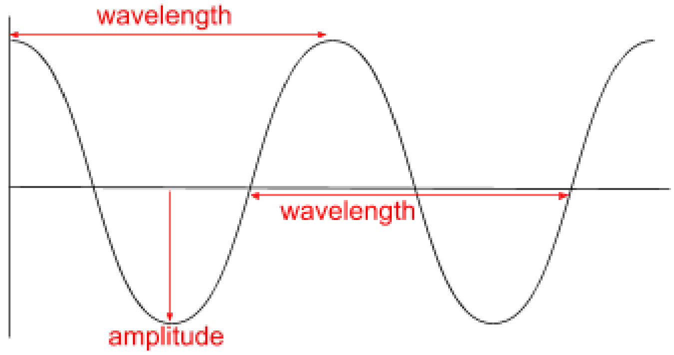
OCR B Physics A Level

Module 4.1: Waves and Quantum Behaviour

Notes

Wave Behaviour

Wave Properties



Wavelength is the distance, in metres, between equivalent points on two consecutive waves (eg. peak to peak or trough to trough).

Displacement is the distance from equilibrium position. The maximum displacement is known as the **amplitude**.

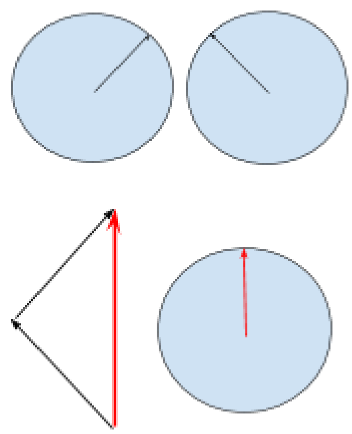
Frequency is the number of complete waves passing a given point in one second.

Time period is the time taken for a wave to completely pass through any given point. This is the **reciprocal** of the frequency: ***1/time period = frequency*** & ***1/frequency = time period***

Phase and Phasors

The **phase** of a wave refers to the stage in the wave cycle. Two waves are **in phase** when they are at the same point at the same time - if two waves are both at a peak or trough they are in phase. If they are at opposite positions (eg. one is at a peak and the other is at a trough) they are in **antiphase**. Anything in between is **out of phase**.

The **phase difference** between two waves that are out of phase, can be worked out using **phasor arrows**.



This is an arrow which rotates 360° in the time it takes for a wave to complete a full cycle.

360° is equal to 2π radians. **Radians** are another unit of angle measurement, and are commonly used to describe phasors.

<u>Phase difference</u>

In phase	0 rad
In antiphase	π rad

Resultant phasors can be worked out in the same way as resultant vectors - scale arrows are drawn tip to tail, and then connected by a resultant arrow. The angle can be measured from a scale drawing.

Coherent waves have a constant phase difference.

Path Difference

Path difference is the difference between the distance travelled by two waves when they meet. A path difference that is a whole number multiple of λ (**nλ**) produces waves **in phase**. A path difference of ***(n + ½)λ*** produces waves in **antiphase**. Anything in between produces waves that are **out of phase**.

Standing Waves

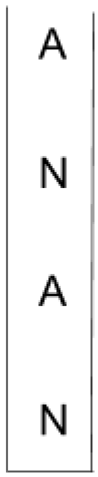
Standing waves are waves that appear to be fixed in position, which occur as a result of **superposition** (or **interference**).

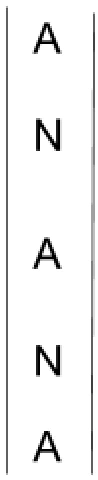
The formation of a standing wave:

1. Waves move in the forwards direction, eg. along a string when plucked.
2. Waves reflect off a boundary (eg. the end of the string).
3. Waves are travelling in both directions and interfere to produce a standing wave pattern.
4. Where waves meet **in phase**, **constructive interference** occurs, causing **antinodes** (maximum displacement) to form.
5. Where waves meet in **antiphase**, there is **destructive interference**, producing **nodes** (regions of minimum displacement). The waves effectively cancel out.
6. The positions of antinodes and nodes remain fixed, giving the appearance that the wave is not moving.

Standing waves can also form with **longitudinal** waves eg. sound waves.

This occurs in air columns, or tubes. Sound waves travel along the tube, reflect at the end of the tube. Waves travel up and down the tube and superimpose.





Remember: **Antinodes always form at open ends, and nodes always form at closed ends.**

This can be used to work out the **speed of sound** in air.

1. Use a **resonance tube** partially submerged in water.
2. Hold a tuning fork over the top and move the tube up and down until resonance occurs, producing a louder sound.
3. Measure the length required to produce the first resonance.
4. Repeat for the second resonance.
5. $L_2 - L_1 = \frac{\lambda}{2}$ so $2(L_2 - L_1) = \lambda$

Refraction

Refraction is the change in speed of a wave (eg. light) when it reaches a boundary between two media.

The **refractive index** is the ratio of the speed of light in two different materials. The **absolute refractive index** of a material is the ratio of the speed of light in that material, to the speed of light in a vacuum.

Snell's law relates the refractive index to the angles of incidence and refraction.

$$refractive\ index = \frac{speed\ in\ medium\ 1}{speed\ in\ medium\ 2} = \frac{sin(i)}{sin(r)}$$

Huygens' wavelet model helps to explain refraction. He described a wave of light as being made up of many smaller wavelets. As the wave reaches a boundary at an angle, the wavelets which reach first, slow down first, causing the wave to bend towards the slower wavelets.

Diffraction

Diffraction is the spreading out of waves when they pass through a gap of roughly the **same width as their wavelength.**

Young's double slit experiment uses diffraction. Light passes through two small slits and spreads out. The waves from each slit interfere with each other, producing a pattern of light (antinodes) and dark (nodes) fringes on a screen.

$$n\lambda = dsin\theta$$

Where d = distance between slits
θ = angle between waves

$$n\lambda = d\frac{x}{L}$$

Where d = distance between slits
x = fringe spacing
L = distance from slit to screen

Diffraction gratings have multiple slits, but work in the same way. The slits are normally expressed in **lines per mm**. You can work out the **slit separation** by $\frac{1}{lines\ per\ m}$ or $\frac{1\times10^{-3}}{lines\ per\ mm}$. The above equations can then be applied.

Single slit diffraction produces the same interference effect. This can be explained, again, by **Huygens'** wavelength model.

Quantum Behaviour

Quanta

Light can also be modelled as a ray of **particles**, or discrete packages of energy called **photons**. A photon carries a fixed quantity of energy, called a **quanta**. The words photon and quanta are often used interchangeably.

The energy of a photon of light depends on its **frequency**.

$$E = hf$$

Where E = energy / J
h = Planck's constant, 6.63×10^{-34} Js
f = frequency / Hz

The energy of waves is normally a very small quantity, so a different unit of energy is used: the **electronvolt.**

This is the energy transferred when one electron is moved through a p.d. of one volt (derived from E = QV). This is a fixed value (see below).

The symbol for electronvolts is **eV**.

$$1\text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

The Photoelectric Effect

The **photoelectric effect** occurs when light is incident on the surface of a metal. The quantas of energy carried by the photons are absorbed by the electrons on the metal, causing them to move up to a higher energy level, or (if sufficient energy is supplied) be liberated from the surface of the metal. 1 photon is absorbed by 1 electron to form 1 **photoelectron**.

Intensity is the amount of energy per second per unit area. It was expected that more intense light would emit higher energy electrons. In fact, more intense light did not change the energy of the electrons, but meant that **more electrons were emitted**.

The energy of the emitted electrons depends on the **frequency** (rather than intensity) of the light. The higher the frequency of the light, the higher the energy of the photoelectrons. However, if the frequency is below a certain level called the **threshold frequency**, no electrons will be emitted at all. The corresponding energy, called the **work function (Φ)**, is the amount of energy required to liberate electrons from the surface of the metal.

The maximum energy of emitted electrons can be worked out as follows:

$$E = hf - \Phi$$

Where **Φ** is the **work function** of the metal.

LEDs rely on the photoelectric effect and can be used to determine **Planck's constant.**

- Find the **striking voltage** (p.d. which causes light to show) of a number of LEDs which produce light of known frequencies
- Use E = QV (where Q is the charge on an electron) and Φ = hf to work out h.

Line Spectra

The reverse of the photoelectric effect occurs when electrons in atoms lose energy and drop down to a lower energy level, releasing light.

This occurs when atoms cool, for example as stars lose energy.

Quantum Model of Light

The **quantum** behaviour of light models a ray of light as taking every possible path between where it is emitted and detected. The paths can all be mapped out using **phasor arrows** added tip to tail. The light is strongest where the largest resultant phasor is produced. In most paths, the phasors "curl up" over each other and cancel out, producing no resultant phasor, and so no light.

Intensity is proportional to the **square** of the length of the resultant phasor.

$$\text{Intensity} \propto (\text{length of resultant phasor})^2$$

Electron Diffraction

In 1897, electrons were observed to diffract in the same way as light to produce diffraction patterns. This is evidence of electrons showing **wave behaviour**. This suggests that electrons have other wave properties such as a wavelength. The de Broglie equation provides a way to work this out:

$$\lambda = \frac{h}{p} \qquad \lambda = \frac{h}{mv}$$

Where λ = wavelength
h = Planck constant
p = momentum of electron

or

Where m = mass
v = velocity