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A-Level · Physics

AP3D Waves: Depth and Exam Drill

AQA 7408 · Calculator allowed · about 120 minutes

Total Marks

Name: ______________________________ Date: ____ / ____ / ______

Answer ALL questions. Show all your working.

1 This question tests core definitions used to describe wave interference.

(a) State what is meant by two sources of waves being coherent. **(1)**

(b) Define what is meant by the path difference between two waves arriving at a point. **(1)**

(c) State the principle of superposition of waves. **(2)**

(Total for Question 1 is 4 marks)

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2 Standing waves on a string. A guitar string of length 0.65 m has mass per unit length 1.2 x 10^{-3} kg/m and is under a tension of 145 N.

(a) Calculate the speed of a transverse wave on the string. **(3)**

(b) The string vibrates in its fundamental mode. Calculate the fundamental frequency. **(2)**

(c) The string is then made to vibrate at its third harmonic. Calculate this frequency and state the number of antinodes present on the string. **(2)**

(Total for Question 2 is 7 marks)

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3 Young's double-slit experiment. A laser illuminates two slits of separation 0.45 mm. The resulting fringe pattern is observed on a screen 1.85 m from the slits. The fringe spacing is measured as 2.28 mm.

(a) Calculate the wavelength of the laser light, giving your answer in nm to 3 significant figures. **(4)**

(b) The fringe spacing was measured to ± 0.05 mm, the slit separation to ± 0.01 mm and the slit-to-screen distance to ± 0.02 m. Calculate the percentage uncertainty in the calculated wavelength. **(3)**

(c) Use your answers to (a) and (b) to state the wavelength with its absolute uncertainty, to an appropriate number of significant figures. **(2)**

(Total for Question 3 is 9 marks)

4 A diffraction grating with 600 lines per mm is illuminated normally with light of wavelength 632.8 nm from a helium-neon laser.

(a) Calculate the grating spacing d in metres. **(1)**

(b) Calculate the angle at which the first-order maximum is observed. **(3)**

(c) Determine the highest order of diffraction maximum that can be observed with this grating and this wavelength, showing your reasoning. **(3)**

(Total for Question 4 is 7 marks)

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5 An optical fibre used in a communications link has a core of refractive index 1.485 surrounded by cladding of refractive index 1.462.

(a) Calculate the critical angle for the core-cladding boundary. **(3)**

(b) Explain why a light ray entering the fibre within the acceptance cone undergoes total internal reflection repeatedly as it travels along the fibre. **(2)**

(c) State and explain two reasons why the fibre is manufactured with a cladding layer rather than being left bare (surrounded by air). **(2)**

(Total for Question 5 is 7 marks)

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6 Unpolarised light of intensity 840 W/m^2 is incident on a polarising filter, then on a second polarising filter whose transmission axis is at 35 degrees to the first.

(a) Calculate the intensity of light transmitted through both filters. **(4)**

(b) Calculate the angle between the transmission axes of the two filters that would be needed to reduce the intensity after the second filter to 10% of the intensity leaving the first filter. **(3)**

(Total for Question 6 is 7 marks)

7 REQUIRED PRACTICAL. A student determines the speed of sound in air using a signal generator, a loudspeaker and two microphones connected to a double-beam oscilloscope. The loudspeaker is driven at a fixed frequency of 2500 Hz. One microphone is fixed; the second is moved directly away from the loudspeaker along the line joining them until the two oscilloscope traces are back in phase for the eighth time. The total distance moved by the second microphone is measured as 1.056 m.

(a) Explain why the student measures the total distance moved for eight complete cycles back into phase, rather than measuring the distance for just one wavelength. **(2)**

(b) Calculate the wavelength of the sound wave. **(2)**

(c) Calculate the speed of sound in air from this result. **(2)**

(d) The ruler used to measure the 1.056 m distance has an uncertainty of ± 1 mm, and the frequency of the signal generator has a negligible uncertainty. Calculate the percentage uncertainty and hence the absolute uncertainty in the calculated speed of sound. **(3)**

(e) The accepted speed of sound in air at 20 degrees C is 343 m/s. Suggest one reason why the student's calculated value is lower than this. **(2)**

(Total for Question 7 is 11 marks)

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8 A point source emits sound waves uniformly in all directions. At a distance of 2.0 m from the source, the intensity of the sound is 4.5×10^{-3} W/m^2.

(a) State how the intensity of sound from a point source varies with distance from the source. **(1)**

(b) Calculate the intensity of the sound at a distance of 6.0 m from the source. **(3)**

(c) Using the relationship between intensity and amplitude, calculate the ratio of the wave amplitude at 6.0 m to the amplitude at 2.0 m. **(3)**

(Total for Question 8 is 7 marks)

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9 Two tuning forks are sounded together. One fork has a known frequency of 512 Hz. The two notes produce 6 beats per second. A small piece of tape is then added to the 512 Hz fork, which slightly lowers its frequency, and the beat frequency is observed to decrease to 4 beats per second.

(a) Calculate the two possible values of the unknown fork's frequency, based on the initial beat frequency alone. **(2)**

(b) Using the effect of loading the 512 Hz fork on the beat frequency, determine which of the two values is correct, explaining your reasoning. **(3)**

(Total for Question 9 is 5 marks)

10 Interference and diffraction experiments, such as Young's double-slit experiment and diffraction through a grating, provide strong evidence for the wave nature of light. However, the photoelectric effect, in which electrons are only emitted from a metal surface above a threshold frequency of incident light regardless of its intensity, cannot be explained by a purely wave-based model and instead supports a photon (particle) model of light. Evaluate how evidence from wave phenomena and evidence from the photoelectric effect together support the modern view that light exhibits wave-particle duality, referring to specific features of each type of evidence in your answer.

(Total for Question 10 is 6 marks)

Mark scheme · AP3D Waves: Depth and Exam Drill

Question 1

- (a) **B1** the sources emit waves of the same frequency (and wavelength) with a constant (fixed) phase difference oe
- **(a) Answer: The sources emit waves of the same frequency with a constant phase difference between them.**
- (b) **B1** the difference in the distance travelled by the two waves from their sources to the point oe
- **(b) Answer: The difference in distance travelled by the two waves from their respective sources to the point considered.**
- (c) **B1** when two or more waves meet at a point, the resultant displacement
- (c) **B1** is the vector sum of the individual displacements of each wave at that point oe
- **(c) Answer: When two or more waves meet at a point, the resultant displacement at that point is the vector sum of the displacements that each wave would cause individually.**

Question 2

- (a) **M1** quote $v = \sqrt{T / \&\mu;}$
- (a) **M1** substitute $v = \sqrt{145 / 1.2 \text{ x } 10^{-3}}$
- (a) **A1** v = 348 m/s (accept 347-348) cao
- **(a) Answer: 348 m/s**
- (b) **M1** use f = v / 2L with L = 0.65 m and v from (a)
- (b) **A1** f = 267 Hz (accept 266-268) cao
- **(b) Answer: 267 Hz**
- (c) **A1** $f3 = 3 \text{ x } f1$ = 802 Hz (accept 799-804 following through from (b))
- (c) **B1** 3 antinodes (and 4 nodes) oe
- **(c) Answer: f3 = 802 Hz; 3 antinodes.**

Question 3

- (a) **M1** quote fringe spacing $w = \lambda D / a$
- (a) **M1** rearrange to $\lambda = w a / D$
- (a) **M1** substitute $\lambda = (2.28 \text{ x } 10^{-3} \text{ x } 4.5 \text{ x } 10^{-4}) / 1.85$
- (a) **A1** λ = 555 nm cao
- **(a) Answer: 555 nm**
- (b) **M1** calculate each percentage uncertainty: w = 0.05/2.28 x 100 = 2.19%, a = 0.01/0.45 x 100 = 2.22%, D = 0.02/1.85 x 100 = 1.08%
- (b) **M1** recognise that for a product/quotient the percentage uncertainties are added
- (b) **A1** total percentage uncertainty = 5.5% cao
- **(b) Answer: 5.5%**
- (c) **M1** absolute uncertainty = 5.5% of 555 nm = 30 nm (accept 30-31)
- (c) **A1** λ = (555 ± 30) nm cao, uncertainty to 1-2 sig figs
- **(c) Answer: (555 ± 30) nm**

Question 4

- (a) **B1** $d = 1 / (600 \text{ x } 10^{3}) = 1.67 \text{ x } 10^{-6}$ m cao
- **(a) Answer: $1.67 \text{ x } 10^{-6}$ m**
- (b) **M1** quote $d \sin(\theta) = n \lambda$ with n = 1
- (b) **M1** substitute $\sin(\theta) = 632.8 \text{ x } 10^{-9} / 1.67 \text{ x } 10^{-6}$
- (b) **A1** θ = 22.3 degrees cao
- **(b) Answer: 22.3 degrees**
- (c) **M1** recognise the maximum order occurs when $\sin(\theta) = 1$, so $n(max) = d / \lambda$
- (c) **M1** calculate $d / \lambda = 1.67 \text{ x } 10^{-6} / 632.8 \text{ x } 10^{-9} = 2.63$
- (c) **A1** n = 2 is the highest order observed, since n = 3 would require $\sin(\theta) = 1.14$ which is impossible cao
- **(c) Answer: n = 2**

Question 5

- (a) **M1** quote $\sin(\theta_c) = n2 / n1$ with n1 = 1.485 (core), n2 = 1.462 (cladding)
- (a) **M1** substitute $\sin(\theta_c) = 1.462 / 1.485 = 0.9845$
- (a) **A1** $\theta_c = 79.9$ degrees cao
- **(a) Answer: 79.9 degrees**
- (b) **B1** the ray strikes the core-cladding boundary at an angle of incidence greater than the critical angle
- (b) **B1** since the core has a higher refractive index than the cladding, all the light is reflected (none is transmitted/refracted into the cladding) at each reflection, so this repeats along the fibre oe
- **(b) Answer: Because the ray always meets the core-cladding boundary at an angle greater than the critical angle, and the core is optically denser than the cladding, total internal reflection occurs at every reflection along the length of the fibre.**
- (c) **B1** cladding protects the core from scratches and contamination that would otherwise scatter light out of the core and cause signal loss oe
- (c) **B1** cladding prevents light escaping into adjacent fibres (crosstalk) when fibres are bundled together, since with air the critical angle would be much smaller and stray contact points could couple light out oe
- **(c) Answer: Cladding protects the core surface from damage and dirt that would scatter light and cause signal loss, and it prevents light coupling between fibres that are in contact when bundled (crosstalk), which would occur more readily with a bare core in air.**

Question 6

- (a) **M1** recognise the first filter transmits half the unpolarised intensity: $I1 = 840/2 = 420\ W/m^2$
- (a) **M1** quote Malus's law $I = I1 \cos^2(\theta)$
- (a) **M1** substitute $I = 420 \times \cos^2(35\ \text{degrees})$
- (a) **A1** $I = 282\ W/m^2$ (accept 280-283) cao
- **(a) Answer: 282 W/m^2**
- (b) **M1** set $\cos^2(\theta) = 0.10$
- (b) **M1** $\theta = \arccos(\sqrt{0.10})$
- (b) **A1** $\theta = 71.6$ degrees cao
- **(b) Answer: 71.6 degrees**

Question 7

- (a) **B1** measuring across several wavelengths and dividing by the number of wavelengths means the absolute uncertainty in the ruler reading is spread over a much larger distance
- (a) **B1** this reduces the percentage uncertainty in the value obtained for a single wavelength, compared with measuring just one wavelength directly oe
- **(a) Answer: Measuring across eight wavelengths and dividing by 8 spreads the fixed absolute uncertainty of the ruler over a much larger measured distance, reducing the percentage uncertainty in the wavelength.**
- (b) **M1** wavelength = total distance / number of wavelengths = 1.056 / 8
- (b) **A1** λ = 0.132 m cao
- **(b) Answer: 0.132 m**
- (c) **M1** use v = f λ = 2500 x 0.132
- (c) **A1** v = 330 m/s cao
- **(c) Answer: 330 m/s**
- (d) **M1** percentage uncertainty in distance = (0.001/1.056) x 100 = 0.095%
- (d) **M1** since frequency uncertainty is negligible, this is also the percentage uncertainty in the speed
- (d) **A1** absolute uncertainty = (0.095/100) x 330 = 0.31 m/s, so v = (330.0 ± 0.3) m/s cao
- **(d) Answer: ± 0.3 m/s**
- (e) **B1** the speed of sound in air increases with temperature, so the laboratory air was likely at a lower temperature than 20 degrees C oe
- (e) **B1** alternatively, a systematic error such as the student misjudging when the traces were exactly back in phase (a small consistent offset in the distance measured) would also explain a discrepancy oe
- **(e) Answer: The laboratory air was probably at a temperature below 20 degrees C, since the speed of sound in air increases with temperature; a systematic timing/alignment error in judging when the traces were exactly in phase is also a plausible cause.**

Question 8

- (a) **B1** intensity is inversely proportional to the square of the distance from the source (inverse square law) oe
- **(a) Answer: Intensity is inversely proportional to the square of the distance from the source.**
- (b) **M1** use $I2 = I1 \times (r1/r2)^2$
- (b) **M1** substitute $I2 = 4.5 \times 10^{-3} \times (2.0/6.0)^2$
- (b) **A1** $I2 = 5.0 \times 10^{-4}$ W/m^2 cao
- **(b) Answer: 5.0×10^{-4} W/m^2**
- (c) **M1** quote I proportional to A^2, so $A2/A1 = \sqrt{I2/I1}$
- (c) **M1** substitute $A2/A1 = \sqrt{5.0 \times 10^{-4} / 4.5 \times 10^{-3}}$
- (c) **A1** A2 : A1 = 1 : 3 (ratio = 0.333) cao
- **(c) Answer: A2 : A1 = 1 : 3**

Question 9

- (a) **M1** use beat frequency = |f1 - f2|, so f = 512 ± 6
- (a) **A1** f = 506 Hz or f = 518 Hz cao
- **(a) Answer: 506 Hz or 518 Hz**
- (b) **M1** adding tape lowers the frequency of the 512 Hz fork slightly
- (b) **M1** if the unknown frequency were 518 Hz, lowering 512 Hz would increase the frequency difference, so the beat frequency would rise, not fall; if the unknown frequency is 506 Hz, lowering 512 Hz reduces the frequency difference, so the beat frequency falls, matching the observation
- (b) **A1** the unknown frequency is 506 Hz cao
- **(b) Answer: 506 Hz**

Question 10

- **Level 3** (5-6): Detailed and well-linked evaluation that correctly explains how interference and diffraction require superposition of waves (path difference, constructive/destructive interference) and could not occur for classical particles, AND explains why the photoelectric effect (existence of a threshold frequency, instantaneous emission, and kinetic energy of electrons depending on frequency not intensity) cannot be explained by a wave model but is explained by discrete photons of energy $E = hf$. Reaches a clear, justified conclusion that light must be treated as having both wave and particle character (wave-particle duality), used in different contexts.
- **Level 2** (3-4): Correctly describes at least one piece of wave evidence and at least one feature of the photoelectric effect, with some explanation of why each supports its respective model, but the argument linking them to a duality conclusion is only partially developed or contains minor inaccuracies.
- **Level 1** (1-2): Basic or one-sided answer: describes either wave evidence or photon evidence in isolation, with little or no attempt to connect the two forms of evidence or reach a conclusion about duality.
- **Indicative content:**
  - Wave evidence: interference and diffraction require superposition of waves and depend on path difference; regions of constructive and destructive interference (bright and dark fringes) can only be explained if light behaves as a wave.
  - A stream of classical particles would not produce a stable interference pattern with alternating maxima and minima; the wave model correctly predicts fringe spacing from wavelength, slit separation and distance to screen.
  - Photoelectric evidence: emission of electrons occurs only above a threshold frequency, independent of intensity, and emission is effectively instantaneous even at very low intensity.
  - A wave model predicts that energy should accumulate over time at any frequency given sufficient intensity, eventually releasing electrons; this is not observed, so the wave model fails here.
  - The photon model ($E = hf$) explains the threshold frequency as the minimum photon energy needed to overcome the work function, and explains why increasing intensity (more photons) increases the rate of emission but not the maximum kinetic energy of each photoelectron, which depends only on frequency.
  - Conclusion: light must be described using both models depending on the phenomenon being explained (wave-particle duality); neither a purely wave model nor a purely particle model alone accounts for all observed behaviour of light.