Edexcel Physics A-level

Topic 5: Waves and Particle Nature of Light

Key Points

Key Terms

Displacement: The distance and direction that a particle has travelled from the equilibrium position.

Amplitude: Maximum displacement of a vibrating particle.

Wavelength: Shortest distance between two particles in phase.

Frequency: Number of wave cycles occurring each second.

Wave speed: Distance travelled by a wave each second.

Phase difference: Measured in degrees or radians, the amount by which one wave lags behind another wave.

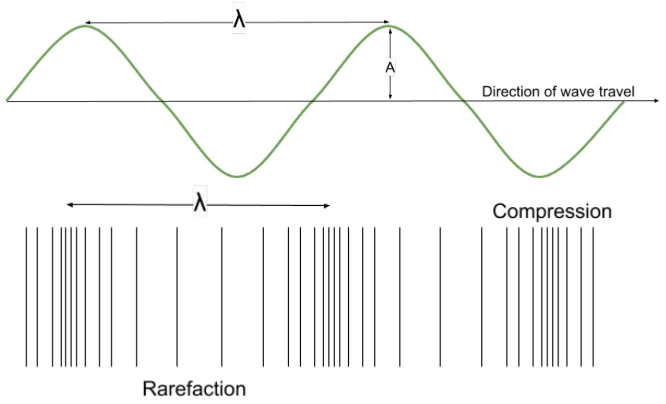
Path difference: Measured in metres, the difference in the distance travelled by two waves.

Progressive wave: Waves whose oscillations transfer energy.

Wavefront: a surface which contains all the points of a wave which are in phase with each other or the front edge of a complete wave

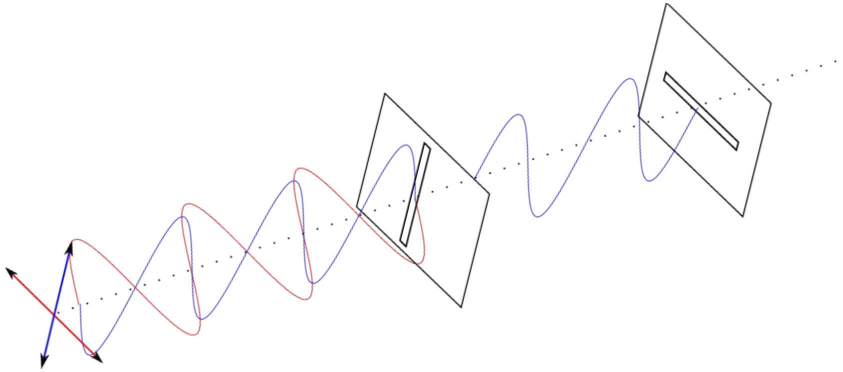
Electronvolt: the energy gained by one electron when passing through a potential difference of 1 volt. This is equal to 1.6 x 10^{-16} J.

Longitudinal and Transverse Waves



Transverse: Waves whose oscillations are **perpendicular** to the direction of propagation of energy e.g. electromagnetic waves

Longitudinal: Waves whose oscillations are **parallel** to the direction of propagation of energy. They consist of **compressions** and **rarefactions** e.g. sound waves



Only transverse waves can be **polarised**, which is where all the waves are oscillate in the same plane. The discovery of polarised light helped prove that light was a **transverse** wave.

Glare and Cameras

Polarisation can be used in things such as polaroid sunglasses to reduce glare or in a camera to enhance the image.

Radio Signals

TV and radio signals are polarised by the direction of the rods on the transmitting aerial. To receive these signals well, you must ensure the receiving aerial and the waves are in the same plane.

Speed of a wave

The **speed** of a wave is equal to the product of its frequency and wavelength. For an EM wave this value is **always equal to c**, the speed of light in a vacuum. This can be expressed as the following equation:

$$v = f\lambda$$

In order to calculate the **speed** of a **transverse wave** on a string you can use the following equation:

$$\mathrm{V} = \sqrt{\frac{T}{\mu}}$$

Where…
T = tension on the string
μ = mass per unit length of the string

Superposition and Interference

Superposition is where the displacements of two waves are combined as they pass each other. The total **displacement** at a point is equal to the sum of the individual displacements at that point. You should know that waves:

- **Constructively** interfere where they are in phase with each other
- **Destructively** interfere where they are in antiphase with each other (180 degrees out of phase).

This can be explained in terms of **peaks** and **troughs**. When the waves are **in phase**, two peaks or two troughs will **constructively** interfere with each other, resulting in a 'double' peak or trough being created. When waves are in **antiphase**, a peak will meet a trough and result in **destructive** interference, which is where they **cancel** each other out and produce a minimum point.

Stationary Waves

A **stationary wave** is one that **stores energy** instead of transferring it from one point to another. You need to know the process of a stationary wave being formed on a string that is fixed at both ends:

1. A wave is generated at one end of the string and travels down it
2. At the other end , this wave is **reflected** and travels back in the **opposite** direction
3. The **frequency** of wave generation and the **length** of the string are such that the next wave generated meets this reflected wave and undergoes **superposition**
4. At places where the two waves are **in phase**, they undergo **constructive** interference and form a **maximum** point known as an **antinode**
5. At places where the two waves are in **antiphase**, they undergo **destructive** interference and form a **minimum** point known as an **node**

Waves on a String

The **fundamental** frequency of a wave on a string can be found from the following equation:

$$f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$$

$$T = mg$$

$$\mu = \frac{M}{l}$$

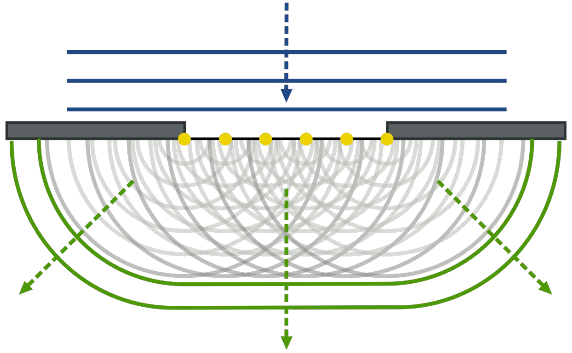
From the equation, we can see that raising the tension or shortening the length of a given string increases the **frequency/pitch**.

Diffraction

Diffraction is the spreading out of waves when they pass through a gap or over an edge. Diffraction depends on the gap width and the wavelength of the wave. If the gap is:

- **A lot bigger** than the wavelength, the diffraction is unnoticeable
- **A bit wider** than the wavelength, the diffraction is noticeable
- **The same size** as the wavelength, the diffraction is most noticeable
- **Smaller** than the wavelength, most of the waves are reflected

Huygen's principle states that every point on a wavefront is a point source to secondary wavelets, which spread out to form the next wavefront. **Huygen's construction**, which is based on this principle, can be used to show what happens when a wave meets an obstacle and experiences diffraction, as shown below:



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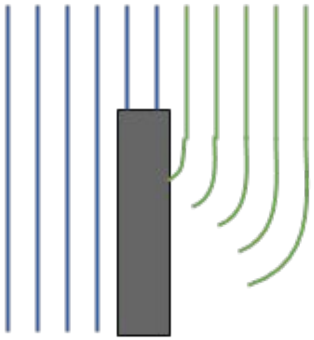


Diffraction grating

Diffraction can be demonstrated by shining light through a diffraction grating. You can use the following equation when using a diffraction grating:

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

Depending on the type of light passed through a diffraction grating, the diffraction pattern will vary. Monochromatic light will form a pattern of alternating light and dark fringes, while white light will form a white central fringe and alternating bright fringes which are spectra.

Intensity (I) is a measure of the **power** delivered per **unit area**.

$$I = \frac{P}{A}$$

Diffraction is purely a wave property. Diffraction grating experiments show that light can experience diffraction, providing evidence for the **wave nature of light**.

Electron diffraction

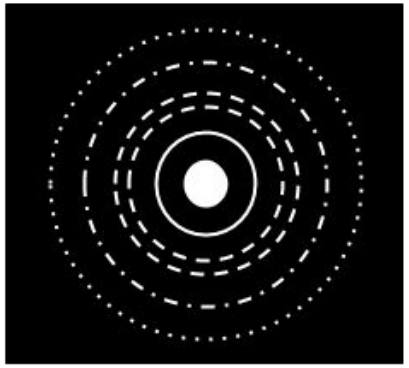
The **de Broglie hypothesis** states that all particles have a wave-like nature and a particle nature, and that the wavelength of any particle can be found using the following equation:

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

Electron diffraction provided experimental evidence for the de Broglie hypothesis as it showed that electrons, which are particles, can also undergo diffraction, which can only be experienced by waves. This provided evidence for the wave-like nature of electrons.

When accelerated electrons passed through a crystal lattice, they interacted with the small gaps between atoms and formed a diffraction pattern like the one seen on the right.

If electrons acted only as particles, you would expect the diffraction pattern to consist of a single bright spot where the electrons passed through the gap, but this was not the case.



The electron diffraction interference pattern forms concentric rings

Double Slit Interference

Young's Double Slit Experiment

When two double slits are illuminated, the two slits act as coherent wave sources.

Coherence means the waves have the same frequency with a constant phase difference. The light diffracts at the slits and the two waves superpose, forming an interference pattern. This is because a combination of constructive and destructive interference occurs.

Evidence for the Wave Nature of EM Radiation

Diffraction and interference are purely wave properties, so this experiment showed that EM radiation has wave properties.

Refraction

Refraction is when a wave changes **speed** when it crosses into a new medium:

- If the medium is **more** optically dense, the wave will **slow down** and bend towards the normal

$$\theta_i > \theta_r$$

- If the medium is **less** optically dense, the wave will **speed up** and bend away from the normal

$$\theta_i < \theta_r$$

A measure of how optically dense a medium is, is the material's **refractive index**:

The **absolute refractive index** of a material measures how much it slows down light. It is a ratio.

$$n = \frac{c}{v}$$

The **relative refractive index** at the boundary between two materials is a ratio of the speed of light in the two materials.

$${}_1n_2 = \frac{c_1}{c_2}$$

Snell's Law

It is possible to calculate the **refractive index** from the **angles of incidence** and **refraction**, or to predict the angles of refraction for a given angle of incidence, using Snell's law.

Snell's law states that:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

This can then be used to form the equation used to calculate the **critical angle** for a given material. The critical angle is the angle of incidence at which the refracted ray just passes along the boundary line, and beyond which the wave will be totally internally reflected.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

$$n_1 \sin \theta_1 = n_2 \sin 90$$

$$n_1 \sin \theta_1 = n_2 \times 1$$

$$\sin \theta_1 = \frac{n_2}{n_1}$$

Where $n_1 > n_2$

Using the fact that the refractive index of air is approximately 1, you form the following equation for the critical angle (C) where one of the mediums being passed through is air:

$$\sin C = \frac{1}{n}$$

Lenses

The **focal point (F)** of a lens is the point at which the rays of light converge, or appear to converge.
The **focal length (f)** of a lense is the distance from the centre of the lense to the focal point.

Power of a Lens:

$$P = \frac{1}{f}$$

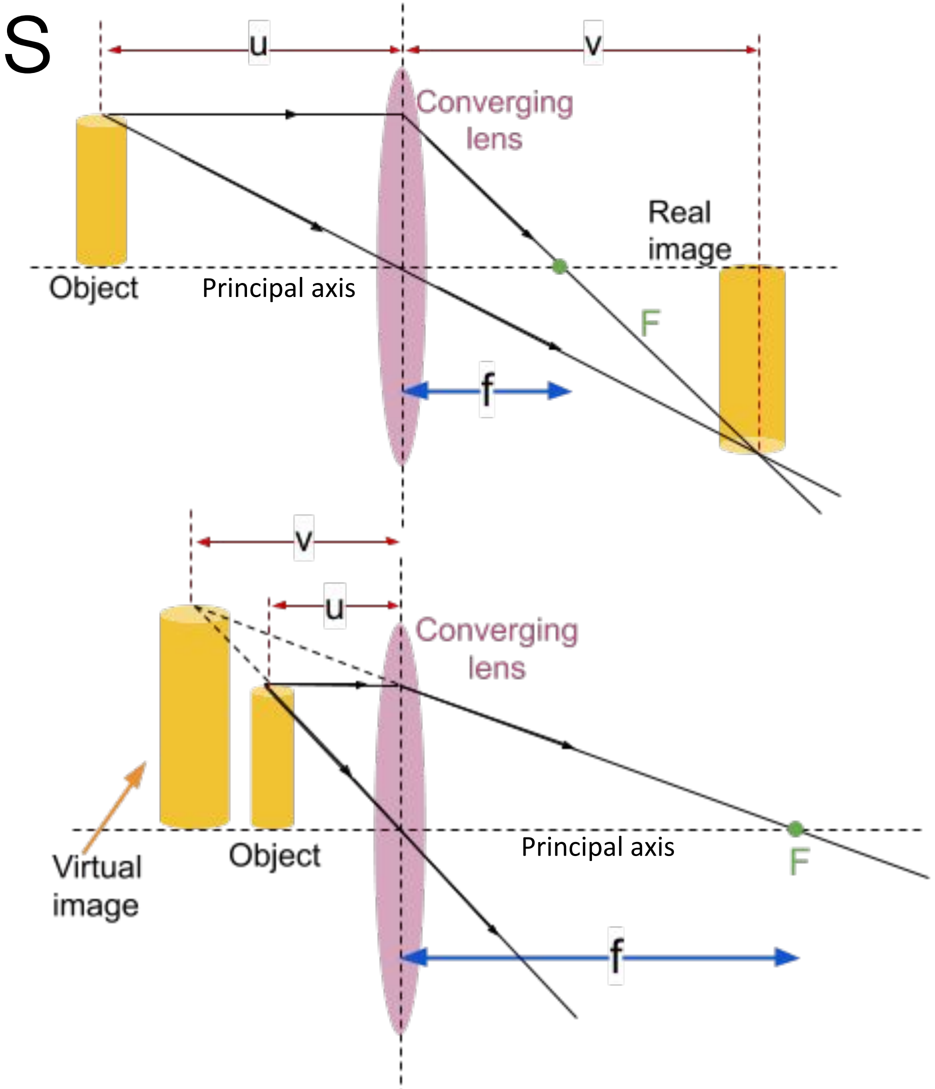
Lenses can produce two different kinds of image:

1. A **real image** is one in which the rays of light actually converge to produce an image that **can** be projected onto a screen
2. A **virtual image** is one in which the rays of light only appear to have converged. Virtual images **cannot** be projected onto a screen

Ray Diagrams

You can use **ray diagrams** in order to map where an image will appear after passing through a lens. To draw a ray diagram:

1. Draw two lines from the **same point** of an object (e.g the top), one which passes through the **centre of the lens** and is left unrefracted and one which **moves parallel** to the principal axis and passes through the focal point (F).
2. If the image is **real**, it will form where the two lines meet. If it is **virtual**, it will appear where the two lines appear to come from - this can be found by drawing a dashed line backwards from both of the initial lines and finding the point they meet.



Lens Calculations

You can calculate the **total power** of thin lenses used in combination using the equation below:

$$P = P_1 + P_2 + P_3 + \ldots$$

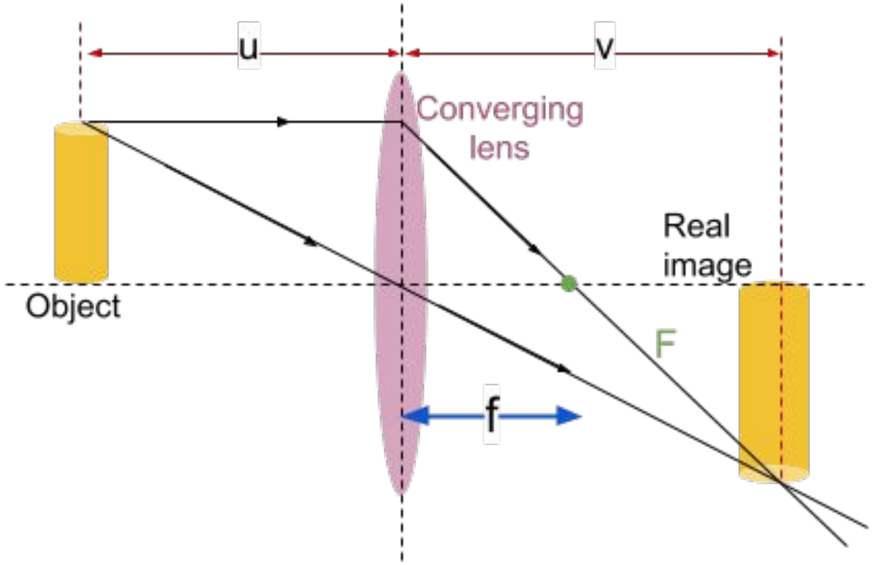
On ray diagrams, such as the one to the right, you can measure the distances **u** and **v**. These distances can be used to calculate the **power** of a lens using the following equation:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

Where **u** = distance between the object and the lens axis, **v** = distance between the lens axis and the image (positive if real, negative if virtual) and f = focal length.

These values can also be used to calculate the **magnification (m)** of the lens using the equation below:

$$m = \frac{v}{u}$$



The Photoelectric Effect

The photoelectric effect is a phenomenon that demonstrates the **particle-like** nature of light.

The observations that are made are:

- If light of a high enough energy is shone on a metal surface, electrons are emitted
- If the frequency of the light is below the **threshold frequency**, no electrons will be emitted, regardless of the intensity of light
- If the intensity of light is increased, the **rate** of electron emission increases
- The electrons are emitted with a **range** of **kinetic energies**

These observations led to the following conclusions:

- Light exists in discrete packets of energy known as **photons,** which have an energy directly proportional to their frequency. This is described by the equation below:

$$E = hf$$

- Each photon transfers all of its energy to a single electron - this is known as a **one-to-one interaction**
- If the energy of the photon is higher than the **work function** of the metal, the electron will be emitted

The Photoelectric Effect

The key definitions you need to know surrounding the photoelectric effect are:

- **Work Function**: The minimum energy required to just release an electron from the surface
- **Threshold Frequency**: The minimum frequency required for electrons to be emitted
- **Intensity:** The number of photons per unit area

$$hf = \varphi + E_{kmax} = \varphi + \tfrac{1}{2} mv^2_{max}$$

Threshold Frequency = φ/h

This phenomenon **can't** be explained by the **wave model** since wave theory would predict that:

- There should be no threshold frequency, since enough energy would accumulate over time
- The energy was spread across the metal's surface and so **instantaneous** emission wouldn't always occur
- Increasing **intensity** should increase the **kinetic energy** that the escaping electrons have

Only the **particle theory** of light can correctly explain the observations, providing evidence for the particle nature of light.

Electron Energy Levels

Electrons only exist in discrete energy levels.

Ionisation is when an electron is removed from an atom. **Excitation** is the movement of electrons up to a higher energy level; either an electron collides with the orbital electron or a photon is absorbed by it, transferring energy to it. When the electron de-excites, it moves down in energy levels and emits a photon.

This can be demonstrated by **emission and absorption spectra.** In an emission spectrum you can see the frequency of photons that certain elements emit. In an absorption spectrum you can see what frequency photons certain elements absorb. These both correlate to the energy levels within its atoms.

Line spectrum

Pulse-Echo Technique

The **pulse-echo technique** is used with ultrasound waves (sounds waves with a frequency greater than 20 kHz) for the imagining of objects, notably for medical imaging.

Below is a brief description the pulse-echo technique:

1. **Short pulse** ultrasound waves are transmitted into the target (e.g the body in medical imaging).
2. As the waves move through the target, they will meet **boundaries of different densities**, therefore they will be reflected. The amount of reflection depends on the difference in densities of the materials; the **greater this difference, the greater the reflection**.
3. The reflected waves are detected as they leave the target.
4. The **intensities** of the reflected waves will determine the structure of the target and the **time taken** for these reflected waves to return will determine the position of objects in the target (using s = vt).

The **resolution** of the image can be increased by:

- Decreasing the **wavelength** of the waves used
- Decreasing the **duration of the pulses** of waves, as this will decrease the likelihood that the waves will overlap