IB DP PHYSICS · THEME C WAVE BEHAVIOUR · C.3 · ~7 MIN READ

C.3 Wave phenomena

Wavefronts and rays, reflection, refraction and Snell's law, critical angle and total internal reflection, diffraction, superposition and interference, Young's double slit, and (HL) single-slit diffraction and diffraction gratings.

Wavefronts & rays | Snell's law | Total internal reflection | Diffraction | Interference | Double slit s = λD/d | Single slit (HL) | Gratings (HL)

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

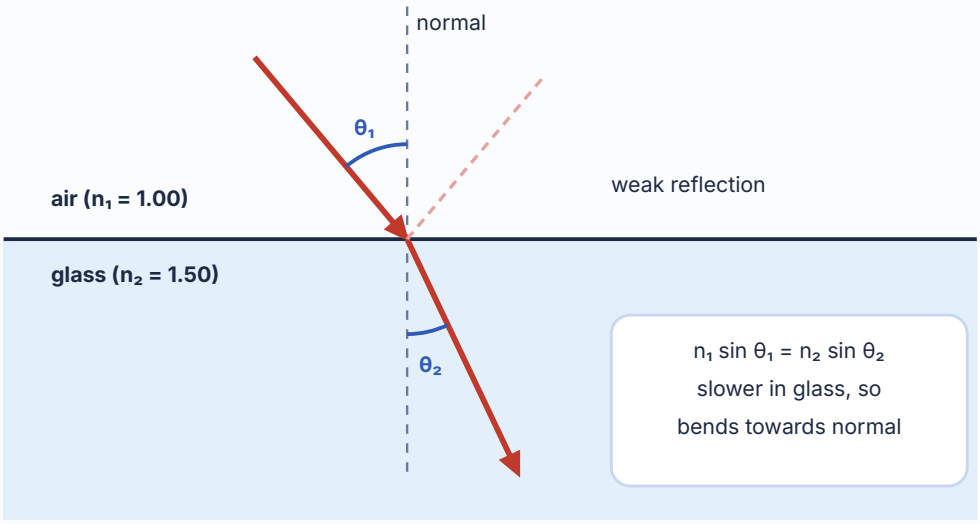
- **Wavefronts** join points in phase; **rays** show the direction of travel and are perpendicular to wavefronts.
- At a boundary waves **reflect**, **refract** (change speed and direction) and **transmit**. Snell's law: $\mathbf{n_1 \sin \theta_1 = n_2 \sin \theta_2}$. Past the **critical angle**, light is totally internally reflected.
- **Diffraction** is spreading through a gap or around an obstacle; it is strongest when the gap is about one wavelength.
- **Superposition** of coherent waves gives interference: bright where the path difference is nλ, dark where it is (n + ½)λ. For two slits the fringe spacing is **s = λD/d**.
- **HL:** single slit minima at θ = λ/b, and sharp grating maxima at nλ = d sin θ.

BY THE END YOU CAN

- Draw wavefront and ray diagrams for reflection, refraction and diffraction.
- Use Snell's law, refractive index and the critical angle.
- Explain the conditions for constructive and destructive interference.
- Use s = λD/d for Young's double slit.
- Describe and use single-slit diffraction, θ = λ/b, and how it modulates the double-slit pattern. HL
- Use nλ = d sin θ for diffraction gratings. HL

1 Reflection and refraction

- **Law of reflection:** angle of incidence = angle of reflection, both measured from the **normal**.



Light slows down in glass, so the ray bends towards the normal; the frequency stays the same.

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$ DATA BOOKLET

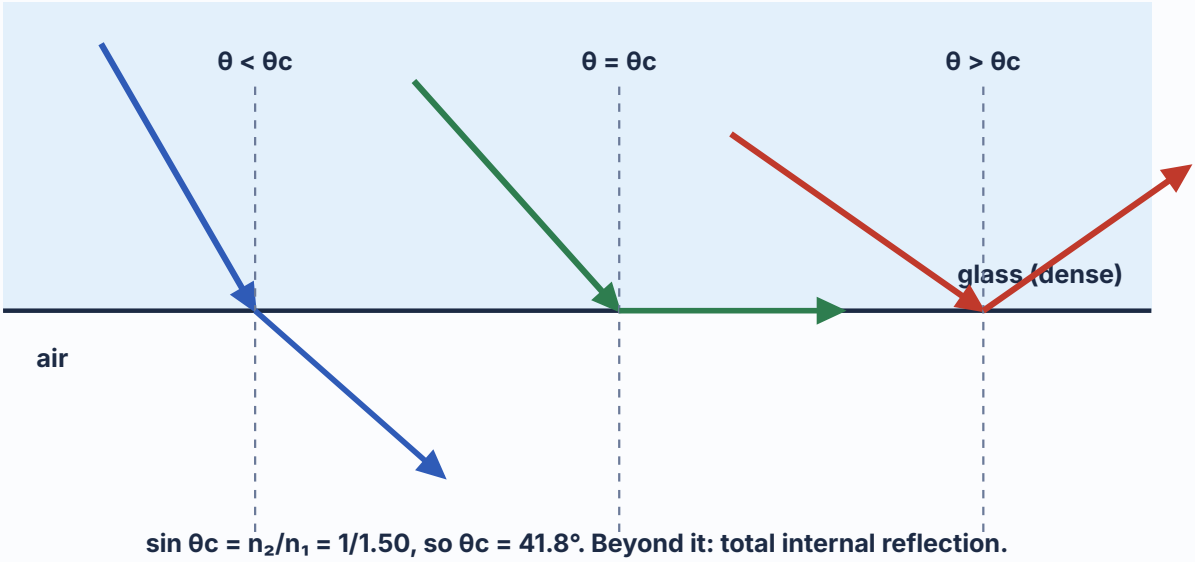
Snell's law; n = c/v for each medium

WORKED EXAMPLE

Light hits glass (n = 1.50) from air at 40° to the normal. Find the angle of refraction and the speed in glass.

1. $\sin\theta_2 = \sin 40°/1.50 = 0.429$ M1
2. $\theta_2 = \mathbf{25°}$ A1
3. $\mathbf{v = c/n = 3.00 \times 10^8/1.50 = 2.0 \times 10^8\ m\ s^{-1}}$ A1

Critical angle and total internal reflection



sin θc = n_2/n_1 = 1/1.50, so θc = 41.8°. Beyond it: total internal reflection.

Going from glass to air, the refracted ray bends away from the normal until it skims the surface at the critical angle.

- **Conditions for TIR:** light travels from a higher to a lower refractive index, and the angle of incidence exceeds the critical angle.

$$\sin \theta_c = \frac{n_2}{n_1}$$

from Snell's law with $\theta_2 = 90°$ ($n_1 > n_2$)

WORKED EXAMPLE

Find the critical angle for glass (n = 1.50) in air.

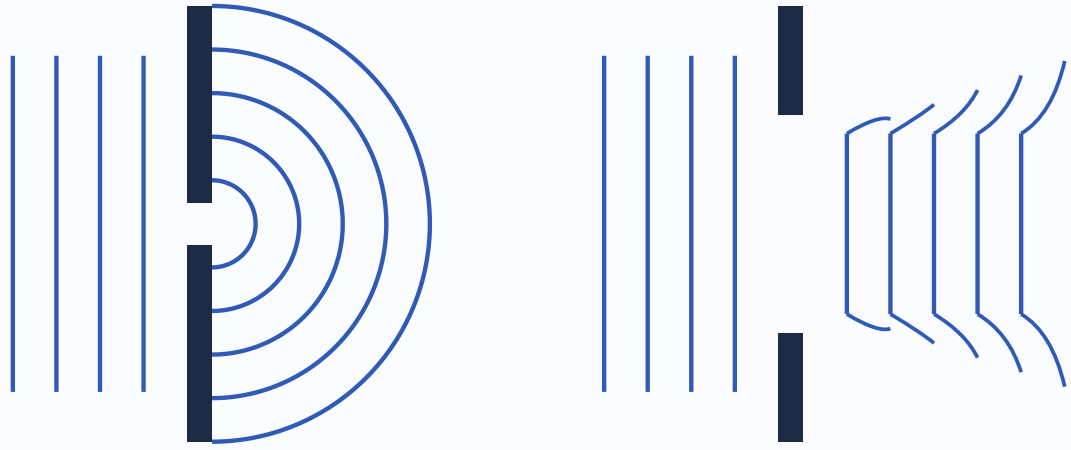
1. $\sin \theta_c = 1/1.50$ M1
2. **$\theta_c = 41.8°$** A1

- **Uses:** optical fibres (signals and endoscopes) bounce light along the core by TIR; the cladding has a lower n than the core.

COMMON MISTAKE

Measuring angles from the surface instead of from the normal. Every angle in Snell's law is measured from the normal.

2 Diffraction



gap ≈ λ: strong spreading **gap ≫ λ: little spreading**

A gap similar in size to the wavelength makes almost circular wavefronts.

- **Diffraction** does not change the wavelength or speed. You hear round corners because sound wavelengths (about 1 m) are similar to doorways; light (about 500 nm) barely diffracts through doorways.

3 Superposition and interference

Principle of superposition — when waves meet, the resultant displacement is the vector sum of the individual displacements.

Coherent sources — sources with the same frequency and a constant phase difference. Needed for a stable interference pattern.

$$\text{path difference} = n\lambda$$

constructive interference (sources in phase)

$$\text{path difference} = (n + \tfrac{1}{2})\lambda$$

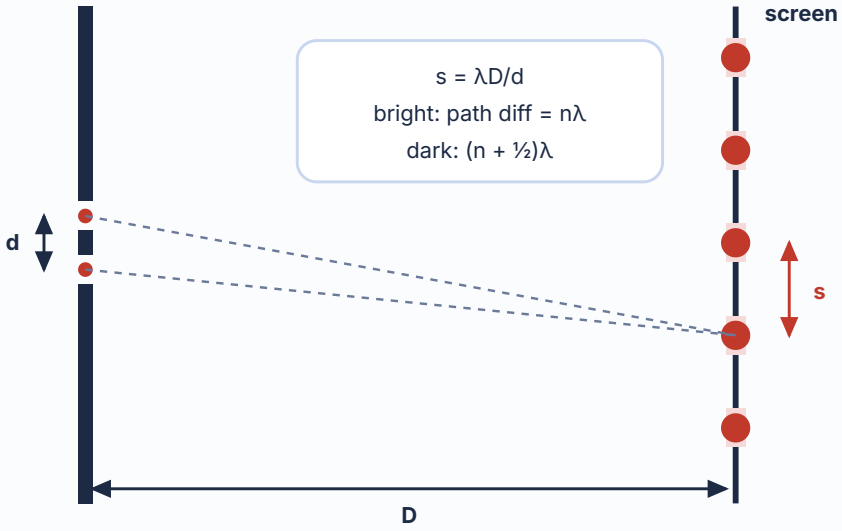
destructive interference (sources in phase)

WORKED EXAMPLE

Two loudspeakers driven in phase emit 680 Hz sound (λ = 0.50 m). At point P the path difference is 1.25 m. What do you hear?

1. 1.25 m = 2.5λ M1
2. **a half-wavelength path difference: destructive interference, so a quiet spot** A1

Young's double slit



Light from two narrow slits overlaps on a distant screen and forms equally spaced bright and dark fringes.

$$s = \frac{\lambda D}{d}$$ DATA BOOKLET

s = fringe spacing, D = slit-to-screen distance, d = slit separation

WORKED EXAMPLE

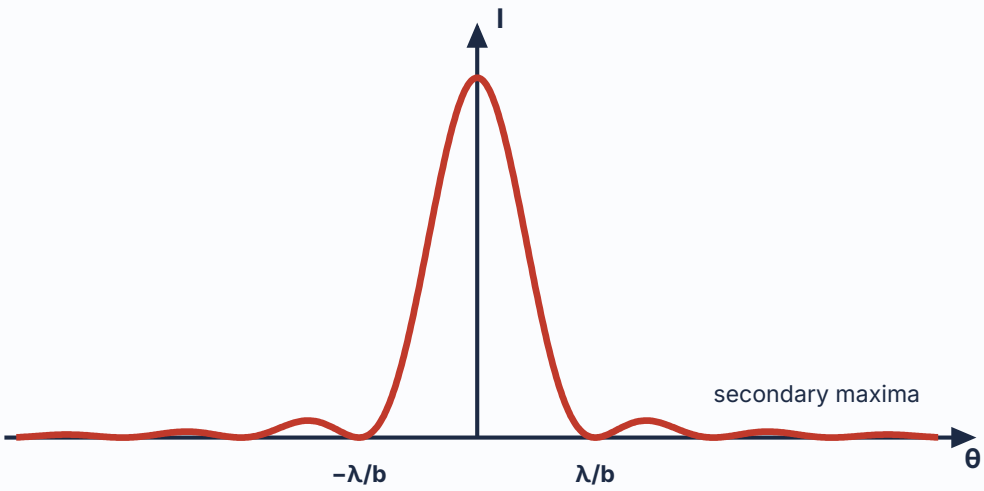
Red laser light (633 nm) passes through slits 0.25 mm apart onto a screen 2.0 m away. Find the fringe spacing.

1. $s = \lambda D/d = 633 \times 10^{-9} \times 2.0/0.25 \times 10^{-3}$ M1
2. **$= 5.1 \times 10^{-3}$ m = 5.1 mm** A1

EXAM TIP

To measure s accurately, measure across many fringes (say 10 spacings) and divide. It cuts the percentage uncertainty.

4 Single-slit diffraction HL



Central maximum is twice as wide as the others. First minimum at θ = λ/b.

Intensity against angle for one slit of width b.

$$\theta = \frac{\lambda}{b}$$ DATA BOOKLET

angle (in radians) to the first minimum for a slit of width b

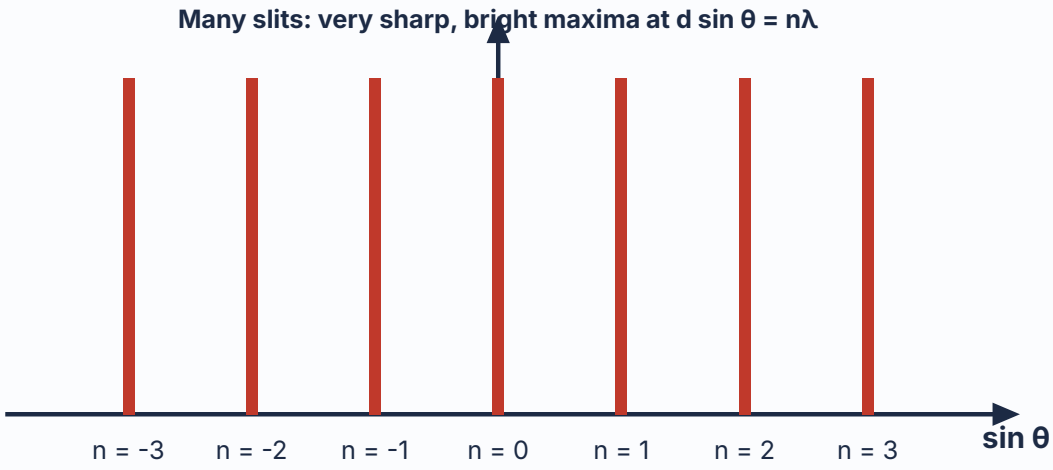
WORKED EXAMPLE

Light of 600 nm passes through a slit 0.10 mm wide. Find the angle to the first minimum and the width of the central maximum on a screen 2.0 m away.

1. $\theta = \lambda/b = 600 \times 10^{-9}/0.10 \times 10^{-3} =$ **6.0×10^{-3} rad** A1
2. central maximum half-width = $D\theta = 2.0 \times 6.0 \times 10^{-3} = 12$ mm
3. **full width = 24 mm** A1

- **Double slit, real version:** each slit has its own width, so the double-slit fringes are modulated by a single-slit envelope. Fringes are brightest in the middle and some fringes go missing where a single-slit minimum falls.

5 Diffraction gratings HL



More slits ⇒ sharper lines; same positions as a double slit with the same d.

Hundreds of slits per mm give bright, very narrow maxima.

$$n\lambda = d \sin\theta$$ DATA BOOKLET

d = slit spacing (1 mm ÷ lines per mm), n = order

WORKED EXAMPLE

A grating has 600 lines per mm. Find the angle of the first-order maximum for sodium light (589 nm) and the highest order visible.

1. $d = 1.0 \times 10^{-3}/600 = 1.67 \times 10^{-6}$ m A1
2. $\sin\theta = \lambda/d = 0.353 \Rightarrow \theta =$ **20.7°** M1 A1
3. **$n_{max} < d/\lambda = 2.83$, so the highest order is 2** R1

COMMON MISTAKE

Using $\theta = \lambda/b$ (single slit) for a grating, or small-angle $s = \lambda D/d$ when angles are large. For gratings, always use $n\lambda = d \sin\theta$.

LINKING QUESTION

Diffraction of electrons through crystals (E.2) is evidence that matter behaves like a wave; the same $n\lambda = d \sin\theta$ idea is used to measure atomic spacings.

IDEA FOR YOUR IA / EXPLORATION

Find the wavelength of a laser with a diffraction grating, or measure the refractive index of a liquid with a semicircular dish and a protractor, plotting $\sin\theta_1$ against $\sin\theta_2$.

Test yourself — cover the answers first

QUICK CHECK

1. What happens to the frequency of light entering glass?
2. State the two conditions for total internal reflection.
3. When is diffraction most noticeable?
4. What does "coherent" mean?
5. In Young's experiment, what happens to s if d is halved?
6. HL What happens to a single-slit central maximum if the slit gets narrower?

EXAM-STYLE

7. An optical fibre core has n = 1.48 and cladding n = 1.46. Find the critical angle at the boundary.
8. HL White light passes through a grating with 300 lines per mm. Find the angular width of the first-order spectrum from 400 nm to 700 nm.

Show answers

1. It stays the same (speed and wavelength fall).
2. from higher to lower n, and angle of incidence > critical angle
3. when the gap is similar in size to the wavelength
4. same frequency and constant phase difference
5. s doubles
6. it gets wider
7. $\sin \theta_c = 1.46/1.48 = 0.986$
   θ_c = **80.6°**
8. $d = 3.33 \times 10^{-6}$ m
   400 nm: $\sin \theta = 0.120 \Rightarrow 6.9°$; 700 nm: $\sin \theta = 0.210 \Rightarrow 12.1°$
   width = **5.2°**

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