumination. For

illumination, subtract this dark current from the measured reverse current to obtain the photocurrent. Calibrate the meter with known light intensities; the photocurrent then gives the unknown intensity at the same wavelength and bias.

Step 3: Conclusion A reverse-biased photodiode measures light intensity through its photocurrent: greater intensity gives greater reverse photocurrent.

Quick Tip to Solve: Keep wavelength and reverse bias fixed, subtract dark current, and read intensity from the calibrated photocurrent.

3(a)(i). Distinguish between isotopes and isobars.

[2 marks total]

Solution:

Concept:

- The atomic number Z counts protons, while the mass number $A = Z + N$ counts protons plus neutrons N .
- The identity of an element depends on Z ; equal mass numbers alone do not identify the same element.

Step 1: Identify isotopes Isotopes are nuclei of the same element with the same atomic number but different mass numbers, so their neutron numbers differ. For example, ${}^{12}_6\text{C}$ and ${}^{14}_6\text{C}$ both have six protons but have six and eight neutrons respectively.

Step 2: Identify isobars Isobars are nuclei of different elements with the same mass number but different atomic numbers. For example, ${}^{14}_6\text{C}$ and ${}^{14}_7\text{N}$ both contain fourteen nucleons, but their proton numbers are six and seven.

Step 3: Conclusion Isotopes: same Z , different A . Isobars: same A , different Z .

Quick Tip to Solve: In nuclear notation compare the lower index for isotopes and the upper index for isobars; also check the other index differs.

3(a)(ii). Two nuclei have different mass numbers A_1 and A_2 . Are these nuclei necessarily the isotopes of the same element? Explain.

Solution:

Concept:

- Isotopes must have the same atomic number Z , as well as different mass numbers A .
- A mass number gives the total number of nucleons and does not uniquely determine the proton number.

Step 1: Test the stated information The condition $A_1 \neq A_2$ establishes only that the nuclei contain different total numbers of nucleons. The question gives no information about their atomic numbers, so it does not establish that they belong to the same element.

Step 2: Provide a counterexample Consider ${}^{12}_6\text{C}$ and ${}^{16}_8\text{O}$. Their mass numbers are different, but their atomic numbers are also different, so they are nuclei of different elements rather than isotopes. By contrast, different mass numbers together with equal atomic numbers would establish isotopes.

Step 3: Conclusion No. The nuclei are isotopes only if their atomic numbers are equal; different mass

numbers alone are insufficient.

Quick Tip to Solve: Before calling two nuclei isotopes, check both conditions: equal proton numbers and unequal mass numbers.

OR

3(b)(i). Name the factors on which photoelectric emission from a surface depends. [2 marks total]

Solution:

Concept:

- Photoelectric emission requires a photon energy $h\nu$ at least equal to the surface work function ϕ , where h is Planck's constant.
- For radiation above threshold, intensity controls the supply of photons and hence the rate of photoelectron emission.

Step 1: Identify the threshold factors Emission depends on the nature and condition of the photosensitive surface through its work function, and on the frequency of the incident radiation. The frequency must meet the threshold condition $\nu \geq \nu_0 = \phi/h$. Radiation below threshold cannot cause ordinary photoelectric emission merely by increasing intensity.

Step 2: Identify the factor controlling the rate When the frequency is above threshold, increasing incident intensity increases the number of photons arriving per unit time and therefore the rate of photoelectron emission. The maximum kinetic energy is controlled by frequency and the work function, according to $K_{\max} = h\nu - \phi$, rather than by intensity.

Step 3: Conclusion Photoelectric emission depends on the nature of the surface, the frequency of the incident light, and its intensity (which controls the emission rate above threshold).

Quick Tip to Solve: Separate the onset of emission, controlled by frequency and material, from its rate, controlled by intensity above threshold.

3(b)(ii). Define the term 'threshold frequency' for a photosensitive material.

Solution:

Concept:

- The work function ϕ is the minimum energy required to remove an electron from the surface of a material.
- A photon of frequency ν has energy $h\nu$, where h is Planck's constant.

Step 1: Apply the minimum-energy condition At the threshold, a photon supplies just the work function. The emitted electron has zero maximum kinetic energy in the ideal threshold limit. Substituting $K_{\max} = 0$ in Einstein's equation $h\nu = \phi + K_{\max}$ gives $h\nu_0 = \phi$.

Step 2: Interpret the frequency limit Thus $\nu_0 = \phi/h$ is characteristic of the photosensitive material. For $\nu < \nu_0$, each photon supplies insufficient energy, so no photoelectric emission occurs, irrespective of the intensity of the incident radiation in the ordinary photoelectric effect.

Step 3: Conclusion Threshold frequency ν_0 is the minimum frequency of incident radiation that can produce photoelectric emission from a given photosensitive material, with $\nu_0 = \phi/h$.

Quick Tip to Solve: At threshold put the maximum kinetic energy equal to zero; do not confuse minimum frequency with minimum intensity.

Section B (24 marks)

4(a). Calculate the frequency of a photon of energy 6.5×10^{-19} J.

[3 marks total]

Solution:

Concept:

- Planck's relation for a photon is $E = h\nu$, where E is its energy, ν its frequency and h Planck's constant.
- Frequency is the number of oscillations per second. Using energy in joules and h in J s gives frequency in s^{-1} , or hertz.

Step 1: Express frequency in terms of energy The given energy belongs to a single photon, so apply Planck's relation directly. Rearranging it gives

$$\nu = \frac{E}{h}.$$

Take $E = 6.5 \times 10^{-19}$ J and the supplied constant $h = 6.63 \times 10^{-34}$ J s. No electron-volt conversion is needed because these quantities already use consistent SI units.

Step 2: Substitute and simplify the powers of ten Divide the numerical coefficients and subtract the exponent in the denominator from that in the numerator:

$$\nu = \frac{6.5 \times 10^{-19}}{6.63 \times 10^{-34}} = \frac{6.5}{6.63} \times 10^{15} \text{ s}^{-1} \simeq 9.80 \times 10^{14} \text{ Hz}.$$

The unit check is $\text{J}/(\text{J s}) = \text{s}^{-1}$, as required for a frequency.

Step 3: Conclusion The frequency of the photon is $\nu \simeq 9.8 \times 10^{14} \text{ Hz}$.

Quick Tip to Solve: For a photon energy already in joules, divide directly by h ; keep the exponent subtraction $-19 - (-34) = 15$ explicit.

4(b). Can this photon cause emission of an electron from the surface of Cs of work function 2.14 eV? If yes, what will be maximum kinetic energy of the photoelectron?

Solution:

Concept:

- Photoelectric emission is possible when the incident photon energy E is at least the work function ϕ , the minimum energy needed to liberate an electron from the metal.

- Einstein's photoelectric equation is $K_{\max} = E - \phi$. Both energies must be in the same units, with $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.

Step 1: Compare the photon energy with the work function The photon in part (a) has energy $6.5 \times 10^{-19} \text{ J}$. Convert the work function of Cs to joules:

$$\phi = 2.14 \times 1.6 \times 10^{-19} = 3.424 \times 10^{-19} \text{ J}.$$

Since $6.5 \times 10^{-19} > 3.424 \times 10^{-19}$, the photon has enough energy to overcome the surface barrier. Thus emission is energetically possible.

Step 2: Find the maximum kinetic energy The work function is spent in freeing the electron; the remaining photon energy becomes its maximum kinetic energy:

$$K_{\max} = (6.5 - 3.424) \times 10^{-19} = 3.076 \times 10^{-19} \text{ J}.$$

Equivalently, the photon energy is $6.5/1.6 = 4.0625 \text{ eV}$, giving $K_{\max} = 4.0625 - 2.14 = 1.9225 \text{ eV}$. Electrons that lose energy within the metal can emerge with smaller kinetic energies.

Step 3: Conclusion Yes, the photon can cause photoelectric emission from Cs. The maximum kinetic energy is $K_{\max} \simeq 3.08 \times 10^{-19} \text{ J} \simeq 1.92 \text{ eV}$.

Quick Tip to Solve: Convert joules and electron-volts to a common unit before comparing energies or subtracting the work function.

Monochromatic light of wavelength 600 nm is incident from air on a water surface. The refractive index of water is 1.33.

5(i). Find the wavelength of reflected and refracted light.

[3 marks total]

Solution:

Concept:

- The frequency of light is unchanged on reflection and refraction at a stationary interface. The relation between speed v , frequency ν and wavelength λ is $v = \nu\lambda$.
- Taking the refractive index of air as unity, water's index n gives $v_{\text{water}} = c/n$ and $\lambda_{\text{water}} = \lambda_{\text{air}}/n$.

Step 1: Identify the medium of the reflected light The incident wavelength is 600 nm. The reflected ray remains in air, so its speed and frequency are the same as those of the incident ray. Its wavelength is therefore unchanged:

$$\lambda_{\text{reflected}} = 600 \text{ nm}.$$

Step 2: Calculate the wavelength in water The refracted wave enters water of refractive index 1.33. Its speed decreases by this factor while its frequency remains fixed, so its wavelength also decreases:

$$\lambda_{\text{refracted}} = \frac{600}{1.33} \text{ nm} \simeq 451 \text{ nm}.$$

The shorter wavelength is consistent with propagation in the optically denser medium.

Step 3: Conclusion The reflected wavelength is 600 nm , and the refracted wavelength is 451 nm (approximately).

Quick Tip to Solve: First identify each ray's medium: reflection stays in air, while the wavelength in water is the air wavelength divided by 1.33.

5(ii). Find the frequency of reflected and refracted light.

Solution:

Concept:

- The incident frequency is $\nu = c/\lambda_{\text{air}}$, taking the speed of light in air as $c = 3 \times 10^8 \text{ m s}^{-1}$.
- At a stationary boundary, the reflected and transmitted waves have the same frequency as the incident wave. The source sets the frequency; a change of medium changes speed and wavelength.

Step 1: Calculate the frequency of the incident light Convert the given incident wavelength to metres before applying the wave relation:

$$\lambda_{\text{air}} = 600 \text{ nm} = 600 \times 10^{-9} \text{ m}.$$

Hence,

$$\nu = \frac{3 \times 10^8}{600 \times 10^{-9}} = 5.0 \times 10^{14} \text{ Hz}.$$

Step 2: Apply frequency continuity at the boundary Both the reflected wave in air and the refracted wave in water are produced by the same incident oscillations. Therefore neither frequency is divided by the refractive index 1.33. In water, speed and wavelength decrease by the same factor, keeping their ratio v/λ unchanged.

Step 3: Conclusion The reflected frequency and the refracted frequency are equal. Each is $5.0 \times 10^{14} \text{ Hz}$.

Quick Tip to Solve: Compute c/λ once in air, then retain that frequency for both rays at the stationary air-water boundary.

5(iii). Find the speed of reflected and refracted light.

Solution:

Concept:

- The refractive index of a medium is $n = c/v$, where c is the vacuum light speed and v is the light speed in that medium. Thus $v = c/n$.
- The reflected ray remains in air, whose refractive index is approximately unity; the refracted ray travels through water, whose given refractive index is 1.33.

Step 1: Determine the reflected light speed Reflection changes the direction of propagation but does not change the medium. Consequently the reflected light has the same speed as the incident light in

air:

$$v_{\text{reflected}} \simeq c = 3.0 \times 10^8 \text{ m s}^{-1}.$$

Step 2: Calculate the refracted light speed Refraction carries the light into water, so use the given refractive index in $v = c/n$:

$$v_{\text{refracted}} = \frac{3.0 \times 10^8}{1.33} \simeq 2.26 \times 10^8 \text{ m s}^{-1}.$$

This is smaller than the speed in air, as expected for a medium with refractive index greater than unity. The frequency stays fixed while the wavelength decreases along with the speed.

Step 3: Conclusion The reflected light speed is $3.0 \times 10^8 \text{ m s}^{-1}$; the refracted light speed is $2.26 \times 10^8 \text{ m s}^{-1}$.

Quick Tip to Solve: Divide c by 1.33 only for the ray inside water; the reflected ray still travels in air.

6(a). Electromagnetic waves of wavelengths λ_1 , λ_2 and λ_3 are used in radar systems, in water purifiers and in remote switches of TV, respectively.

(i) Identify the electromagnetic waves, and

(ii) Write one source of each of them.

[3 marks]

Solution:

Concept:

- The electromagnetic spectrum contains waves with different wavelengths and applications. All travel in vacuum with speed c , related to frequency ν by $c = \nu\lambda$.
- Identify the spectral region from the stated application, then give a device or physical process that produces that radiation. The source must correspond to the identified wave.

Step 1: Identify the radiation used by radar Radar systems use **microwaves**, so the radiation of wavelength λ_1 belongs to the microwave region. Their short wavelength permits a well-directed beam, and the reflected signal is used to locate an object. One source is a **magnetron**, in which the motion of electrons in electric and magnetic fields generates microwave radiation.

Step 2: Identify the radiation used in water purification Water purifiers use **ultraviolet radiation**, so λ_2 belongs to the ultraviolet region. This radiation has a germicidal action, damaging microorganisms and reducing their ability to reproduce. One source is a **mercury-vapour discharge lamp**, which emits ultraviolet radiation when excited mercury atoms return to lower energy states.

Step 3: Identify the radiation used in a television remote Television remote switches use **infrared radiation**, so λ_3 belongs to the infrared region. A coded infrared signal sent from the handset is detected by a receiver in the television. One source is an **infrared light-emitting diode (LED)**, which emits infrared radiation when current flows through its forward-biased semiconductor junction.

Step 4: Conclusion λ_1 : microwaves, produced by a magnetron; λ_2 : ultraviolet radiation, produced by a mercury-vapour lamp; λ_3 : infrared radiation, produced by an infrared LED.

Quick Tip to Solve: Match the three applications in the printed order: radar means microwaves, sterilisation means ultraviolet, and a TV remote means infrared.

6(b). (i) State two conditions for two light sources to be coherent.

(ii) Give two points of difference between an interference pattern due to a double-slit and a diffraction pattern due to a single slit.

[3 marks]

Solution:

Concept:

- Coherence means that the relative phase of two waves remains fixed with time. For sources of frequencies ν_1 and ν_2 , their phase difference changes as $\Delta\phi(t) = 2\pi(\nu_1 - \nu_2)t + \Delta\phi_0$.
- Double-slit interference results from superposition of waves from two coherent slits. Single-slit diffraction results from superposition of secondary wavelets from different points across the same slit.

Step 1: State the two conditions for coherence (i) The two sources must emit light of the **same frequency** (and hence the same wavelength in the same medium). (ii) They must maintain a **constant phase difference** with time. The phase difference need not be zero. Equal frequency removes the time-dependent term in $\Delta\phi(t)$, while the second condition excludes random changes of relative phase. Equal amplitudes are useful for high contrast but are not a condition for coherence.

Step 2: Compare the widths of the fringes For ideal double-slit interference, successive bright or successive dark fringes are equally spaced, with fringe width $\beta = \lambda D/d$, where d is slit separation and D is screen distance. For single-slit diffraction, the central bright maximum has width $2\lambda D/a$, twice the approximate width $\lambda D/a$ of each secondary bright maximum, where a is slit width. Thus the diffraction central maximum is broader than its secondary maxima, whereas the ideal interference fringes have equal widths.

Step 3: Compare the intensities of the bright fringes In ideal double-slit interference with equal slit intensities and negligible diffraction envelope, the bright fringes have equal maximum intensity. In single-slit diffraction, the central maximum is the most intense, and successive secondary maxima become progressively weaker on either side. For real slits of finite width, interference fringes are modulated by a diffraction envelope; the equal-intensity comparison refers to the standard ideal interference pattern.

Step 4: Conclusion Coherent sources have equal frequencies and a constant phase difference. The two pattern differences concern width (equal interference fringes versus a diffraction central maximum of twice the secondary width) and intensity (equal ideal interference maxima versus progressively weaker diffraction maxima).

Quick Tip to Solve: For this comparison, use the two headings width and intensity. State the ideal double-slit assumption before saying that all its bright fringes are equally intense.

7. State Bohr's postulate to explain stable orbits in a hydrogen atom. Prove that the speed with which the electron revolves in n^{th} orbit is proportional to $(1/n)$.

[3 marks]

Solution:

Concept:

- Bohr's stationary-orbit postulate states that an electron can revolve only in certain permitted orbits without radiating energy. Its energy is constant while it remains in a stationary orbit.

- In an allowed orbit, angular momentum is quantised: $m_e v_n r_n = n\hbar = nh/(2\pi)$, where $n = 1, 2, 3, \dots$, m_e is the electron mass, v_n its speed and r_n the orbit radius.
- For hydrogen, electrostatic attraction between charges $+e$ and $-e$ supplies the centripetal force; $k = 1/(4\pi\epsilon_0)$.

Step 1: State the condition for stable orbits Although a revolving electron is accelerated, Bohr postulated that it does not emit electromagnetic radiation while occupying an allowed stationary orbit. It therefore does not continuously lose energy and spiral into the nucleus. Only those circular orbits for which $m_e v_n r_n = n\hbar/(2\pi)$ are permitted. Radiation is emitted or absorbed only when the electron makes a transition between stationary orbits.

Step 2: Write the orbital force equation Equating the magnitude of Coulomb attraction to the centripetal force gives

$$\frac{ke^2}{r_n^2} = \frac{m_e v_n^2}{r_n} \Rightarrow m_e v_n^2 r_n = ke^2.$$

Here the nucleus is treated as fixed, as in the standard Bohr model for hydrogen. This equation relates the electron's speed to the radius of the same orbit.

Step 3: Eliminate the radius using quantisation Divide the force equation in the form $m_e v_n^2 r_n = ke^2$ by the angular-momentum equation $m_e v_n r_n = n\hbar$:

$$v_n = \frac{ke^2}{n\hbar} = \frac{e^2}{2\epsilon_0 h} \frac{1}{n}.$$

All factors except n are constants for hydrogen, so increasing the orbit number decreases the orbital speed in inverse proportion.

Step 4: Conclusion Bohr's allowed stationary orbits are stable because the electron does not radiate in them, and their angular momentum is quantised. The orbital speed is $v_n = e^2/(2\epsilon_0 h n)$, hence

$$v_n \propto 1/n.$$

Quick Tip to Solve: Divide $m_e v_n^2 r_n = ke^2$ by $m_e v_n r_n = n\hbar$; the radius cancels immediately, leaving the required dependence of speed on n .

8. Draw the energy band diagrams for conductors, semiconductors and insulators. Which band determines the electrical conductivity of a solid? How is the electrical conductivity of a semiconductor affected with rise in its temperature? Explain. [3 marks]

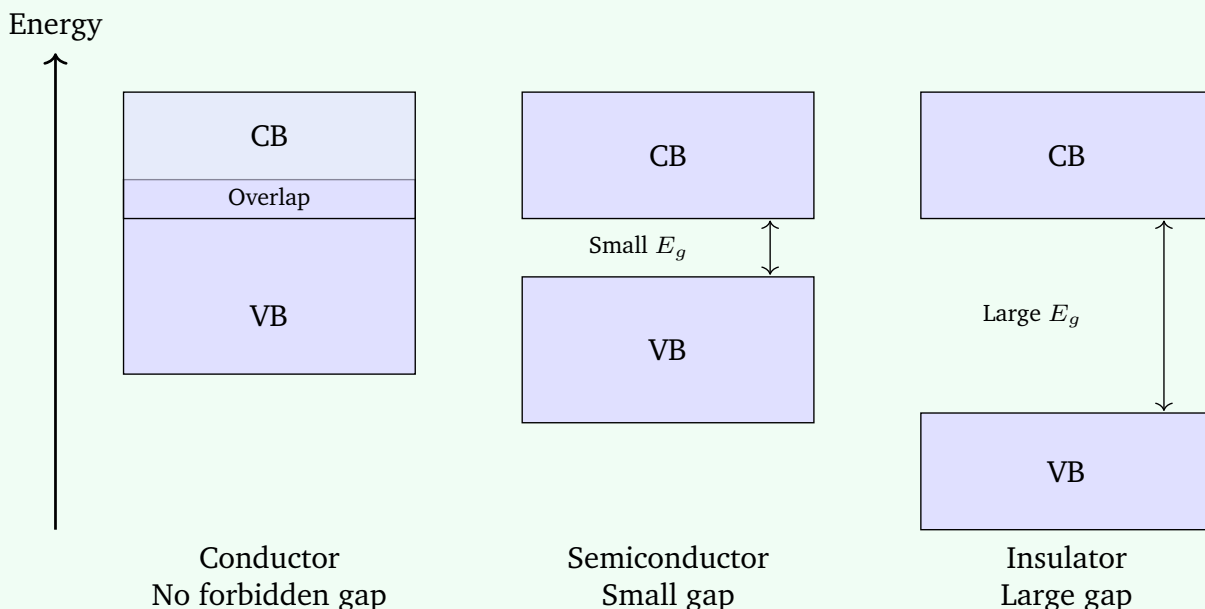
Solution:

Concept:

- The valence band (VB) contains the valence-electron states; the conduction band (CB) contains higher-energy states in which mobile electrons can contribute to conduction.
- The forbidden energy gap is $E_g = E_C - E_V$, where E_C is the bottom of the conduction band and E_V the top of the valence band. Its size controls how readily electrons can reach the conduction band.
- Semiconductor conductivity is $\sigma = e(n\mu_e + p\mu_h)$, where n, p are electron and hole concentrations and μ_e, μ_h their mobilities.

Step 1: Compare the three energy-band diagrams The schematic diagrams below show increasing

energy upwards. In a conductor, the valence and conduction bands overlap (or an allowed band is partly filled), so nearby vacant states are available and electrons respond readily to an electric field. In a semiconductor the bands are separated by a small forbidden gap, typically of the order of 1 eV. In an insulator the gap is much larger, so very few electrons gain sufficient thermal energy to cross it at ordinary temperatures. The shaded rectangles represent allowed bands, and the blank space between separated bands represents forbidden energies.



Schematic energy bands: CB = conduction band, VB = valence band (not to scale).

Step 2: Identify the band responsible for conduction The **conduction band**, particularly the availability of mobile electrons and vacant states in it, determines electron conduction in a solid. A completely filled valence band cannot carry a net current by itself because there are no nearby vacant states for electrons to occupy. In a semiconductor, excitation of an electron into the conduction band also leaves a mobile hole in the valence band; both carriers contribute to conductivity.

Step 3: Explain the effect of increasing temperature On heating a semiconductor, more valence electrons acquire enough energy to cross the small forbidden gap. Each excitation creates a conduction electron and a valence-band hole, increasing both carrier concentrations. Although increased lattice scattering tends to reduce mobility, the thermal increase in carrier concentration dominates in the usual intrinsic-semiconductor description. Thus $\sigma = e(n\mu_e + p\mu_h)$ increases and resistivity $\rho = 1/\sigma$ decreases; semiconductors have a negative temperature coefficient of resistance in this regime.

Step 4: Conclusion Conductors have overlapping or partly filled bands; semiconductors have a small band gap and insulators a large gap. The conduction band enables electron conduction. A semiconductor's conductivity increases on heating because thermal excitation creates more electron-hole pairs.

Quick Tip to Solve: Draw the same conduction-band level in all three sketches, then show overlap, a small gap and a large gap. On heating a semiconductor, count the extra electron-hole pairs.

9. A narrow beam of protons, each having 4.1 MeV energy is approaching a sheet of lead ($Z = 82$). Calculate:

(i) the speed of a proton in the beam, and

(ii) the distance of its closest approach.

[3 marks]

Solution:

Concept:

- The kinetic energy of a non-relativistic proton is $K = \frac{1}{2}m_p v^2$, where m_p is its mass and v is its speed.
- In a head-on approach to a heavy nucleus, electrostatic repulsion converts the proton's initial kinetic energy into electric potential energy. At the closest approach, $K = \frac{1}{4\pi\epsilon_0} \frac{Ze^2}{r_{\min}}$, taking potential energy zero at infinity.

Step 1: Convert the energy to SI units The beam particles are protons, each of charge $+e$. With $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$, their kinetic energy is

$$K = 4.1 \times 10^6 \times 1.6 \times 10^{-19} = 6.56 \times 10^{-13} \text{ J}.$$

Use $m_p = 1.67 \times 10^{-27} \text{ kg}$ and the nuclear charge $Ze = 82e$.

Step 2: Calculate the proton speed for part (i) Rearranging the kinetic-energy formula gives

$$v = \sqrt{\frac{2K}{m_p}} = \sqrt{\frac{2(6.56 \times 10^{-13})}{1.67 \times 10^{-27}}} = \sqrt{7.86 \times 10^{14}} \text{ m s}^{-1}.$$

The resulting speed is about $0.093c$, so the non-relativistic expression is appropriate for the required accuracy.

Step 3: Apply energy conservation for part (ii) For the minimum head-on distance, the proton momentarily comes to rest relative to the lead nucleus. Neglecting recoil of the much heavier nucleus, its entire initial kinetic energy becomes electrostatic potential energy. Hence

$$\begin{aligned} r_{\min} &= \frac{(9 \times 10^9)(82)(1.6 \times 10^{-19})^2}{6.56 \times 10^{-13}} \\ &= 2.88 \times 10^{-14} \text{ m}. \end{aligned}$$

The charge product is $e(82e)$, because the incident particle is a proton; the alpha-particle factor of two does not apply.

Step 4: Conclusion (i) The proton speed is $v \approx 2.8 \times 10^7 \text{ m s}^{-1}$. (ii) Its distance of closest approach to the lead nucleus is $r_{\min} \approx 2.9 \times 10^{-14} \text{ m}$.

Quick Tip to Solve: Convert MeV to joules before finding speed, and use the proton charge e , not $2e$, in the closest-approach energy equation.

10. How is the spacing between fringes in a double slit experiment affected if:

(i) the slits separation is increased,

(ii) the colour of light used is changed from red to blue,

(iii) the whole apparatus is submerged in a oil of refractive index 1.2?

Justify your answer in each case.

[3 marks]

Solution:

Concept:

- In Young's double-slit experiment, the fringe spacing is $\beta = \frac{\lambda D}{d}$, where λ is the wavelength in the propagation medium, D the slit-to-screen distance, and d the slit separation.
- When light enters a medium of refractive index μ , its frequency remains unchanged while its speed and wavelength decrease: $v = c/\mu$ and $\lambda_{\text{medium}} = \lambda_{\text{air}}/\mu$, taking the refractive index of air as unity.

Step 1: Increase the slit separation for part (i) Keep the wavelength and screen distance fixed. If the slit separation changes from d to d' , then

$$\frac{\beta'}{\beta} = \frac{d}{d'}.$$

Since $d' > d$, this ratio is less than one. The fringes move closer together because fringe spacing is inversely proportional to slit separation.

Step 2: Replace red light with blue light for part (ii) With the same slit separation and screen distance, fringe spacing is directly proportional to the wavelength. Blue light has a shorter wavelength than red light, so

$$\frac{\beta_{\text{blue}}}{\beta_{\text{red}}} = \frac{\lambda_{\text{blue}}}{\lambda_{\text{red}}} < 1.$$

Thus the blue fringe pattern has smaller spacing. A numerical ratio cannot be specified without the particular red and blue wavelengths.

Step 3: Immerse the entire apparatus in oil for part (iii) The geometrical distances D and d are unchanged. The wavelength in oil becomes $\lambda/1.2$, because light travels more slowly while its frequency stays fixed. Therefore

$$\beta_{\text{oil}} = \frac{(\lambda/1.2)D}{d} = \frac{\beta_{\text{air}}}{1.2} = \frac{5}{6}\beta_{\text{air}}.$$

The fractional decrease is $1 - 5/6 = 1/6$, corresponding to about 16.7% of the original fringe spacing.

Step 4: Conclusion Fringe spacing decreases in all three cases: (i) it varies inversely with slit separation, (ii) blue light produces narrower fringes than red light, and (iii) in oil it becomes 5/6 of its value in air.

Quick Tip to Solve: Start with $\beta = \lambda D/d$: change only the quantity specified in each part, and replace λ by λ/μ when the whole apparatus is immersed.

11(a)(a). Write two necessary conditions for total internal reflection.

[3 marks total]

Solution:

Concept:

- Total internal reflection is the complete return of a ray into the incident medium at an interface, with no refracted ray propagating into the other medium.

- For refractive indices $n_1 > n_2$, the critical angle C is defined by $\sin C = n_2/n_1$; at this angle the refracted ray grazes the interface.

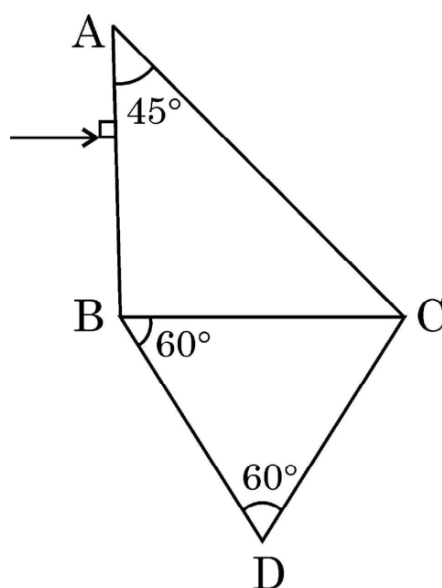
Step 1: Identify the direction of travel The ray must travel from an optically denser medium towards an optically rarer medium, so that $n_1 > n_2$. In this direction refraction bends the ray away from the normal. A ray travelling from a rarer to a denser medium cannot undergo total internal reflection at that interface.

Step 2: Compare incidence with the critical angle The angle of incidence i , measured from the normal in the denser medium, must be strictly greater than C . Snell's law would then require $\sin r = (n_1/n_2) \sin i > 1$, which is impossible for a transmitted ray. At $i = C$, the limiting refracted ray lies along the interface; therefore equality is not the condition for total internal reflection.

Step 3: Conclusion The two necessary conditions are: light travels from an optically denser to an optically rarer medium, and its angle of incidence exceeds the critical angle for that pair of media, $i > C$.

Quick Tip to Solve: Always measure incidence from the normal, and use the strict inequality $i > C$, not $i = C$.

11(a)(b). Two prisms ABC and DBC are arranged as shown in figure. The critical angles for the two prisms with respect to air are 41.1° and 45° respectively. Trace the path of the ray through the combination.



Solution:

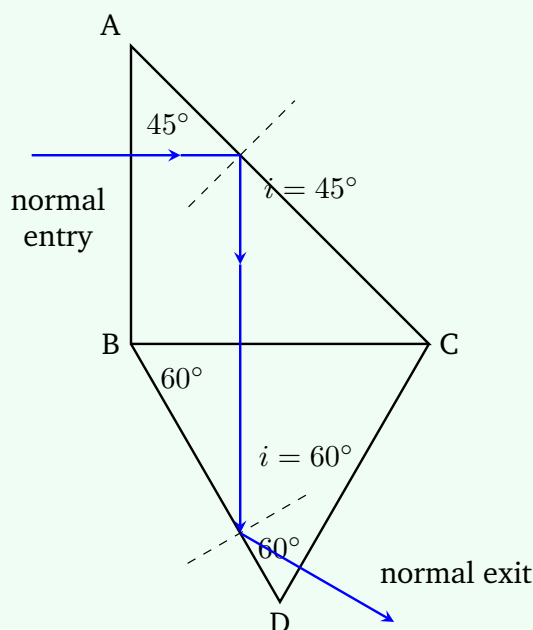
Concept:

- A ray entering normally does not change direction. Total internal reflection occurs at a prism–air face when the incidence angle exceeds that prism's critical angle.
- At a reflecting face, the angle of reflection equals the angle of incidence; all angles of incidence are measured from the normal.

Step 1: Trace the ray through prism ABC The incident horizontal ray meets the vertical face AB normally and enters without deviation. Since $\angle A = 45^\circ$, it meets AC at $i = 45^\circ$. As $45^\circ > 41.1^\circ$, it undergoes total internal reflection at AC and travels vertically downwards. It meets the common face BC normally and enters prism DBC without angular deviation, even though the two prisms have

different refractive indices.

Step 2: Trace the ray through prism DBC In the equilateral prism DBC, BD makes 60° with BC. The downward ray therefore makes 60° with the normal to BD. Since $60^\circ > 45^\circ$, it undergoes a second total internal reflection. The reflected ray then travels towards DC perpendicular to that face, and emerges into air without further deviation. The arrows in the diagram show this sequence through both prisms.



Ray path through ABC and DBC; dashed lines show the normals at the reflecting faces.

Step 3: Conclusion The path is: normal entry at AB, total internal reflection at AC, normal crossing of BC, total internal reflection at BD, and normal emergence from DC.

Quick Tip to Solve: After the first reflection draw the ray perpendicular to BC; the equilateral lower prism then gives 60° incidence at BD and normal exit at DC.

OR

An object is placed in front of a converging lens. Obtain the conditions under which the magnification produced by the lens is

11(b)(a)(i). negative and

[3 marks total]

Solution:

Concept:

- For a thin converging lens, $f > 0$. A real object on the incident side has $u = -a$, where $a > 0$ is its distance from the lens.
- The lens formula and transverse magnification are $1/f = 1/v - 1/u$ and $m = v/u$, respectively.

Step 1: Express magnification using object distance With $u = -a$, the lens formula gives $1/v = 1/f - 1/a$, hence $v = fa/(a - f)$ and $m = -f/(a - f)$.

Step 2: Determine when the sign is negative Since $f > 0$, magnification is negative if $a - f > 0$. Thus the real object must lie beyond the principal focus on the incident side. The image then lies on the

other side of the lens and is real and inverted. At $a = f$, the emerging rays are parallel and there is no finite image.

Step 3: Conclusion Negative magnification occurs when the object is beyond the principal focus: $|u| > f$, or $u < -f$.

Quick Tip to Solve: For a real object, negative magnification means an inverted image; a converging lens gives this when the object is outside its focal length.

11(b)(a)(ii). positive.

Solution:

Concept:

- For a converging lens $f > 0$, while a real object at distance a on the incident side has $u = -a$.
- Transverse magnification is $m = v/u = -f/(a - f)$, obtained from the thin-lens formula.

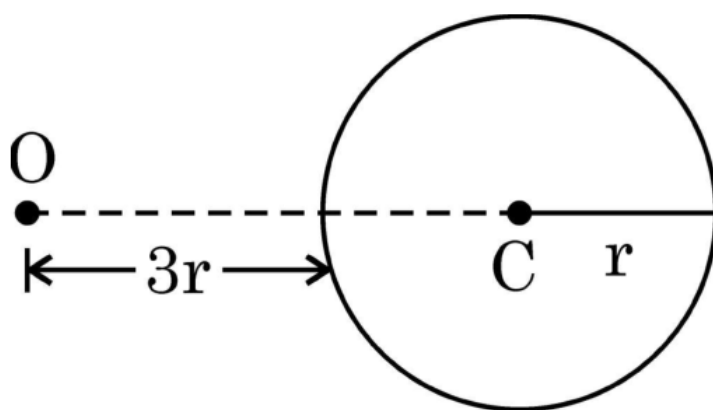
Step 1: Apply the positive-sign condition For $m > 0$, the denominator $a - f$ must be negative. As $a > 0$, this requires $0 < a < f$: the object lies between the optical centre and the principal focus.

Step 2: Identify the corresponding image Now $v = fa/(a - f) < 0$, so the image is on the same side as the object. It is virtual and erect, with $m = f/(f - a) > 1$. At the focal point the image is at infinity, so this boundary position is excluded from the finite positive-magnification case.

Step 3: Conclusion Positive magnification occurs for an object between the optical centre and principal focus: $0 < |u| < f$, or $-f < u < 0$.

Quick Tip to Solve: Inside the focal length, a converging lens acts as a magnifier: its image is virtual, erect and enlarged.

11(b)(b). A point object is placed at O in front of a glass sphere as shown in figure. Show the formation of image by the sphere.



Solution:

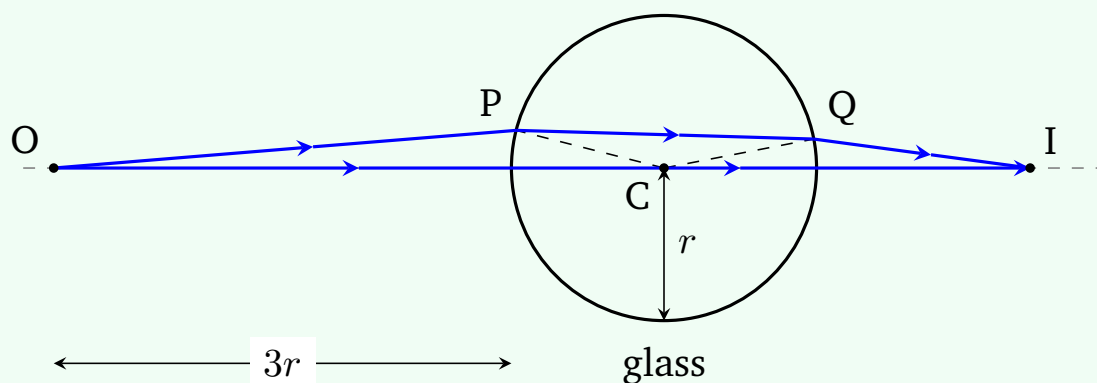
Concept:

- A glass sphere forms an image by successive refraction at its front and rear spherical surfaces. The normal at either surface is the radius through the point of incidence.
- At the air–glass surface a ray bends towards the normal; at the glass–air surface it bends away

from the normal. The axial ray passes normally through both surfaces.

Step 1: Refract the rays at the first surface Draw the axial ray from O through C; it remains undeviated. A second paraxial ray from O strikes the upper part of the front surface at P and bends towards the radius CP on entering glass. It travels through the sphere to Q on the rear surface.

Step 2: Locate the final image At Q the ray emerges into air, bending away from the radius CQ. Its intersection with the undeviated axial ray gives the final real image I on the far side of the sphere, as shown schematically for ordinary glass. O is placed $3r$ from the front surface, as in the given figure. The question supplies no numerical refractive index, so the sketch does not assign a numerical distance to I.



Schematic paraxial image formation by the sphere; dashed radii give the normals.

Step 3: Conclusion The two successive refractions form the image at I, where the emerging paraxial ray meets the principal axis beyond the glass sphere.

Quick Tip to Solve: Draw the radii CP and CQ first: they are the two different normals needed to bend the ray correctly at entry and exit.

Section C (5 marks)

CASE STUDY

12. A compound microscope consists of two converging lenses. One of them, of smaller aperture and smaller focal length is called objective and the other of slightly larger aperture and slightly larger focal length is called eye-piece. Both the lenses are fitted in a tube with an arrangement to vary the distance between them. A tiny object is placed in front of the objective at a distance slightly greater than its focal length. The objective produces the image of the object which acts as an object for the eye-piece. The eye piece, in turn produces the final magnified image. [5 marks]

12(I). In a compound microscope the images formed by the objective and the eye-piece are respectively [1 mark]

- (A) virtual, real
- (B) real, virtual
- (C) virtual, virtual
- (D) real, real

Correct Answer: (B) real, virtual

Solution:

Concept:

- A converging lens forms a real image of a real object placed beyond its focal length.
- The eyepiece acts as a simple magnifier: the intermediate image is within its focal length, or at its focal plane for normal adjustment.

Step 1: Identify the objective image The tiny object is just beyond the objective's principal focus. Rays from it actually converge after passing through the objective, producing a real, inverted and enlarged intermediate image. Thus options (A) and (C), which call this image virtual, are incorrect.

Step 2: Identify the eyepiece image The intermediate image acts as the object for the eyepiece. The eyepiece is adjusted to give a magnified virtual final image for comfortable viewing. It is at the near point or, in normal adjustment, at infinity. Option (D) incorrectly describes the eyepiece image as real.

Step 3: Conclusion The objective forms a real image and the eyepiece forms a virtual image. Hence, the correct option is (B).

Quick Tip to Solve: Follow the two lenses separately: the objective projects a real intermediate image, and the eyepiece magnifies it virtually.

12(II). The magnification due to a compound microscope does not depend upon

[1 mark]

- (A) the aperture of the objective and the eye-piece
- (B) the focal length of the objective and the eye-piece
- (C) the length of the tube
- (D) the colour of the light used

Correct Answer: (A) the aperture of the objective and the eye-piece

Solution:

Concept:

- For normal adjustment, the magnitude of magnifying power is approximately $M = (L/f_o)(D/f_e)$, where L is the optical tube length, f_o, f_e are the focal lengths, and D is the least distance of distinct vision.
- Lens aperture governs light collection and influences resolution, while the paraxial magnification depends on focal lengths and conjugate distances.

Step 1: Check the geometric quantities The magnification formula explicitly includes the objective focal length, eyepiece focal length and tube length. Consequently, changing these quantities changes the magnifying power, so options (B) and (C) are unsuitable. Neither lens aperture appears in the expression.

Step 2: Check the effect of colour For ordinary refracting lenses the refractive index depends on wavelength. A change of colour therefore changes the focal lengths and can change magnification. Option (D) is not the required independent quantity. Altering aperture alone, with the same lens powers and geometry, changes illumination or resolving ability but not the paraxial magnification.

Step 3: Conclusion Magnification does not depend upon the aperture of the objective and the eyepiece. Hence, the correct option is (A).

Quick Tip to Solve: Write the magnification formula first; remember that colour can enter indirectly through the wavelength dependence of focal length.

12(III). Which of the following is not correct in the context of a compound microscope?

[1 mark]

- (A) Both the lenses are of short focal lengths.
- (B) The magnifying power increases by decreasing the focal lengths of the two lenses.
- (C) The distance between the two lenses is more than $(f_o + f_e)$.
- (D) The microscope can be used as a telescope by interchanging the two lenses.

Correct Answer: (D) The microscope can be used as a telescope by interchanging the two lenses.

Solution:

Concept:

- A compound microscope uses an objective of short focal length f_o and an eyepiece of short focal length f_e to magnify a nearby tiny object.
- In normal adjustment, the magnifying power is approximately $M = (L/f_o)(D/f_e)$, where L is the optical tube length and D is the least distance of distinct vision.

Step 1: Check the microscope statements Both focal lengths are short, so (A) is correct. For fixed tube length, reducing either focal length increases the magnifying power, so (B) is correct. In normal

adjustment the objective forms its real intermediate image at distance $v_o > f_o$, and the eyepiece is a further f_e away. Thus the lens separation $v_o + f_e$ exceeds $f_o + f_e$, consistent with (C).

Step 2: Compare the telescope requirements An astronomical telescope requires an objective of large aperture and long focal length, together with an eyepiece of short focal length. Interchanging the two short-focal-length microscope lenses does not provide the required telescope objective. Thus (D) is the incorrect statement sought here; the other options describe the usual microscope arrangement.

Step 3: Conclusion Merely interchanging the two lenses does not convert a compound microscope into a telescope. Hence, the correct option is (D).

Quick Tip to Solve: For an incorrect-statement question, contrast the short-focal-length microscope objective with the long-focal-length telescope objective.

12(IV). A compound microscope consists of an objective of 10X and an eye-piece of 20X. The magnification due to the microscope would be [1 mark]

- (A) 2
- (B) 10
- (C) 30
- (D) 200

Correct Answer: (D) 200

Solution:

Concept:

- The objective produces an enlarged intermediate image; the eyepiece then magnifies that image for the observer.
- The total magnifying power is the product $M = |m_o|M_e$, where $|m_o|$ is the objective's linear magnification and M_e is the eyepiece's angular magnification.

Step 1: Identify the two magnifications The label 10X on the objective means that its intermediate image is ten times the object size. The 20X eyepiece supplies a further factor of twenty in angular magnification. Hence $|m_o| = 10$ and $M_e = 20$; these are successive factors, not focal lengths.

Step 2: Multiply the successive factors The eyepiece acts on the image already enlarged by the objective, so

$$M = 10 \times 20 = 200.$$

Dividing gives 2 and adding gives 30, but neither operation describes successive magnification. The value 10 accounts only for the objective and omits the eyepiece. These observations rule out (A), (C), and (B), respectively.

Step 3: Conclusion The microscope has magnifying power 200, conventionally written 200X. Hence, the correct option is (D).

Quick Tip to Solve: Multiply the objective and eyepiece X ratings; never add them or take their ratio for a compound microscope.

12(V). The focal lengths of objective and eye-piece of a compound microscope are 1.2 cm and 3.0 cm respectively. The object is placed at a distance of 1.25 cm from the objective. If the final image is formed at infinity, the magnifying power of the microscope would be [1 mark]

- (A) 100
- (B) 150
- (C) 200
- (D) 250

Correct Answer: (C) 200

Solution:

Concept:

- For the objective, the Cartesian lens formula is $1/f_o = 1/v_o - 1/u_o$, where $u_o < 0$ for a real object and $v_o > 0$ for its real image.
- For the final image at infinity, $M = |v_o/u_o|(D/f_e)$, with the standard least distance of distinct vision $D = 25$ cm.

Step 1: Locate the intermediate image Use $f_o = 1.2$ cm and $u_o = -1.25$ cm. The lens formula gives

$$\frac{1}{v_o} = \frac{1}{1.2} - \frac{1}{1.25} = \frac{5}{6} - \frac{4}{5} = \frac{1}{30} \text{ cm}^{-1},$$
$$v_o = 30 \text{ cm}.$$

Thus the objective's magnification has magnitude $|m_o| = 30/1.25 = 24$.

Step 2: Apply the eyepiece magnification The eye is relaxed because the final image is at infinity. The eyepiece therefore has magnifying power $M_e = D/f_e = 25/3$, without the extra 1 used for a final image at the near point. Hence

$$M = 24 \times \frac{25}{3} = 200.$$

The other values 100, 150, and 250 do not equal the product of the objective and eyepiece factors. Magnifying power here denotes the positive magnitude; the final image is inverted relative to the object.

Step 3: Conclusion The magnifying power of the compound microscope is 200. Hence, the correct option is (C).

Quick Tip to Solve: When the object distance is supplied, find the exact objective magnification first; for a final image at infinity use only D/f_e .