Edexcel International A Level (IAL) Physics

Your notes

Waves, Electrons & Photons

Contents

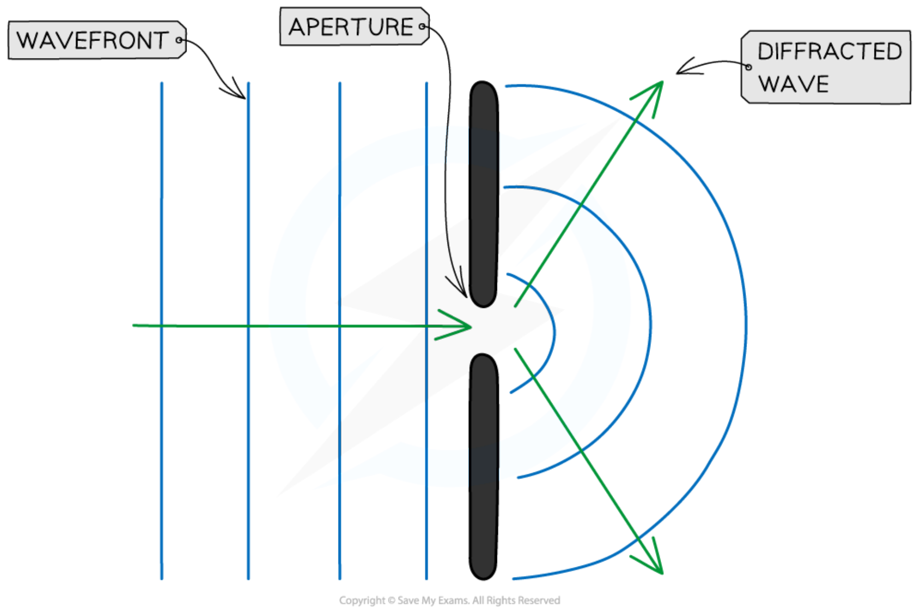
Your notes

Diffraction

Diffraction is the **spreading out** of waves when they pass an obstruction

Diffraction through a gap

- This obstruction is typically a narrow gap (a slit, or aperture)



- Diffraction is usually represented by a wavefront as shown by the vertical lines in the diagrams above
- The only property of a wave that changes when its diffracted is its **amplitude**
  - This is because some energy is **dissipated** when a wave is diffracted through a gap

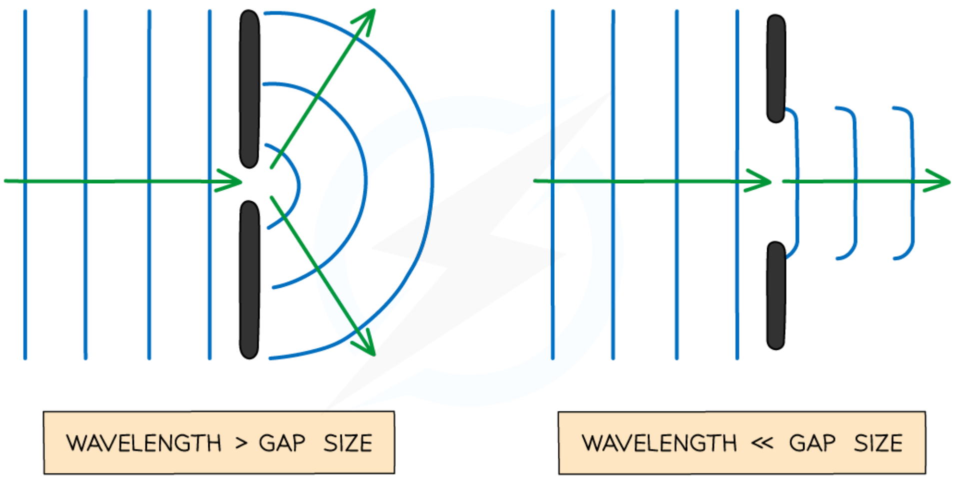
Diffraction around an obstacle

- The diffraction pattern for a large slit can be thought of as a wave passing two completely separate obstacles
  - This shows that when a wave meets an obstacle a diffraction pattern forms around the edges.
  - Behind the obstacle a 'shadow' forms where no part of the wave reaches

Factors that affect diffraction

- The effects of diffraction are most prominent when the gap size or obstacle is approximately the same or smaller than the wavelength of the wave

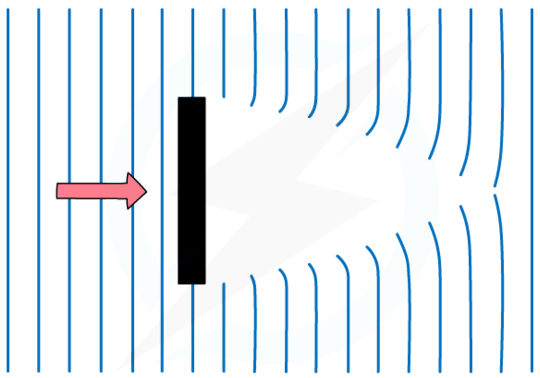
- As the size of the gap or obstacle increases, the effect gradually gets less pronounced
- When the gap is much larger than the wavelength, the waves are no longer spread out



The size of the gap (compared to the wavelength) affects how much the waves spread out

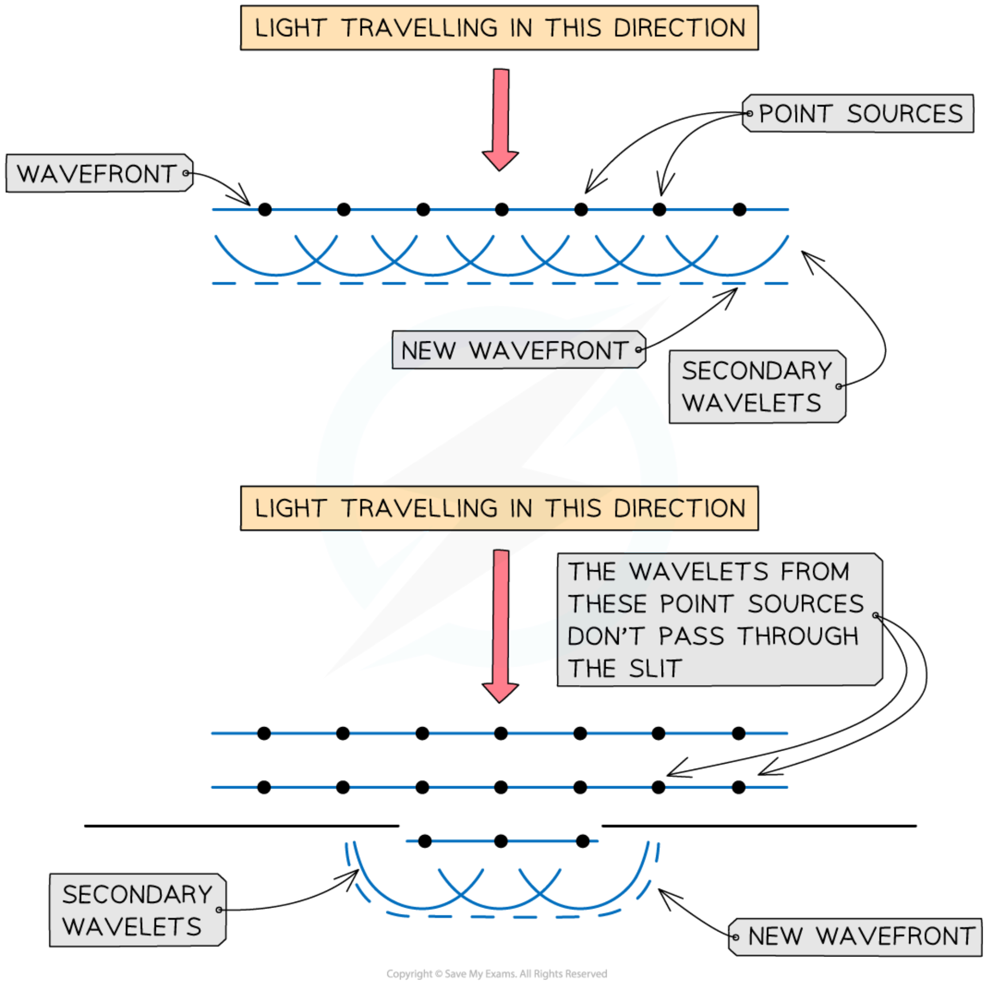
Explaining diffraction

- Huygens developed a model for wave propagation which suggested that every point on a wavefront can be considered to be a point source of secondary waves (which he called wavelets)
    - This leads to a diagram, called **Huygens' construction**, which shows that new wavefronts are tangential to the secondary wavelets
    - The tangents create the curve of the new wavefront emerging either through the gap or around the obstacle



When a wave meets an obstacle a diffraction pattern forms around the edges, with a 'shadow' created behind the obstacle where no part of the wave reaches

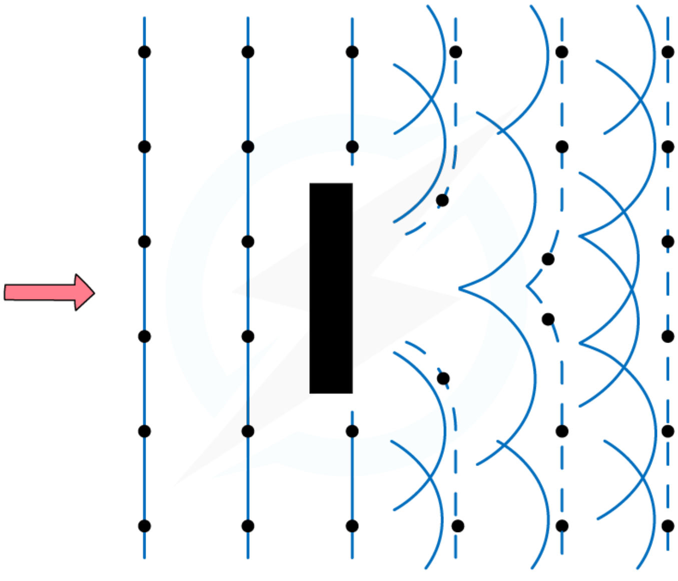
Huygens' Construction for Diffraction Through a Gap



Those point sources which pass through the gap create new wavelets on the other side, leading to the characteristic curved shape of the diffracted wave

Huygens' Construction for Diffraction Around an Obstacle

Your notes



Those point sources which pass around the obstacle create new wavelets on the other side, leaving empty space where the 'shadow' is seen

Your notes

Worked Example

When a wave is travelling through air, which scenario best demonstrates diffraction?

A. UV radiation through a gate post

B. Sound waves passing a steel rod

C. Radio waves passing between human hair

D. X-rays passing through atoms in a crystalline solid

Answer: D

- Diffraction is most prominent when the wavelength is close to the aperture size
- UV waves have a wavelength between $4 \times 10^{-7} - 1 \times 10^{-8}$ m so won't be diffracted by a gate post
- Sound waves have a wavelength of $1.72 \times 10^{-2} - 17$ m so would not be diffracted by the diffraction grating
- Radio waves have a wavelength of $0.1 - 10^{6}$ m so would not be diffracted by human hair
- X-rays have a wavelength of $1 \times 10^{-8} - 4 \times 10^{-13}$ m which is roughly the gap between atoms in a crystalline solid
    - Therefore, the correct answer is **D**

Your notes

Examiner Tips and Tricks

When drawing diffracted waves, take care to keep the wavelength constant. It is only the amplitude of the wave that changes when diffracted.

Huygen's diagrams can be tricky to draw, so are definitely worth practicing.

The Diffraction Grating Equation

- A **diffraction grating** is a plate on which there is a very large number of parallel, identical, close-spaced slits
- When **monochromatic light** is incident on a grating, a pattern of narrow bright fringes is produced on a screen

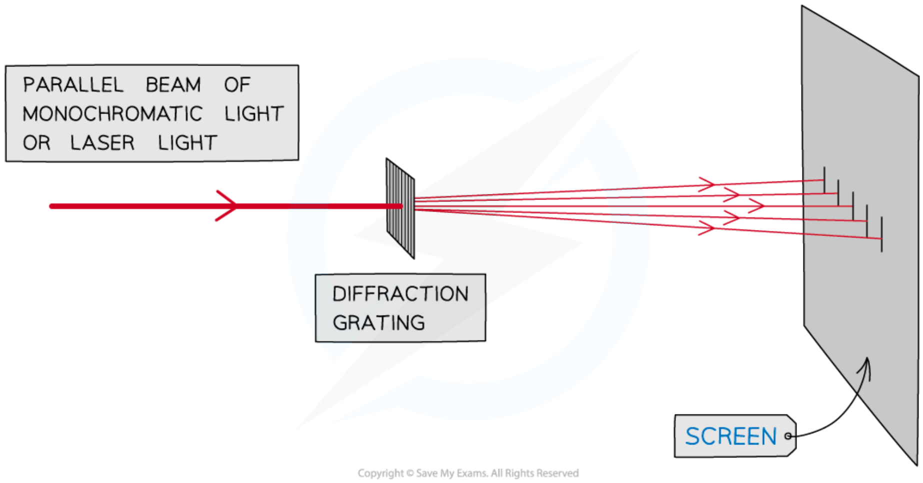
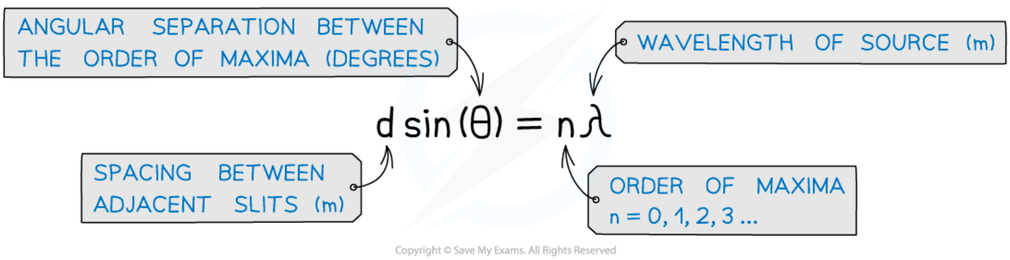


Diagram of diffraction grating used to obtain a fringe pattern

- The angles at which the maxima of intensity (constructive interference) are produced can be deduced by the diffraction grating equation



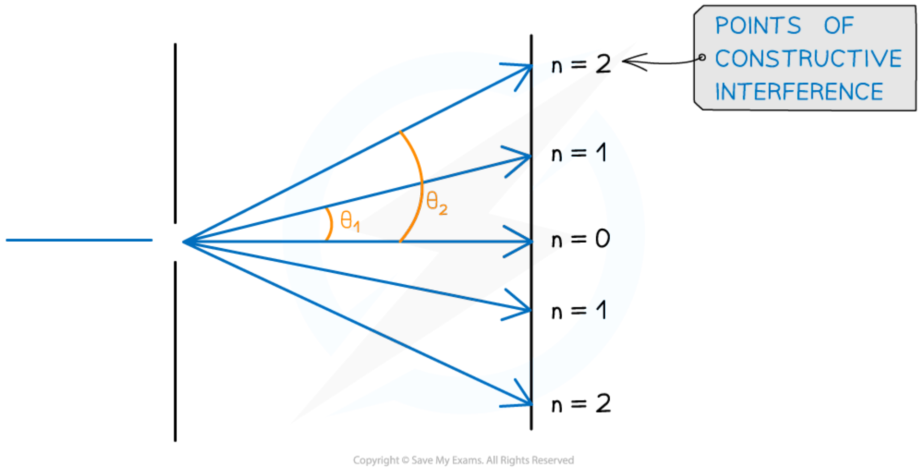
Diffraction grating equation for the angle of bright fringes

- Exam questions sometime state the **lines per m** (or per mm, per nm etc.) on the grating which is represented by the symbol *N*
- *d* can be calculated from *N* using the equation

$$d = \frac{1}{N}$$

Angular Separation

- The angular separation of each maxima is calculated by rearranging the grating equation to make θ the subject
- The angle θ is taken from the centre meaning the higher orders are at greater angles



Angular separation

- The angular separation between two angles is found by subtracting the smaller angle from the larger one
- The angular separation between the first and second maxima n_1 and n_2 is $\boldsymbol{\theta_2 - \theta_1}$

Orders of Maxima

- The maximum angle to see orders of maxima is when the beam is at right angles to the diffraction grating
  - This means $\theta = 90°$ and $\sin\theta = 1$
- The highest order of maxima visible is therefore calculated by the equation:

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

- Note that since *n* must be an integer, if the value is a decimal it must be rounded **down**
  - E.g If *n* is calculated as 2.7 then *n* = 2 is the highest order visible

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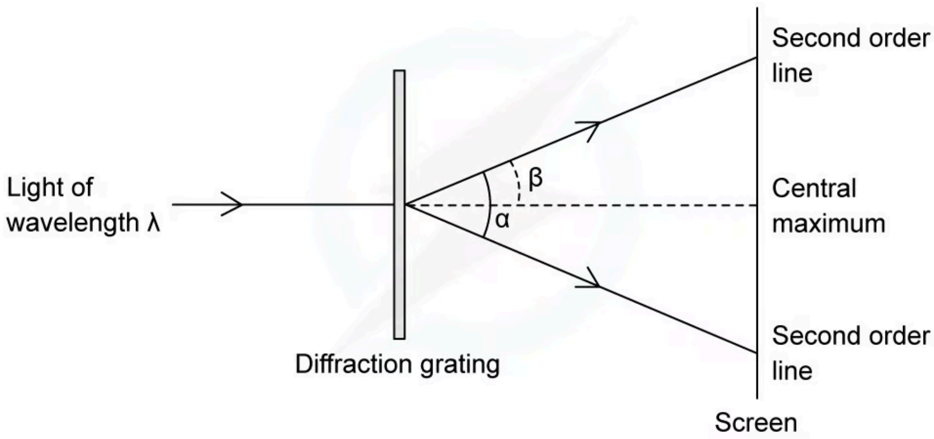
Worked Example

An experiment was set up to investigate light passing through a diffraction grating with a slit spacing of 1.7 μm. The fringe pattern was observed on a screen. The wavelength of the light is 550 nm.



Calculate the angle α between the two second-order lines.

Answer:

STEP 1

DIFFRACTION GRATING EQUATION

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

n = 2 FOR THE SECOND ORDER LINE

D = 1.7 μm

λ = 550 nm

STEP 2

REARRANGE FOR $\sin(\theta)$

$\sin(\theta) = \frac{n\lambda}{d}$

STEP 3

SUBSTITUTE IN VALUES

$\sin(\theta) = \frac{2 \times 550 \times 10^{-9}}{1.7 \times 10^{-6}} = 0.64705... = 0.65$ (2 s.f.)

STEP 4

FIND θ THROUGH THE INVERSE SINE

$\sin^{-1}(0.65) = 40.54°$

STEP 5

θ IS ANGLE FROM THE CENTRE TO THE SECOND ORDER LINE (β ON THE DIAGRAM)

$\alpha = \theta \times 2 = 81°$ (2 s.f.)

Examiner Tips and Tricks

Take care that the angle θ is the correct angle taken from the centre and not the angle taken between two orders of maxima.

Your notes

Core Practical 6: Investigating Diffraction Gratings

Aim of the Experiment

- To find the **wavelength** of light using a **diffraction grating**

Variables

- Independent variable = Distance between maxima, h
- Dependent variable = The angle between the normal and each order, θ_n (where n = 1, 2, 3 etc)
- Control variables
  - Distance between the slits and the screen, D
  - Laser wavelength, λ
  - Slit separation, d

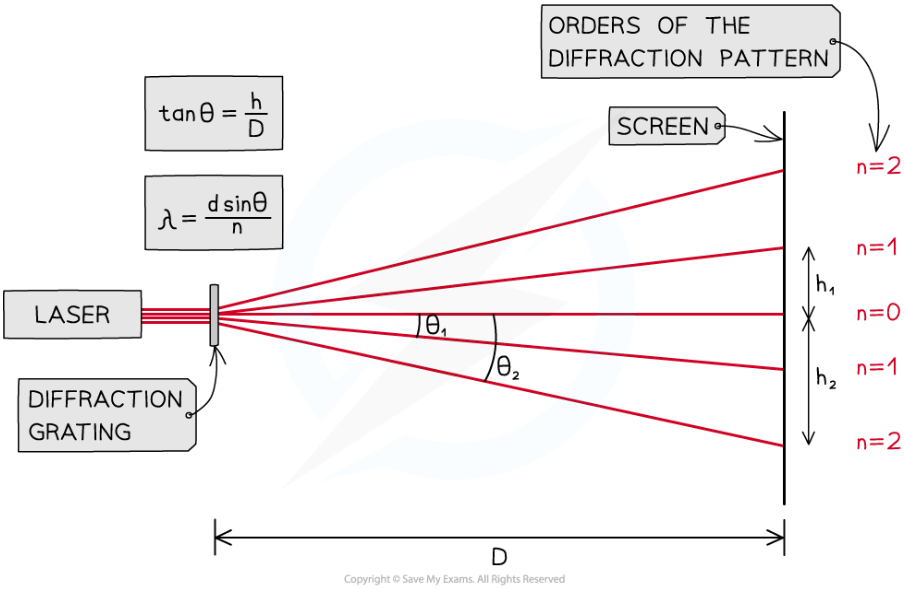
Equipment List

Apparatus	Purpose
Laser	To use as a source of monochromatic light
Single Slit	To focus the laser beam onto the double slit (optional)
Double Slit	To diffract the beam into two sources of coherent light
Diffraction Grating	To diffract the beam into multiple sources of coherent light
Metre ruler	To measure the distance between the slits and the screen (D)
Vernier Callipers	To measure the fringe width (w) and slit separation (if not quoted on double slit)
Retort Stand	To support the laser and slits at the same height
White Screen	To project the interference pattern on to
Set Square	To ensure all components are aligned to the normal perfectly

- Resolution of measuring equipment:
  - Metre ruler = 1 mm

- Vernier Callipers = 0.01 mm

Method

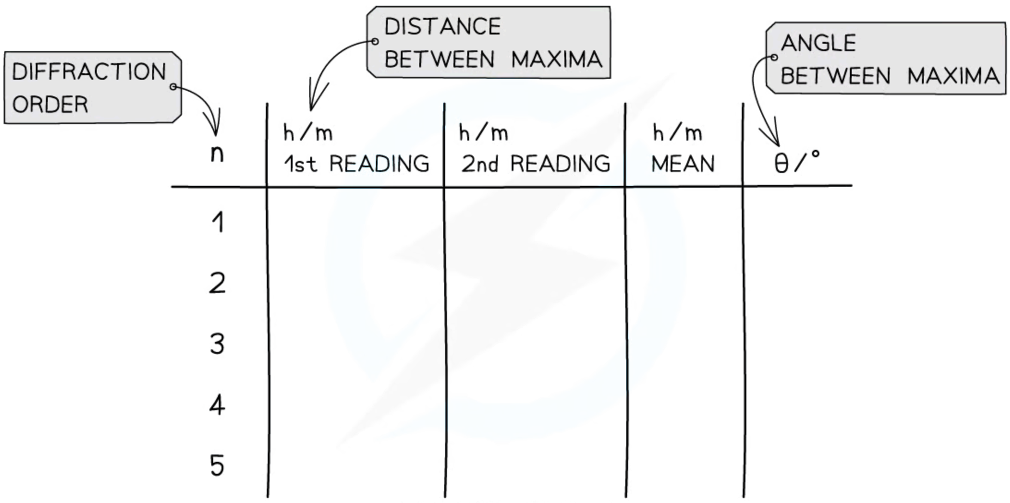


The setup of apparatus required to measure the distance between maxima h at different angles θ

1. Place the **laser** on a **retort stand** with the **diffraction grating** in front of it
2. Use a set square to ensure the beam passes through the grating at **normal incidence** and meets the screen perpendicularly
3. Set the **distance *D*** between the grating and the screen to be 1.0 m using a metre ruler
4. **Darken** the **room** and turn on the laser
5. Identify the **zero-order maximum** (the central beam)
6. Measure the **distance *h*** to the nearest two first-order maxima (i.e. n = 1, n = 2) using a vernier calliper
7. Calculate the **mean** of these two values
8. Measure **distance *h*** for increasing orders
9. **Repeat** with a diffraction grating with a different number of slits per mm

- An example table might look like this:

Your notes



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Analysing the Results

The diffraction grating equation is given by:

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

- Where:
  - n = the order of the diffraction pattern
  - λ = the wavelength of the laser light (m)
  - d = the distance between the slits (m)
  - θ = the angle between the normal and the maxima (°)
- The distance between the slits is equal to:

$$d = \frac{1}{N}$$

- Where
  - N = the number of slits per metre (m^{-1})
- Since the angle is not small, it must be calculated using **trigonometry** with the measurements for the distance between maxima, h, and the distance between the slits and the screen, D

$$\tan \theta = \frac{h}{D} \quad \rightarrow \quad \theta = \tan^{-1}\left(\frac{h}{D}\right)$$

- Calculate a **mean** θ value for each order

- Calculate a **mean** value for the **wavelength** of the laser light and compare the value with the accepted wavelength
  - This is usually 635 nm for a standard school red laser

Evaluating the Experiments

Systematic errors:

- Ensure the use of the set square to avoid **parallax error** in the measurement of the fringe width
- Using a grating with more **lines per mm** will result in greater values of *h*. This lowers its percentage uncertainty

Random errors:

- The **fringe spacing** can be subjective depending on its **intensity** on the screen, therefore, take multiple measurements of *w* and *h* (between 3–8) and find the average
- Use a **Vernier scale** to record distances *w* and *h* to reduce percentage uncertainty
- Reduce the uncertainty in *w* and *h* by **measuring across all visible fringes** and dividing by the number of fringes
- **Increase** the **grating to screen distance *D*** to increase the fringe separation (although this may decrease the intensity of light reaching the screen)
- Conduct the experiment in a darkened room, so the fringes are clear

Safety Considerations

- Lasers should be Class 2 and have a maximum output of no more than 1 mW
- Do not allow laser beams to shine into anyone's eyes
- Remove reflective surfaces from the room to ensure no laser light is reflected into anyone's eyes

Worked Example

A student investigates the interference patterns produced by two different diffraction gratings. One grating used was marked 100 slits / mm, and the other was marked 300 slits / mm. The distance between the grating and the screen is measured to be 3.75 m.

The student recorded the distance between adjacent maxima after passing a monochromatic laser source through each grating. These results are shown in the tables below.

Your notes

300 slits/mm	h_1/cm	h_2/cm	Average h/cm	Cumulative Total h/cm
n=0 to 1	71.7	71.5	71.6	71.6
n=1 to 2	79.8	79.8	79.8	151.4

100 slits/mm	h_1/cm	h_2/cm	Average h/cm	Cumulative Total h/cm
n=0 to 1	23.8	24.0	23.9	23.9
n=1 to 2	24.0	25.0	24.5	48.4

Calculate the mean wavelength of the laser light and compare it with the accepted value of 635 nm. Assess the percentage uncertainty in this result.

Answer:

Step 1: Calculate the distance between the slits

For 300 slits / mm: $d = \frac{1}{N} = \frac{1}{300 \times 10^3}$

For 100 slits / mm: $d = \frac{1}{N} = \frac{1}{100 \times 10^3}$

Step 2: Calculate the mean angle for each order

$$\theta = \tan^{-1}\left(\frac{h}{D}\right)$$

Your notes

- For 300 slits / mm:

$$\theta_1 = \tan^{-1}\left(\frac{71.6}{375}\right) = 10.81°$$

$$\theta_2 = \tan^{-1}\left(\frac{151.4}{375}\right) = 21.99°$$

- For 100 slits / mm:

$$\theta_1 = \tan^{-1}\left(\frac{23.9}{375}\right) = 3.647°$$

$$\theta_2 = \tan^{-1}\left(\frac{48.4}{375}\right) = 7.354°$$

Step 3: Use the grating equation to determine the wavelengths for each order

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

- For 300 slits / mm:

$$n = 1: \lambda = \frac{1}{300 \times 10^3} \times \sin 10.81° = 6.25 \times 10^{-7} = 625 \text{ nm}$$

$$n = 2: \lambda = \frac{1}{2 \times (300 \times 10^3)} \times \sin 21.99° = 6.24 \times 10^{-7} = 624 \text{ nm}$$

- For 100 slits / mm:

$$n = 1: \lambda = \frac{1}{100 \times 10^3} \times \sin 3.647° = 6.36 \times 10^{-7} = 636 \text{ nm}$$

$$n = 2: \lambda = \frac{1}{2 \times (100 \times 10^3)} \times \sin 7.354° = 6.40 \times 10^{-7} = 640 \text{ nm}$$

Step 4: Calculate the mean wavelength

$$\text{Mean } \lambda = \frac{625 + 624 + 636 + 640}{4} = 631.25 = 631 \text{ nm}$$

Step 5: Determine the percentage uncertainty in this value

- The difference between the calculated and accepted value is:

$$635 - 631 = 4 \text{ nm}$$

$$\% \text{ uncertainty} = \frac{4}{635} \times 100\% = 0.6\%$$

Your notes

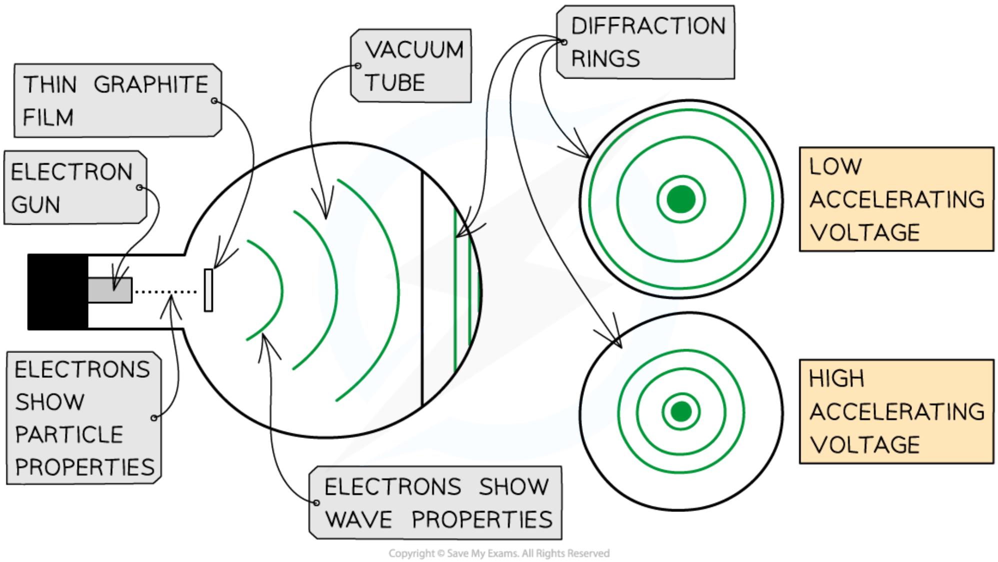
Your notes

Examiner Tips and Tricks

Remember to read the question carefully and make sure dimensions such as the fringe separation are put into meters.

The Wave Nature of Electrons

- Electron diffraction was the first clear evidence that matter can behave like light and has wave properties
  - This is demonstrated using the electron diffraction tube
- The electrons are accelerated in an electron gun to a high potential, such as 5000 V, and are then directed through a thin film of graphite
  - The lattice structure of the graphite acts like the slits in a diffraction grating
- The electrons diffract from the gaps between carbon atoms and produce a circular pattern on a fluorescent screen made from phosphor



Electrons accelerated through a high potential difference demonstrate wave-particle duality

- In order to observe the diffraction of electrons, they must be focused through a gap similar to their size, such as an atomic lattice
- Graphite film is ideal for this purpose because of its crystalline structure
  - The gaps between neighbouring planes of the atoms in the crystals act as slits, allowing the electron waves to spread out and create a diffraction pattern
- The diffraction pattern is observed on the screen as a series of concentric rings
  - This phenomenon is similar to the diffraction pattern produced when light passes through a diffraction grating
  - If the electrons acted as particles, a pattern would not be observed, instead, the particles would be distributed uniformly across the screen

- It is observed that a larger accelerating voltage reduces the diameter of a given ring, while a lower accelerating voltage increases the diameter of the rings

Your notes

Your notes

The de Broglie Equation

- Using ideas based upon the quantum theory and Einstein's theory of relativity, de Broglie theorised that not only do EM waves sometimes behave as particles, but that very small, fast moving particles like electrons could also behave as waves
  - He called these **matter waves**
- The Broglie equation relates the wavelength of some particles to their mass and velocity, which combine to give their momentum
  - Hence:

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

- λ = the de Broglie wavelength (m)
  - *h* = Planck's Constant (J s)
  - *m* = mass (kg)
  - *v* = velocity (m s^{-1})
  - *p* = momentum (kg m s^{-1})

Worked Example

Determine the de Broglie wavelength of a person of mass 70 kg moving at 2 ms^{-1} and comment on your answer.

Answer:

Step 1: Write the known values

- Mass, m = 70 kg
- Velocity, v = 2 m s^{-1}
- Planck's constant, h = 6.63×10^{-34} Js

Step 2: Write the equation and substitute the values

$$\lambda = \frac{h}{mv} = \frac{(6.63 \times 10^{-34})}{70 \times 2} = 4.74 \times 10^{-36}$$

Step 3: Write the answer to the correct number of significant figures and include units

- de Broglie wavelength of a moving person, $\lambda = 4.7 \times 10^{-36}$ m

Step 4: Think about the magnitude of the result and comment on it

- The person does have a de Broglie wavelength but since it is about 10^{20} times smaller than a nucleus, it can be ignored
- People behave like particles, not waves

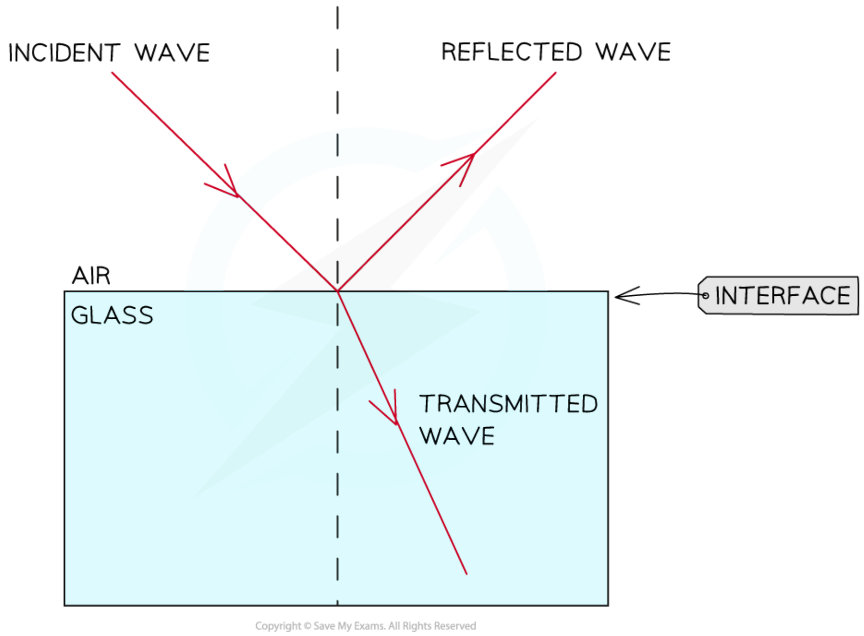
Your notes

Examiner Tips and Tricks

If you've not been given the mass of a particle in a question, make sure to look at your data sheet which includes the rest mass of various particles

Transmission & Reflection of Waves

- When waves are incident on the interface between two different media, they are either **transmitted** or **reflected**
  - 'Incident on' simply means 'to meet'
  - The interface is also called the **boundary** between media
  - Transmitted means to pass through



- When the media have **similar** densities the energy of the wave is mostly **transmitted**
- When the media have **different** densities most of the energy is **reflected**

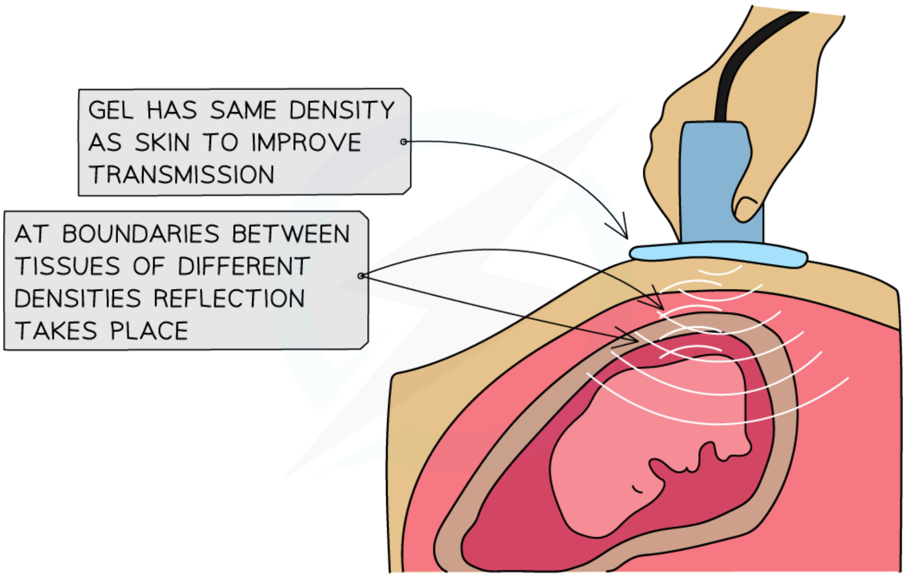
Reflected waves in use

- Uses of reflected waves include:
  - Medical x-rays
  - Sonar
  - Ultrasound scans

Transmitted waves in use

- In the above examples the waves have to be transmitted through one medium first, before they are reflected

- X-rays are transmitted through soft tissue
- Sonar is transmitted through air or water
- Ultrasound is transmitted through a gel of similar density to the skin so that it reaches the tissues inside the body



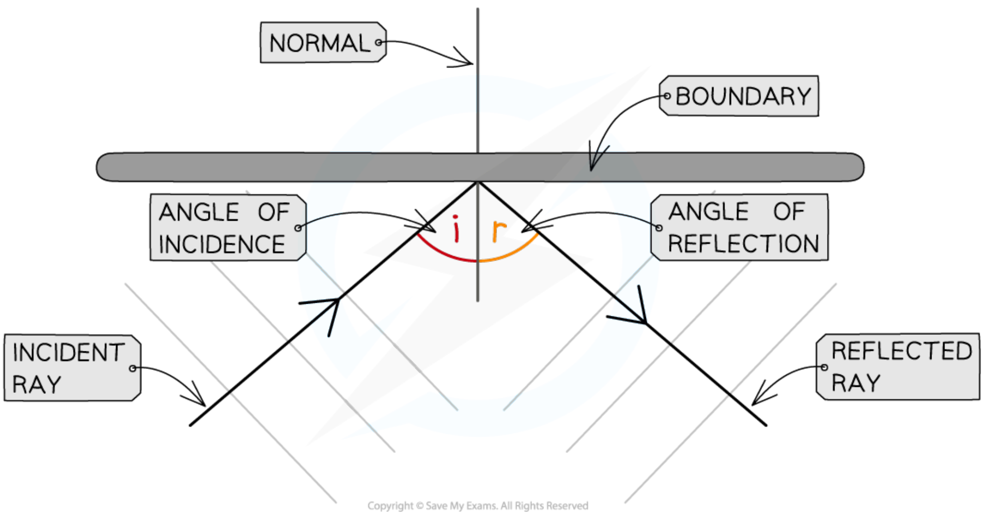
Reflection

- Reflection occurs when:

  A wave hits a boundary between two media and does not pass through, but instead stays in the original medium

- The law of reflection states:

  The angle of incidence = The angle of reflection



Reflection of a wave at a boundary

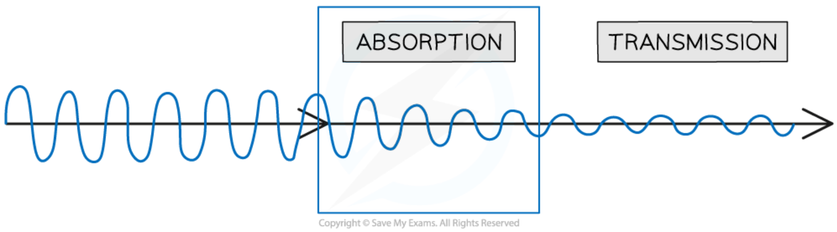
- Some of the wave may also be absorbed or transmitted
  - Echos are examples of sound waves being reflected off a surface
- **Flat** surfaces are the **most** reflective
  - The smoother the surface, the stronger the reflected wave is
- **Rough** surfaces are the **least** reflective
  - This is because the light scatters in all directions
- **Opaque** surfaces will reflect light which is not absorbed by the material
  - The electrons will absorb the light energy, then reemit it as a reflected wave

Transmission

- Transmission occurs when:

  A wave passes through a substance

- For light waves, the more transparent the material, the more light will pass through
  - Transmission can involve **refraction** but it is not exactly the same
  - For the process to count as transmission, the wave must pass through the material and **emerge** from the other side
- When passing through a material, waves are usually partially absorbed
  - The transmitted wave may have a lower **amplitude** because of some absorption
    - For example, sound waves are **quieter** after they pass through a wall



When a wave passes through a boundary it may be absorbed and transmitted

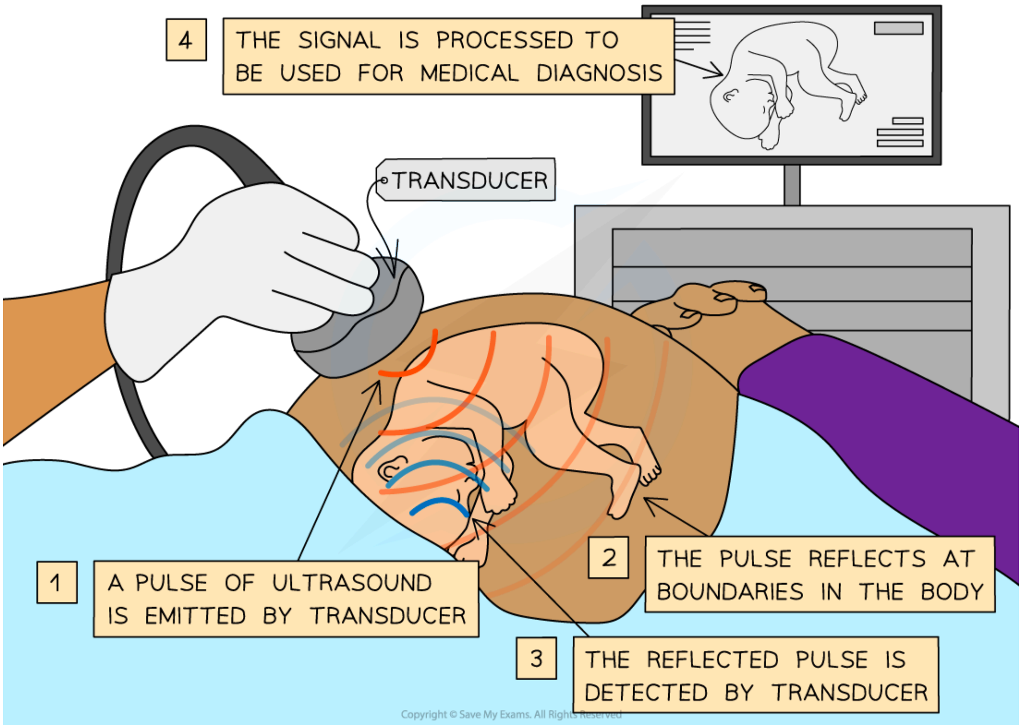
Your notes

Your notes

Pulse-Echo Technique

Foetal Scanning

- In medicine, ultrasound can be used to construct images of a **foetus** in the womb
  - An ultrasound detector is made up of a **transducer** that produces and detects a beam of ultrasound waves into the body
  - The ultrasound waves are reflected back to the transducer by different **boundaries** between tissues in the path of the beam
  - For example, the boundary between fluid and soft tissue or tissue and bone
- Using the speed of sound and the time of each echo's return, the detector calculates the distance from the transducer to the tissue boundary
- Gel is put onto the scanner so that the boundary between the instrument and the skin is of the same density as the skin, this allows the signal to be easily **transmitted**
- By taking a series of ultrasound measurements, sweeping across an area, the time measurements may be used to build up an **image**
  - Unlike many other medical imaging techniques, ultrasound is **non-invasive** and **harmless**

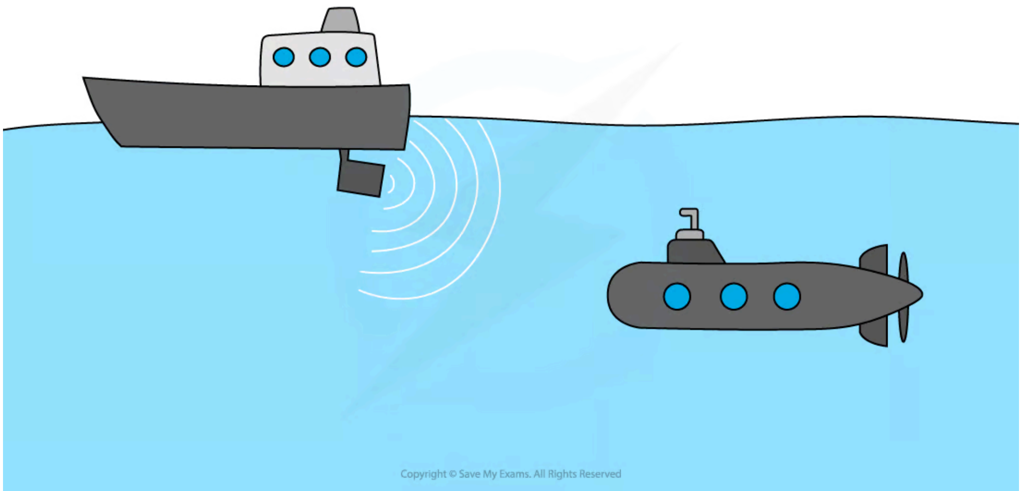


Ultrasound can be used to construct an image of a foetus in the womb

Your notes

Sonar

- **Sonar** uses **ultrasound** to detect objects underwater
- The sound wave is **reflected** off the object being tracked
- Examples include;
  - Finding fish by fishing fleets
  - Military uses looking for underwater vessels
  - Mapping the ocean bottom

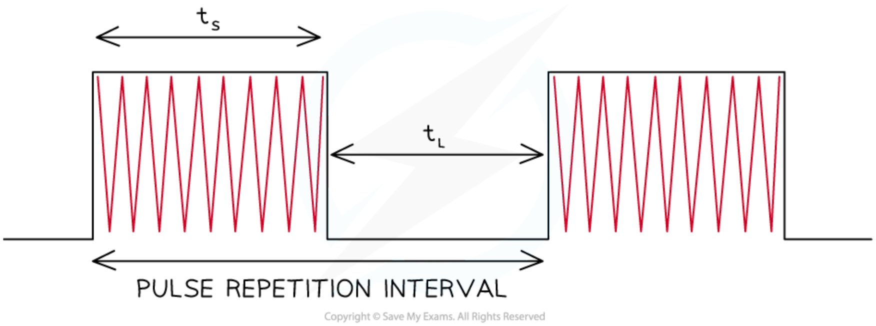


- The **time** it takes for the sound wave to return is used to calculate the **depth** of the water
- The **distance** the wave travels is **twice the depth** of the ocean
  - This is the distance to the ocean floor plus the distance for the wave to return

Pulse Duration and Wavelength

- The amount of detail which can be captured (the **resolution**) of pulse-echo techniques depends on the wavelength
  - **Shorter** wavelengths have **smaller (better)** resolution
  - **More** detail can be seen since they diffract (spread out) less
  - More energy is needed as short wavelength waves have higher frequency
- Wavelength is chosen to be similar in size to the object that is being resolved
  - This makes best use of diffraction effects
- Pulse duration is a consideration because ultrasound transducers cannot transmit and receive pulses at the same time.
  - If incoming and outgoing pulses overlap the information is lost and image quality suffers

- This affects the range since a longer wait time for pulses to return reduces the amount of information which can be collected



- Ultrasound pulses are very short, only a few microseconds, to reduce reflections from nearby interfaces
- The gap between pulses is relatively long, measured in milliseconds, to prevent overlapping signals
  - This combination of **short pulses** with relatively **large spaces** between them produces the **clearest** images

Worked Example

A sonar system uses ultrasound with frequency of 3.2 kHz to map the ocean floor. The speed of sound in water is 1 500 m s^{-1}.

An echo is detected 3.6 s after the pulse is transmitted.

a) Determine the depth of the sea at this point.

b) Suggest a resolution for this ultrasound survey of the seafloor

Part (a)

Step 1: Write the known values from the question

- Frequency, f = 3.2 kHz = 3 200 Hz
- Speed of sound, v = 1 500 m s^{-1}
- Time, t = 3.6 s

Step 2: Write the correct equation and substitute the values

- Distance;

$$d = vt = 1500 \times 3.6 = 5\,400 \text{ m}$$

Step 3: Account for the received signal being an echo

- Total distance travelled by the signal = 5 400 m
- Depth of the sea floor = 1/2 × 5 400 = 2 700 m

Part (b)

Your notes

Step 1: Write the wave equation and rearrange to make wavelength the subject

$$v = f\lambda$$

$$\rightarrow \lambda = \frac{v}{f}$$

Step 2: Calculate to find wavelength

$$\lambda = \frac{1500}{3200} = 0.47$$

Step 3: Write the final answer to correct significant figures and give units

The resolution of the signal is similar to the wavelength, and λ = 0.47 m

Your notes

Wave-Particle Duality

- Light can behave as a particle (i.e. photons) **and** a wave
- This phenomenon is called the wave-particle nature of light or **wave-particle duality**
- Light interacts with matter, such as electrons, **as a particle**
  - The evidence for this is provided by the photoelectric effect
- Light propagates through space **as a wave**
  - The evidence for this comes from the diffraction and interference of light in Young's Double Slit experiment

Light as a Particle

- Einstein proposed that light can be described as a quanta of energy that behave as particles, called photons
- The photon model of light explains that:
  - Electromagnetic waves carry energy in discrete packets called photons
  - The energy of the photons are quantised according to the equation $E = hf$
  - In the photoelectric effect, each electron can absorb only a single photon - this means only the frequencies of light above the threshold frequency will emit a photoelectron
- The wave theory of light does **not** support the idea of a threshold frequency
  - The wave theory suggests any frequency of light can give rise to photoelectric emission if the exposure time is long enough
  - This is because the wave theory suggests the energy absorbed by each electron will increase gradually with each wave
  - Furthermore, the kinetic energy of the emitted electrons should increase with radiation intensity
  - However, in the photoelectric effect, this is not what is observed
- If the frequency of the incident light is above the threshold and the intensity of the light is increased, **more photoelectrons are emitted per second**
- Although the wave theory provides good explanations for phenomena such as interference and diffraction, it fails to explain the photoelectric effect

Compare wave theory and particulate nature of light

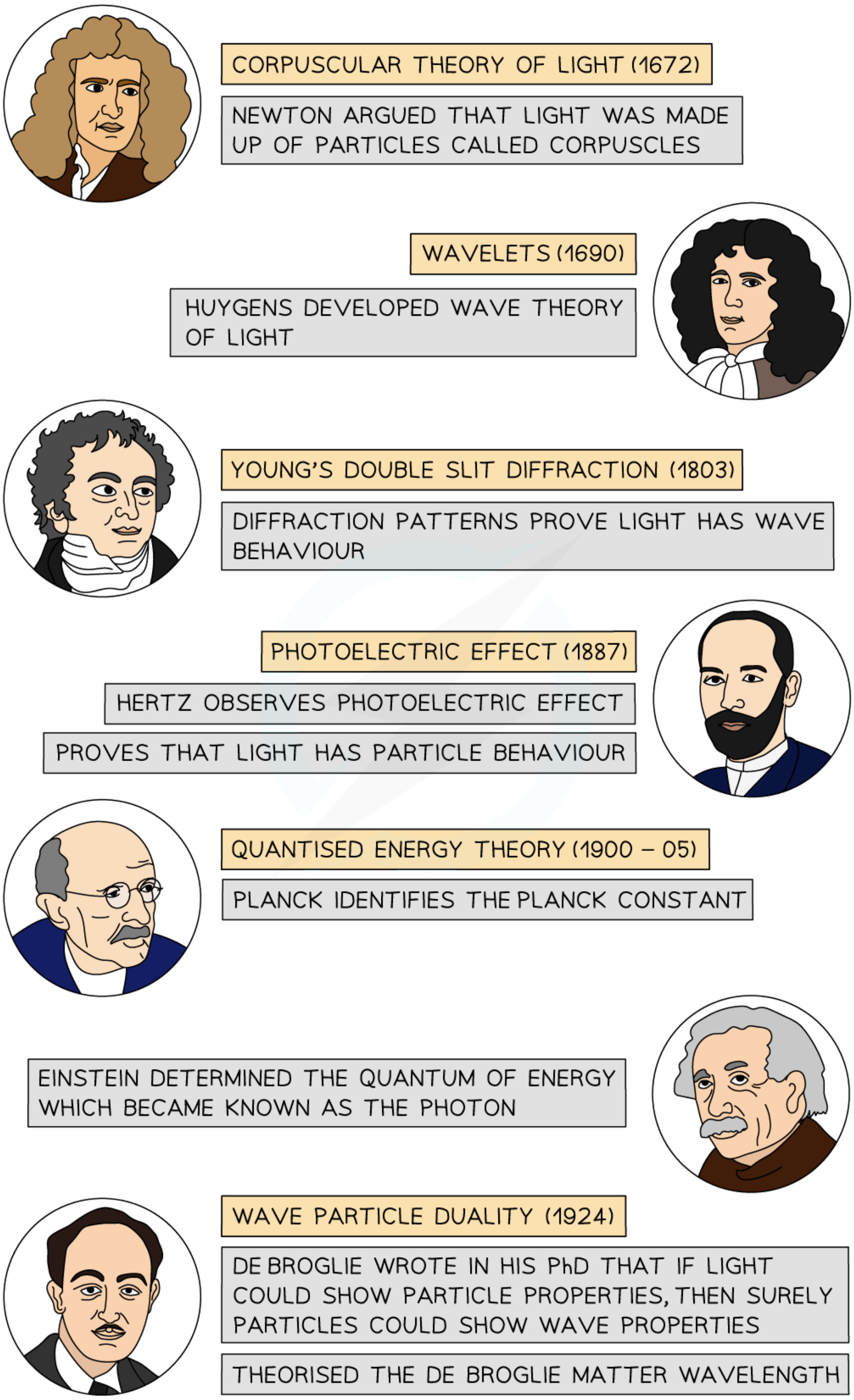
Your notes

The wave theory of light suggests...	This is wrong because...
Any frequency of light can give rise to photoelectric emission if the exposure time is long enough	Photoelectrons will be released immediately if the frequency is above the threshold for that metal
The energy absorbed by each electron will increase gradually with each wave	Energy is absorbed instantaneously – photoelectrons are either emitted or not emitted after exposure to light
The kinetic energy of the emitted electrons should increase with radiation intensity	If the intensity of the light is increased, more photoelectrons are emitted per second

Development of the Theory of Wave-Particle Duality

- Ideas about the nature of light were contested by modern science for around 300 years
- The evidence to prove both theories was available
  - Some prominent scientists argued light was a wave
  - Others contested that light was a particle
- It was not until the early 20th century that scientists settled on a theory of duality

Your notes

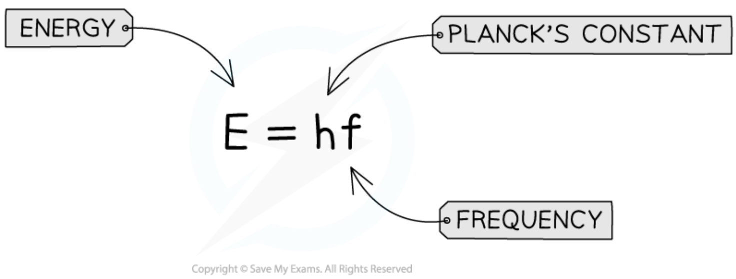

CORPUSCULAR THEORY OF LIGHT (1672)
NEWTON ARGUED THAT LIGHT WAS MADE UP OF PARTICLES CALLED CORPUSCLES
WAVELETS (1690)
HUYGENS DEVELOPED WAVE THEORY OF LIGHT
YOUNG'S DOUBLE SLIT DIFFRACTION (1803)
DIFFRACTION PATTERNS PROVE LIGHT HAS WAVE BEHAVIOUR
PHOTOELECTRIC EFFECT (1887)
HERTZ OBSERVES PHOTOELECTRIC EFFECT
PROVES THAT LIGHT HAS PARTICLE BEHAVIOUR
QUANTISED ENERGY THEORY (1900 – 05)
PLANCK IDENTIFIES THE PLANCK CONSTANT
EINSTEIN DETERMINED THE QUANTUM OF ENERGY WHICH BECAME KNOWN AS THE PHOTON
WAVE PARTICLE DUALITY (1924)
DE BROGLIE WROTE IN HIS PhD THAT IF LIGHT COULD SHOW PARTICLE PROPERTIES, THEN SURELY PARTICLES COULD SHOW WAVE PROPERTIES
THEORISED THE DE BROGLIE MATTER WAVELENGTH

Energy of a Photon

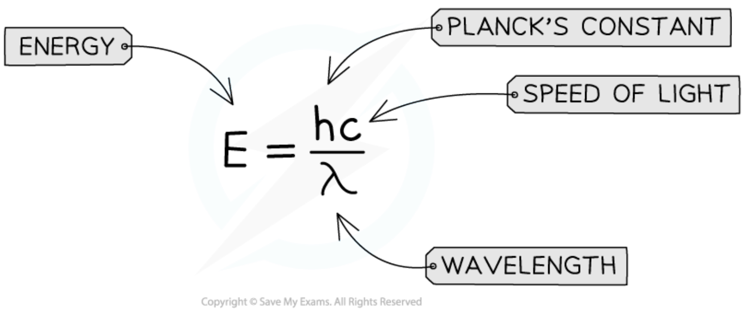
- Photons are fundamental particles which make up all forms of electromagnetic radiation
- A photon is a massless "packet" or a "quantum" of electromagnetic energy
- What this means is that the energy is not transferred continuously, but as discrete packets of energy
- In other words, each photon carries a specific amount of energy, and transfers this energy all in one go, rather than supplying a consistent amount of energy

Calculating Photon Energy

- The energy of a photon can be calculated using the formula:



- Using the wave equation, energy can also be equal to:



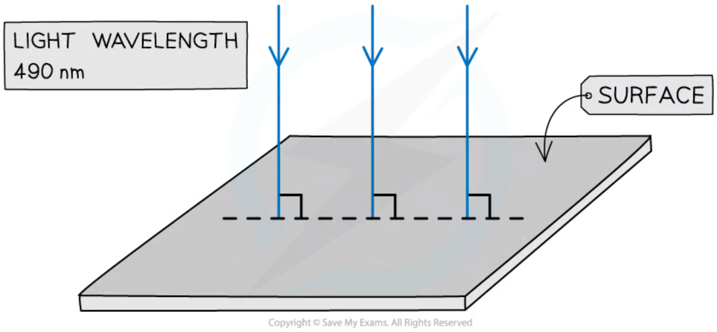
- Where:
  - E = energy of the photon (J)
  - h = Planck's constant (J s)
  - c = the speed of light (m s^{-1})
  - f = frequency (Hz)

- λ = wavelength (m)
- This equation tells us:
  - The higher the frequency of EM radiation, the higher the energy of the photon
  - The energy of a photon is inversely proportional to the wavelength
  - A long-wavelength photon of light has a lower energy than a shorter-wavelength photon

Your notes

Worked Example

Light of wavelength 490 nm is incident normally on a surface, as shown in the diagram.



The power of the light is 3.6 mW. The light is completely absorbed by the surface.
Calculate the number of photons incident on the surface in 2.0 s.

Answer:

Your notes

Step 1: Write the known quantities

Wavelength, λ = 490 nm = 490×10^{-9} m

Power, P = 3.6 mW = 3.6×10^{-3} W

Time, t = 2.0 s

Step 2: Write the equations for wave speed and photon energy

$$\text{Wave speed: } c = f\lambda \rightarrow f = \frac{c}{\lambda}$$

$$\text{Photon energy: } E = hf \rightarrow E = \frac{hc}{\lambda}$$

Step 3: Calculate the energy of one photon

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}) \times (3.0 \times 10^{8})}{490 \times 10^{-9}} = 4.06 \times 10^{-19} \text{ J}$$

Step 4: Calculate the number of photons hitting the surface every second

$$\frac{\text{Power of light source}}{\text{Energy of one photon}} = \frac{3.6 \times 10^{-3}}{4.06 \times 10^{-19}} = 8.9 \times 10^{15} \text{ s}^{-1}$$

Step 5: Calculate the number of photons that hit the surface in 2 s

$$(8.9 \times 10^{15}) \times 2 = 1.8 \times 10^{16}$$

Examiner Tips and Tricks

Make sure you learn the definition for a photon: *discrete quantity / packet / quantum of electromagnetic energy* are all acceptable definitions.

The values of Planck's constant and the speed of light will always be available on the datasheet, however, it helps to memorise them to speed up calculation questions!