IB DP PHYSICS

Theme C · Wave Behaviour

MARK SCHEME

C.1 Simple Harmonic Motion · C.2 Wave Model · C.3 Wave Phenomena
C.4 Standing Waves and Resonance · C.5 Doppler Effect

Standard and Higher Level · Syllabus 2025

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Original exam-style questions written for the IB Diploma Programme Physics course (first assessment 2025)

Section A — Multiple Choice: Answer Key (15 marks)

1. Answer: **C** — SHM is defined by $a = -\omega^2 x$: the acceleration is always directed towards the equilibrium position and is proportional to the displacement from it.

2. Answer: **C** — $T = 2\pi\sqrt{(m/k)} = 2\pi\sqrt{(0.50/20)} = 0.99$ s.

3. Answer: **B** — $E = \frac{1}{2}kx_0^2 = 0.5 \cdot 20 \cdot 0.10^2 = 0.10$ J.

4. Answer: **B** — $v = f\lambda = 50 \cdot 0.020 = 1.0$ m s^{-1}.

5. Answer: **A** — In a longitudinal wave (e.g. sound), particles oscillate parallel to (along) the direction in which the wave — and its energy — travels.

6. Answer: **C** — All electromagnetic waves travel at the same speed c in a vacuum, regardless of frequency or wavelength.

7. Answer: **A** — $n_1 \sin\theta_1 = n_2 \sin\theta_2 \Rightarrow \theta_2 = \sin^{-1}(\sin 30° \cdot 1.00/1.33) = 22.1°$.

8. Answer: **B** — Noticeable diffraction requires the wavelength to be comparable to or larger than the size of the aperture or obstacle.

9. Answer: **B** — A path difference of a whole number of wavelengths means the two waves arrive in phase, producing constructive interference (a bright fringe).

10. Answer: **B** — For a string fixed at both ends, $\lambda_1 = 2L = 1.0$ m, so $f_1 = v/\lambda_1 = 200/1.0 = 200$ Hz.

11. Answer: **B** — A node is a point of permanent zero displacement, formed by destructive superposition of the two component waves at that point.

12. Answer: **C** — A closed pipe has a displacement node at the closed end and an antinode at the open end; this boundary condition can only be satisfied by odd-numbered harmonics.

13. Answer: **C** — $f_{observed} = f_0 v/(v - v_s) = 1000 \cdot 340/(340 - 20) = 1062.5$ Hz.

14. Answer: **B** — Relative motion between the source and observer changes the effective wavelength of the waves reaching the observer, and hence the frequency they detect; the wave speed through the medium itself is unaffected.

15. Answer: **C** — An increase in observed wavelength (redshift) corresponds to the source receding from the observer, by the Doppler effect for light.

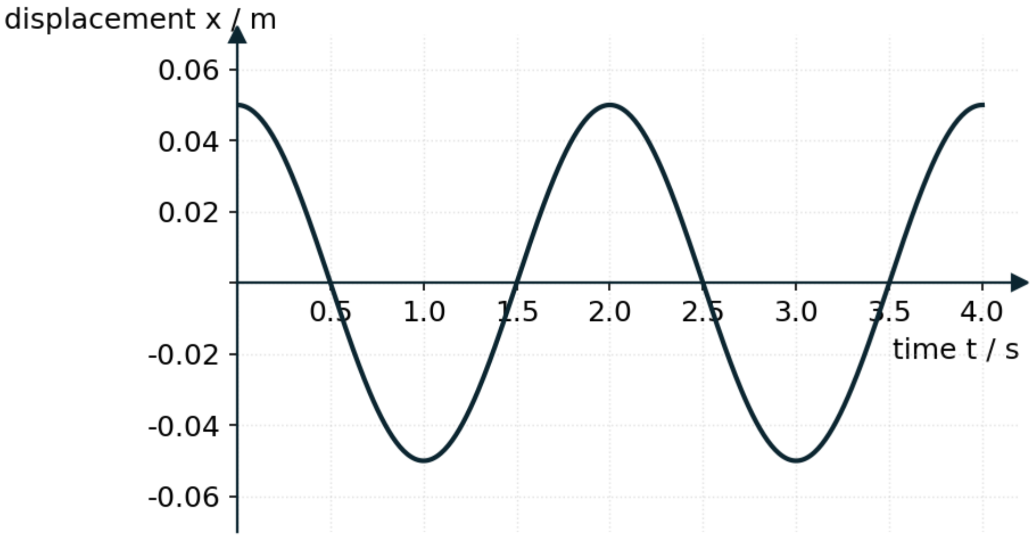
Section B — Structured Questions: Worked Solutions (66 marks)

Mark-scheme notation: M = method mark, A = accuracy mark (dependent on the preceding M mark), R = reasoning mark.

C.1 Simple Harmonic Motion

Question 1 [6 marks]

A small object undergoes simple harmonic motion. The graph shows its displacement x from the equilibrium position as a function of time t.



Displacement–time graph for the SHM oscillator (amplitude and period are the given data for this question).

(a) Use the graph to determine the amplitude and period of the oscillation, and hence calculate the angular frequency ω. **[2]**

Amplitude x_0 = 0.050 m; period T = 2.0 s. **M1 A1**
$\omega = 2\pi/T = 2\pi/2.0 =$ **3.142 rad s^{-1}**.

(b) Calculate the maximum speed of the object during the oscillation. **[2]**

$v_{max} = \omega x_0 = 3.142 \cdot 0.050 =$ **0.157 m s^{-1}**. **M1 A1**

(c) Calculate the magnitude of the maximum acceleration of the object. **[2]**

$a_{max} = \omega^2 x_0 = 3.142^2 \cdot 0.050 =$ **0.493 m s^{-2}**. **M1 A1**

Question 2 [6 marks]

A simple pendulum of length 0.80 m swings with amplitude 0.030 m and bob mass 0.20 kg. Take g = 9.8 m s^{-2}. For small oscillations, a simple pendulum undergoes approximately simple harmonic motion with $T = 2\pi\sqrt{L/g}$.

(a) Calculate the period of oscillation of the pendulum. **[2]**

$T = 2\pi\sqrt{L/g} = 2\pi\sqrt{0.80/9.8} =$ **1.795 s**. **M1 A1**

(b) Calculate the maximum speed of the pendulum bob as it swings through the equilibrium position. **[2]**

$\omega = 2\pi/T = 3.500$ rad s^{-1}. **M1 A1**
$v_{max} = \omega x_0 = 3.500 \cdot 0.030 =$ **0.1050 m s^{-1}**.

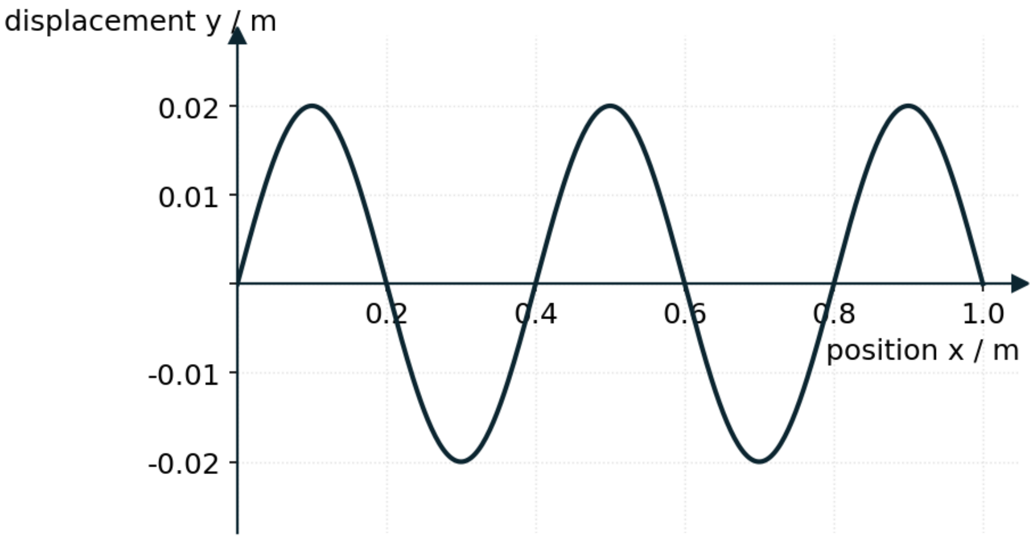
(c) Calculate the maximum kinetic energy of the bob during the swing. **[2]**

$KE_{max} = ½mv_{max}^2 = 0.5 \cdot 0.20 \cdot 0.1050^2 =$ **1.10×10^{-3} J**. **M1 A1**

C.2 Wave Model

Question 3 [7 marks]

A transverse wave travels along a stretched string. The graph shows a snapshot of the string's shape at one instant. The wave source oscillates at a frequency of 5.0 Hz.



Displacement–position snapshot of the wave (wavelength and amplitude are given data).

(a) Read the wavelength from the graph, and calculate the speed of the wave. **[2]**

$\lambda = 0.40$ m (from graph). **M1 A1**
$v = f\lambda = 5.0 \cdot 0.40 =$ **2.00 m s^{-1}**.

(b) Calculate the period of oscillation of a particle on the string. **[2]**

$T = 1/f = 1/5.0 =$ **0.20 s**. **M1 A1**

(c) Calculate the maximum transverse speed of a particle on the string as the wave passes. **[3]**

$\omega = 2\pi f = 2\pi \cdot 5.0 = 31.4$ rad s^{-1}. **M1 M1 A1**
$v_{particle,max} = \omega A = 31.4 \cdot 0.020 =$ **0.6283 m s^{-1}**.

Question 4 [6 marks]

A small point source radiates sound energy uniformly in all directions. At a distance of 2.0 m from the source, the intensity is 20 W m^{-2}.

(a) State how intensity varies with distance from a point source, and hence calculate the intensity at a distance of 6.0 m. **[3]**

For a point source, intensity follows an inverse-square law: $I \in 1/r^2$. **A1 M1 A1**
$I_2 = I_1(r_1/r_2)^2 = 20\cdot(2.0/6.0)^2 =$ **2.222 W m^{-2}**.

(b) Calculate the total power radiated by the source. **[3]**

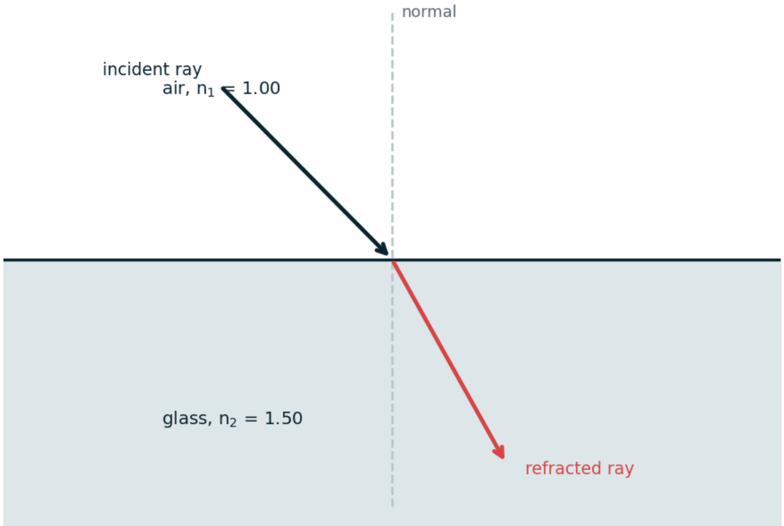
Power is spread over a sphere of area $4\pi r^2$ at radius r = 2.0 m: **M1 M1 A1**
$P = I\cdot 4\pi r^2 = 20\cdot 4\pi\cdot 2.0^2 =$ **1005.3 W**.

C.3 Wave Phenomena

Question 5 [7 marks]

A ray of light travelling in air (n_1 = 1.00) is incident on a glass surface (n_2 = 1.50) at an angle of incidence of 40°, as shown.

Refraction of a light ray at an air–glass boundary



Refraction of the ray as it enters the glass.

(a) State Snell's law, and use it to calculate the angle of refraction in the glass. **[3]**

Snell's law: $n_1\sin\theta_1 = n_2\sin\theta_2$. **A1 M1 A1**
$\theta_2 = \sin^{-1}(n_1\sin\theta_1/n_2) = \sin^{-1}(\sin40°\cdot1.00/1.50) =$ **25.4°**.

(b) Calculate the critical angle for total internal reflection at this glass−air boundary. **[3]**

At the critical angle, θ_2 = 90°: $n_2\sin\theta_c = n_1\sin90°$. **M1 A1 A1**
$\theta_c = \sin^{-1}(n_1/n_2) = \sin^{-1}(1.00/1.50) =$ **41.8°**.

(c) State what happens to a ray travelling from glass into air at an angle of incidence greater than the critical angle. **[1]**

Total internal reflection occurs: all of the light is reflected back into the glass, with none transmitted into the air. **A1**

Question 6 [6 marks]

In a Young's double-slit experiment, the slit separation is 5.0×10^{-4} m and the screen is 2.0 m from the slits. Red light of wavelength 6.0×10^{-7} m is used.

(a) Calculate the fringe spacing observed on the screen. **[2]**

$\Delta y = \lambda D/d = (6.0\times10^{-7}\cdot2.0)/5.0\times10^{-4}$ = **2.40 mm**. **M1 A1**

(b) The red light is replaced with blue light of wavelength 4.5×10^{-7} m, with d and D unchanged. Calculate the new fringe spacing. **[2]**

$\Delta y = \lambda D/d = (4.5\times10^{-7}\cdot2.0)/5.0\times10^{-4}$ = **1.80 mm** (fringes closer together, since $\Delta y \in \lambda$). **M1 A1**

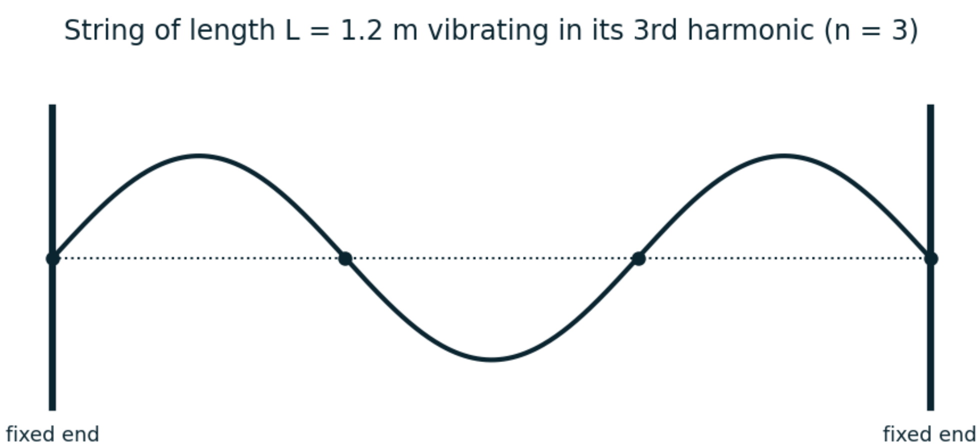
(c) State one condition necessary for the two slits to produce a stable (observable) interference pattern. **[2]**

The two sources (slits) must be coherent – they must emit waves of the same frequency/wavelength with a constant phase relationship (or phase difference) between them. **A1 A1**

C.4 Standing Waves and Resonance

Question 7 [7 marks]

A string of length L = 1.2 m, fixed at both ends, is set vibrating in the pattern shown, corresponding to its 3rd harmonic (n = 3). The transverse wave speed on the string is 40 m s^{-1}.



Standing wave pattern for the 3rd harmonic on the fixed string.

(a) Determine the wavelength of the standing wave pattern shown. **[2]**

For a string fixed at both ends, $\lambda_n = 2L/n = (2\cdot1.2)/3$ = **0.80 m**. **M1 A1**

(b) Calculate the frequency of this 3rd-harmonic oscillation. **[2]**

$f_3 = v/\lambda_3 = 40/0.80$ = **50.0 Hz**. **M1 A1**

(c) Calculate the fundamental frequency (1st harmonic, n = 1) of the string, and state the relationship between the harmonic frequencies. **[3]**

$\lambda_1 = 2L$ = **2.40 m**; $f_1 = v/\lambda_1 = 40/2.40$ = **16.67 Hz**. **M1 A1 R1**
The higher harmonics are integer multiples of the fundamental: $f_n = nf_1$ (check: $3\cdot16.67 \approx 50.0$ Hz, consistent with part (b)).

Question 8 [7 marks]

A tube of air, closed at one end and open at the other, has length 0.85 m. The speed of sound in air is 340 m s^{-1}. For a pipe closed at one end, $\lambda_n = 4L/n$ for odd n only.

(a) Calculate the wavelength and frequency of the fundamental (1st harmonic) note produced by the tube. **[3]**

$\lambda_1 = 4L = 4 \cdot 0.85 =$ **3.40 m**. **M1 M1 A1**
$f_1 = v/\lambda_1 = 340/3.40 =$ **100.0 Hz**.

(b) Calculate the frequency of the next higher resonant note (the next harmonic) the tube can produce. **[2]**

Only odd harmonics occur in a closed pipe, so the next resonance is the 3rd harmonic: $f_3 = 3f_1 = 3 \cdot 100.0 =$ **300.0 Hz**. **M1 A1**

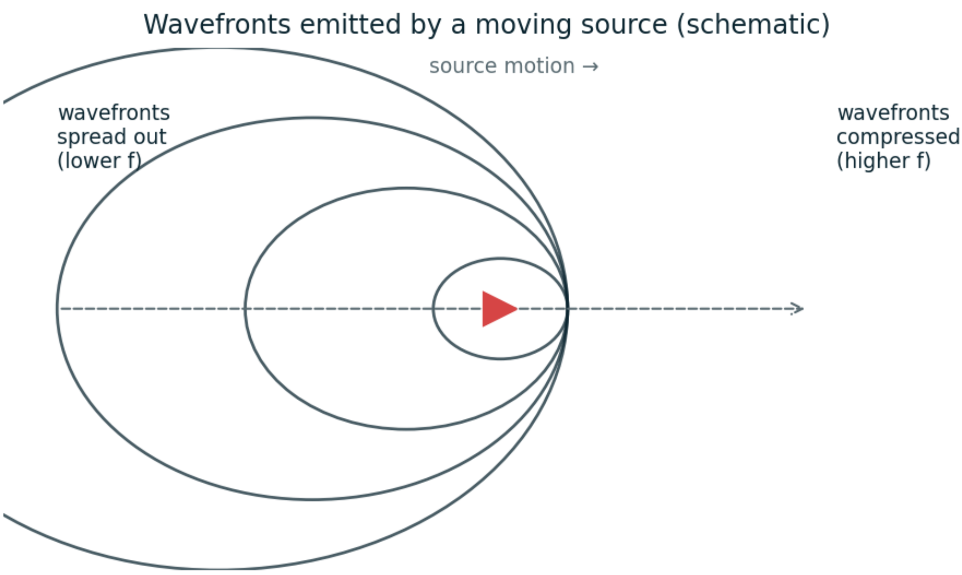
(c) State the boundary conditions on displacement that apply at the closed end and at the open end of the tube. **[2]**

At the **closed end**, the air displacement must be zero (a node), since the rigid boundary prevents motion. At the **open end**, the displacement is a maximum (an antinode), as the air is free to oscillate. **A1 A1**

C.5 Doppler Effect

Question 9 [8 marks]

A police siren emits sound at a source frequency $f_0 = 500$ Hz. The car moves at a constant speed of 30 m s^{-1} through still air, in which the speed of sound is 340 m s^{-1}. The diagram shows the resulting wavefront pattern.



Wavefronts emitted by the moving source are compressed ahead of it and spread out behind it.

(a) Calculate the frequency heard by a stationary observer that the car is approaching. **[3]**

$f_{approach} = f_0 v/(v - v_s) = 500 \cdot 340/(340 - 30) =$ **548.4 Hz**. **M1 M1 A1**

(b) Calculate the frequency heard by a stationary observer that the car has just passed and is now moving away from. **[3]**

$f_{recede} = f_0 v/(v+v_s) = 500 \cdot 340/(340+30) =$ **459.5 Hz**. **M1 M1 A1**

(c) State whether the wavelength directly in front of the moving source is longer or shorter than the source's stationary wavelength, and explain why. **[2]**

It is **shorter**. As the source moves towards that region between emitting successive wave crests, it "catches up" a little with the wave already emitted, compressing successive wavefronts closer together and reducing the wavelength. **A1 R1**

Question 10 [6 marks]

A particular spectral line of hydrogen has a laboratory (rest-frame) wavelength of 656.3 nm. The same line, observed in the spectrum of a distant galaxy, is measured at 661.1 nm. Take $c = 3.0\times10^8$ m s^{-1}.

(a) Calculate the wavelength shift, $\Delta\lambda$, between the observed and laboratory wavelengths. **[2]**

$\Delta\lambda = 661.1 - 656.3 =$ **4.8 nm**. **M1 A1**

(b) Using the non-relativistic Doppler approximation $\Delta\lambda/\lambda = v/c$, calculate the recession velocity of the galaxy. **[2]**

$v = c\Delta\lambda/\lambda = (3.0\times10^8 \cdot 4.8)/656.3 =$ **2.19×10^6 m s^{-1}** ($\approx$ 2194 km s^{-1}). **M1 A1**

(c) State whether the galaxy is moving towards or away from Earth, and explain how you know. **[2]**

The galaxy is moving **away from** Earth. The observed wavelength is longer than the laboratory wavelength (redshifted), which by the Doppler effect indicates recession. **A1 R1**