4 Waves and our universe

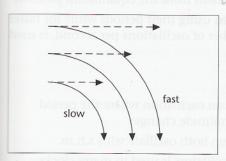
# Part 1

## art 1 Oscillations and waves

## K Introduction

Waves are the result of a disturbance such as the oscillation of an object. The simplest form of a wave is one represented by a sine or cosine function, indicating that the oscillator producing it moves with simple harmonic motion. The to-and-fro motion of such an oscillator is similar to the side-toside motion of a body moving around a circular path at a constant speed. As you study oscillations and waves, you learn why a body following a circular path continues to move at a constant speed despite the fact that it is accelerating. You find that a simple harmonic oscillator has a constant period and can be used for accurate timing. You investigate how the period of a pendulum depends on its length and use the resulting relationship to calculate a value for the acceleration of gravity. You study the effect of damping on the resonance curve of a forced oscillator and meet with everyday situations involving resonance. You become familiar with terms such as amplitude, speed, wavelength, frequency and phase, which are used to describe a wave. You discover the difference between progressive and stationary waves, between longitudinal and transverse waves and between mechanical and electromagnetic waves. You find that waves can reinforce or cancel depending on their phase difference and you measure wavelength from a number of superposition experiments.

## $\leqslant$ Things to understand



**Fig 4.1** The speed increases with path radius for objects with the same angular speed

#### **Circular motion**

- angular speed  $\omega$  describes the circular motion of a body in terms of the rate of change of the angle  $\Delta \theta$  at the centre of its path,  $\omega = \Delta \theta / \Delta t$
- this angle is measured in radians (rad) and angular speed in rad s<sup>-1</sup>
  - there are  $2\pi$  radians in a whole circle, so dividing  $2\pi$  by  $\omega$  gives the period *T*, the time taken to complete one revolution
- the period can also be found by dividing the distance around the circular path (circumference = 2πr) by the linear speed v of the object
   bodies can have the same angular speed but different linear speeds depending on how far they are from the centre of the circle (Figure 4.1)

- a body moving around a circular path is continually changing its direction of motion
- the body's velocity (a vector) is continually changing although its speed (a scalar) remains constant
- since its velocity is continually changing, the body is always accelerating
- the acceleration is towards the centre of the circular path (centripetal acceleration)
- the acceleration of gravity is the centripetal acceleration for satellites orbiting the Earth
- a resultant force (centripetal force) must act towards the centre to produce this acceleration
- without this force, the body would continue in a straight line along a tangent
- the work done  $(F\Delta x)$  by a centripetal force is zero as there is no displacement  $(\Delta x = 0)$  in the direction of the force
- a centripetal force does not change the kinetic energy or speed of a body, only its direction of motion

#### Weightlessness

- you can only be weightless when you are a long way from all other masses
- if you were falling freely, you would experience apparent weightlessness as all parts of your body would then be accelerating downwards at the same rate
- astronauts in orbit around the Earth are continually accelerating towards its centre at a rate equal to the acceleration of gravity and experience apparent weightlessness

#### Oscillations

- many systems undergo to-and-fro movements called oscillations
- all oscillations eventually die away as energy dissipates to the surroundings
- the position of an oscillating body is given as its displacement (a vector) from its equilibrium position
- when at its equilibrium position, the resultant force on a body is zero
- displacements vary from positive to negative to positive during the course of one oscillation
- amplitude is the maximum displacement from the equilibrium position
- slow oscillations are usually described using their periods while for faster oscillations the frequency, the number of oscillations per second, is used

#### **Simple harmonic motion**

- Simple harmonic motion (s.h.m.) is an oscillation where the period remains constant even when the amplitude changes
- a pendulum and a mass-spring system both oscillate with s.h.m.
- the regularity of simple harmonic oscillators is used in many clocks
- plotting displacement against time for such an oscillator produces a sinusoidal graph

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OSCILLATIONS AND WAVES

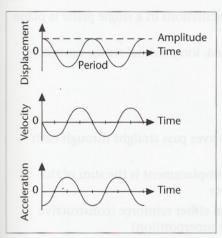


Fig 4.2 Displacement, velocity and acceleration for s.h.m.

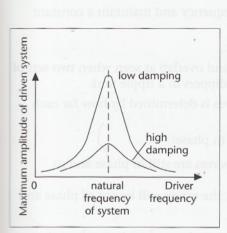


Fig 4.3 Response of a system that is being forced to oscillate

- the velocity-time graph can be deduced from the variation of the gradient of the displacement-time graph
- the acceleration-time graph can be deduced from the variation of the gradient of the velocity-time graph
- velocity and acceleration also vary sinusoidally with time although all three quantities are out of step with each other (Figure 4.2)
- at the equilibrium position (zero displacement), velocity is a maximum (either positive or negative) and acceleration is zero (it has to be since resultant force is zero)
- positive and negative velocities show the body moving in opposite directions
- at either amplitude, velocity is zero (the body momentarily stops moving as it changes direction) and acceleration is a maximum (either positive or negative)
- positive and negative accelerations show the body accelerating in opposite directions
- acceleration is always directed towards the equilibrium position and increases with distance from it
- acceleration is proportional to displacement but in the opposite direction (acceleration and displacement always have opposite signs)
- the relationship  $a \propto -x$  results in s.h.m. and is used to define it

#### **Forced oscillations**

- every system has its own natural frequency at which it oscillates
- a system oscillates with its largest amplitude (resonates) when forced to oscillate at its natural frequency
- resonance is sharper when damping is low (Figure 4.3)
- resonance can be put to good use (e.g. wind instruments) but can cause serious damage (e.g. bridge failures)

#### **Progressive waves**

- all progressive waves travel away from their source and convey energy
- as a wave spreads out from a point source, it conveys energy over a larger area
- intensity (power per unit area) decreases with increasing distance from a point source
- as a result of energy conservation, the reduction in intensity of a wave spreading out uniformly in all directions obeys an inverse square law provided none is absorbed along the way
- waves are either mechanical (e.g. along a spring, on water, in air) or electromagnetic (e.g. visible light, microwaves)
- mechanical waves are either transverse (e.g. on water) or longitudinal (e.g. sound)
- a transverse wave consists of oscillations perpendicular to the direction of travel
- a longitudinal wave consists of oscillations parallel to the direction of travel
- all electromagnetic waves are transverse and move at  $3 \times 10^8$  m s<sup>-1</sup> in *vacuo*

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- a transverse wave which has all its oscillations in a single plane is plane polarised
  - only transverse waves can be polarised, longitudinal waves cannot be polarised

#### Wave superposition

In phase	() =	$\bigcap$
Out of phase	U =	he body i coteleratio now the b

**Fig 4.4** When waves combine, their phase determines the outcome

- when the paths of waves cross, the waves pass straight through each other
- where the paths cross, the resulting displacement is the sum of the displacements of the individual waves
- displacement is a vector so waves can either reinforce (constructive superposition) or cancel (destructive superposition)
- waves in phase reinforce to produce maxima whereas those out of phase cancel to produce minima (Figure 4.4)
- complete cancellation occurs only when the out of phase waves have identical amplitudes

#### Two source superposition

- sources used must have the same frequency and maintain a constant phase difference (usually zero)
- such sources are said to be coherent
- waves spread out from each source and overlap as seen when two sets of circular waves are produced by two dippers in a ripple tank
- phase difference of overlapping waves is determined by how far each has travelled from its source
- for waves from two sources that are in phase:
  - where path difference =  $n\lambda$  the waves are still in phase and so produce a maximum
  - where path difference =  $(n + \frac{1}{2})\lambda$ , the waves will be out of phase and so produce a minimum
- two slits can be used with a single source to produce two coherent sources
- waves spread out (diffract) as they pass through the slits
  - amount of diffraction depends on the slit width and the wavelength of the waves
  - the narrower the slit and the larger the wavelength, the greater the diffraction (Figure 4.5)

#### **Stationary** waves

- produced by the superposition of two identical waves travelling in opposite directions
- resulting pattern has points where the amplitude is always zero (nodes) and those where there is a maximum amplitude (antinodes)
- adjacent nodes are half wavelength apart, as are adjacent antinodes
- all points between adjacent nodes move in phase
- points either side of a node move out of phase
- a stationary wave does not transfer energy although it does have energy 'trapped' within its antinodal regions

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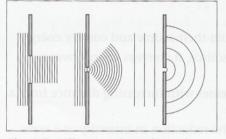


Fig 4.5 Diffraction depends on slit width and wavelength

#### Things to learn

You should learn the following for your Unit PHY4 Test. Remember that it may also test your understanding of the 'general requirements' (see Appendix 1).

#### Equations that will not be given to you in the test

 $\Box$  centripetal force = mass × speed<sup>2</sup>/radius

 $F = mv^2/r$ 

wave speed = frequency × wavelength

 $v = f\lambda$ 

 $\lambda$  = wavelength

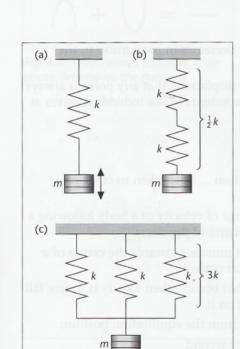
#### Laws

- inverse square law: when a quantity decreases in proportion to the square of the increasing distance
- principle of superposition: resultant displacement at any point is always equal to the vector sum of the displacements of the individual waves at that point

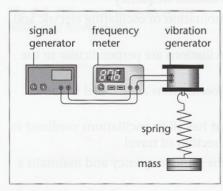
#### **General definitions**

- period: time to complete one revolution ... time taken to cover one complete oscillation
- centripetal acceleration: rate of change of velocity of a body following a circular path, directed towards the centre of the circle
- centripetal force: resultant force that must act towards the centre of a circle to make a body follow a circular path
- apparent weightlessness: situation that occurs when a body is in free fall with only the force of gravity acting on it
- amplitude: maximum displacement from the equilibrium position
- frequency: number of oscillations per second
- simple harmonic motion: motion where the acceleration is directly proportional to the displacement from a fixed point and always directed towards that point
- natural frequency: the frequency at which an isolated system oscillates after it has been displaced and then released
- resonance: the large-amplitude oscillations that arise as a result of a system being forced to oscillate at its natural frequency
- electromagnetic wave: transverse combination of oscillating electric and magnetic fields
- transverse wave: a wave where the oscillations are perpendicular to the direction of travel
- longitudinal wave: a wave where the oscillations are parallel to the direction of travel
- plane polarised: a transverse wave that has all its oscillations confined to a single plane perpendicular to the direction of travel
- coherent sources: sources that have the same frequency and maintain a constant phase difference
- node: a point on a stationary wave where the displacement is always zero

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**Fig 4.6** (a) Vertical oscillations of a mass-spring system, (b) and (c) Varying the force constant



**Fig 4.7** The vibration generator forces the mass to oscillate

antinode: a point on a stationary wave that oscillates with the maximum amplitude

#### Word equation definitions

Use the following word equations when asked to define:

angular speed = change in central angle/time taken

#### Experiments

#### 1. Oscillations of a pendulum

Set up a pendulum and measure the length *l* of its string (from support to centre of bob).

Displace the bob a small amount (pendulum swings with s.h.m. only when its amplitude is small).

Release the bob and time at least 10 oscillations.

Repeat, average and calculate the period T.

Vary the length to obtain a series of corresponding readings for l and T. Plot a graph of  $T^2$  against l.

Graph is a straight line through the origin showing that  $T^2 \propto l$ .

Since  $T = 2\pi \sqrt{(l/g)}$ 

 $T^2 = 4\pi^2 l/g$ 

so gradient of graph =  $4\pi^2/g$ 

 $g = 4\pi^2/\text{gradient}$ 

#### **2.** Oscillations of a mass-spring system

Suspend a mass m on the end of a vertical spring (Figure 4.6a) Displace the mass a small amount – don't stretch it beyond its elastic limit Release the mass and time at least 10 oscillations.

Repeat, average and calculate the period *T*.

Vary the mass to obtain a series of corresponding readings for m and T. Plot a graph of  $T^2$  against m.

Graph is a straight line through the origin showing that  $T^2 \propto m$ . Use different arrangements of identical springs to vary the force constant (Figures 4.6b and c)

Obtain a series of corresponding readings for k and T.

Plot a graph of  $T^2$  against 1/k.

Graph is a straight line through the origin showing that  $T^2 \propto 1/k$ . So  $T^2 \propto m/k$  and  $T \propto \sqrt{(m/k)}$  which agrees with the equation  $T = 2\pi\sqrt{(m/k)}$ 

#### **3.** Forced oscillations and resonance

Suspend a 200 g mass from a vertical spring.

Displace the mass a small amount, release and time at least 10 oscillations. Repeat, average and calculate the period *T* and the natural frequency f (= 1/T).

Attach the spring and mass to a vibration generator (Figure 4.7). Set the signal generator to a frequency below the natural frequency. Record the mass's maximum amplitude.

Increase the signal generator's frequency in steps to a value above the natural frequency.

Record the mass's maximum amplitude at each frequency.

Plot a graph of maximum amplitude against signal generator's frequency. Repeat the experiment with the mass immersed in a beaker of water to increase damping.

Graphs should be similar to those in Figure 4.3.

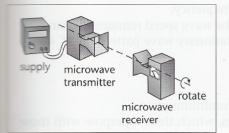


Fig 4.8 Rotate the receiver in the direction of the arrow

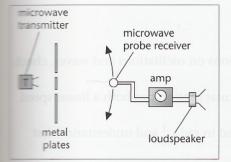


Fig 4.9 Move the probe receiver in the directions of the arrows



Fig 4.10 Equally spaced fringes are seen on the screen

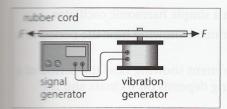


Fig 4.11 The vibration generator brees the rubber cord to oscillate

#### 4. Demonstrating polarisation

Using microwaves:

Set up a microwave transmitter facing a receiver (Figure 4.8).

Rotate the receiver in the direction of the arrow.

The signal strength falls to zero and rises again twice during a full rotation. This shows that microwaves from the transmitter are plane polarised.

#### Using light:

Observe some reflected light (e.g. from a shiny bench) through a Polaroid filter.

Rotate the filter.

The observed intensity falls to zero and rises again twice during a full rotation.

This shows that reflected light is plane polarised.

#### **5.** Superposition experiments

#### Using microwaves:

Set up the apparatus in Figure 4.9.

Use a slit width of 2 cm and a slit separation of 7 cm (use a 5 cm central plate).

Move the probe receiver as shown along an arc 30 cm from the slits. Find the position of the first maximum intensity away from the centre. Use a ruler to measure the distance from the centre of each slit to the probe receiver.

The difference in these two distances (path difference) is the wavelength. Find the position of the second maximum intensity away from the centre and measure the distances.

The difference in these two distances is twice the wavelength. Similarly, the difference in the two distances to the first minimum is half the wavelength.

Use all the values to find an average value for the wavelength.

#### Using light:

This experiment is often referred to as Young's double slit experiment. Use a laser to illuminate two narrow slits with a separation s of 0.5 mm. Observe the superposition pattern produced on a screen a distance D of 6 m from the double slits (Figure 4.10).

Use a ruler to measure the width of several fringes and calculate the fringe spacing *x*.

Use the equation  $\lambda = xs/D$  to calculate the wavelength of the laser light.

#### 6. Stationary waves

Using a stretched rubber cord:

Stretch a rubber cord attached to a vibration generator and clamp its ends (Figure 4.11).

Starting at a low value, slowly increase the frequency of the vibration generator.

Observe the stationary wave pattern of the fundamental frequency f. Measure the distance between the two nodes and double it to get the wavelength  $\lambda$ .

Use the equation  $v = f\lambda$  to calculate the speed of waves on the rubber cord.

Continue to increase the frequency slowly until the next stationary wave pattern is produced.



#### microwave aluminium probe receiver plate T microwave transmitter amp loudspeaker

Fig 4.12 Move the probe receiver to locate the nodes and antinodes

The position of a node can be pinpointed more accurately than that of an antinode.

This occurs at twice the fundamental frequency.

The wavelength halves showing that the wave speed remains the same. Repeat this procedure to observe the stationary wave patterns at 3f, 4f and 5f.

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#### Using microwaves:

Point a microwave transmitter at an aluminium plate.

The aluminium reflects the microwaves, which then superpose with those leaving the transmitter.

Move a probe receiver along the line between transmitter and reflector (Figure 4.12).

Locate the positions of the nodes and antinodes.

Use a ruler to measure the total distance between 10 sets of adjacent nodes. Divide this distance by 5 to get the wavelength of the microwaves.

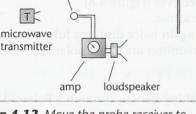
## Checklist

Before attempting the following questions on oscillations and waves, check that you:

- know that a body moving with circular motion has both a linear speed and an angular speed
- know that angular speed is measured in rad s<sup>-1</sup> and understand what this means
- can explain why a body moving at constant speed around a circular path is accelerating
- appreciate that its acceleration is directed towards the centre of the circle
- realise that a resultant force is needed towards the centre of the circle to produce this acceleration
- understand why this resultant force doesn't do any work
- know what happens to the body when the resultant force is suddenly removed
- understand the concept of apparent weightlessness and the condition in which this occurs
- can use the terms displacement, amplitude, period and frequency to describe oscillations
- appreciate that, as a result of frictional forces, all oscillations eventually die away
- have learnt a definition of simple harmonic motion
- appreciate why many clocks contain a simple harmonic oscillator
- have learnt a description of an experiment showing how the period of a pendulum depends on its length
- lack have learnt a description of an experiment showing how the period of a mass oscillating on the end of a spring depends on its mass and the force constant of the spring

 $\Box$  can sketch linked graphs showing how the displacement ( $x_0 \cos \omega t$ ), velocity  $(-\omega x_0 \sin \omega t)$  and acceleration  $(-\omega^2 x_0 \cos \omega t)$  of a simple harmonic oscillator vary with time

know that at the centre of an oscillation the velocity is maximum  $(v_{\text{max}} = \omega x_0)$  and the acceleration is zero



#### OSCILLATIONS AND WAVES

- □ know that at the extreme positions, the velocity is zero and the acceleration is maximum  $(a_{max} = -\omega^2 x_0)$
- appreciate that all oscillators have their own natural frequency
- understand that resonance occurs when an oscillator is forced to oscillate at its natural frequency and that this results in large amplitude oscillations

have learnt a description of an experiment to plot resonance curves for a mass oscillating on the end of a spring

know the difference between a progressive and a stationary wave

can use the inverse square law to calculate the intensity of a wave spreading out from a point source at various distances from the source

- know the difference between a transverse and a longitudinal wave
- appreciate that all electromagnetic waves are transverse and move at the same speed in vacuo
- have learnt the seven main regions of the electromagnetic spectrum and know the order of magnitude of their wavelength ranges (e.g. visible: 400 to 700 nm)
- understand what is meant by plane polarisation and appreciate why only transverse waves can be polarised
- have learnt a description of experiments demonstrating plane polarisation using microwaves and light
- lacktrian lacktrian have learnt a statement of the principle of superposition
- can explain the formation of maxima and minima in terms of the relative phase of the waves involved
- appreciate why two sources have to be coherent to form a stable superposition pattern
- understand the connection between phase difference and path difference,  $\Delta$ (phase) =  $2\pi\Delta$ (path)/ $\lambda$
- know how the path difference determines whether a maximum or a minimum is formed
- appreciate the part played by diffraction in a two slit superposition experiment
- know the effects of slit width and wavelength on the amount of diffraction
- have learnt a description of experiments demonstrating two source superposition using microwaves and light and know how to find the wavelength of the waves used

appreciate the limitations in the use of the equation  $\lambda = xs/D$ 

- understand the conditions needed for the production of a stationary wave
- are familiar with the terms nodes and antinodes, and know how to find wavelength from the distances between them
- have learnt a description of experiments demonstrating stationary waves on a stretched rubber cord and in microwaves and know how to find the wavelength of the waves used
- are familiar with the 'general requirements' (see Appendix 1) and how they apply to the topic of oscillations and waves

Unit

Answers to these questions, together with explanations, are in the Answers section which follows Chapter 6.

### K Testing your knowledge and understanding

#### Quick test

Select the correct answer to each of the following questions from the four answers supplied. In each case only one of the four answers is correct. Allow about 40 minutes for the 20 questions.

- **1** A cogwheel having 25 teeth is rotated with an angular speed of  $6\pi$  rad s<sup>-1</sup>. When a thin strip of metal is positioned so that the cogs strike it, the frequency of the note heard is
  - **A** 25 Hz **B** 75 Hz **C** 180 Hz **D** 4500 Hz
- **2** A body travels at a constant rate along a circular path. Which of the following quantities associated with its motion does NOT remain constant?
  - A Angular speed
  - **B** Kinetic energy
  - C Linear momentum
  - **D** Linear speed
- **3** The speed of a satellite in a circular orbit of radius 10 Mm around the Earth is 6.3 km s<sup>-1</sup>. Its acceleration is approximately
- A 0.16 m s<sup>-2</sup>
  B 0.25 m s<sup>-2</sup>
  C 4.0 m s<sup>-2</sup>
  D 6.3 m s<sup>-2</sup>
  4 A spacecraft is in orbit round the Earth and is approximately 1600 km above the Earth's surface. An astronaut in the spacecraft experiences apparent weightlessness. This is because the gravitational force exerted by the Earth on the astronaut is
  - A balanced by gravitational forces exerted on the astronaut by the Moon
  - **B** completely shielded from the astronaut by the enclosing spacecraft shell
  - **C** exactly equal to the force required to keep the astronaut moving in orbit
  - **D** zero at this distance from the Earth
- **5** In a fairground shooting gallery there is a gun that automatically fires at random times at a moving target. The player has to aim the gun in one direction and leave it there. The target moves back and forth with simple harmonic motion. Five regions of the motion, labelled 1 to 5, are marked in Figure 4.13.

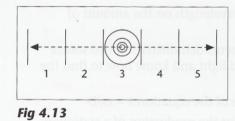
Which of the following indicates the region(s) at which it is sensible to take fixed aim so as to score the greatest number of hits?

- **A** Aim at region 1 or region 5
- **B** Aim at region 2 or region 4
- C Aim at region 3
- **D** Aim at any region as the chance is the same for all five
- **6** The gravitational field strength *g* on the Moon is one-sixth that on Earth. A pendulum with a period of 1 s on Earth would have, on the Moon, a period of

C √6 s

**A** 1/6 s **B**  $1/\sqrt{6}$  s

**D** 6 s



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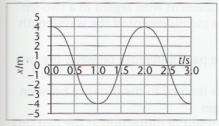
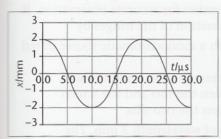


Fig 4.14





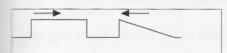
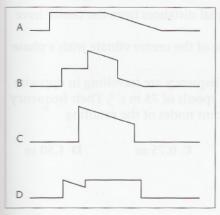


Fig 4.16





7 A particle performs simple harmonic motion, the displacement x from the equilibrium position varying with time t as shown in Figure 4.14. The maximum acceleration of the particle is

**A** 
$$\pi$$
 m s<sup>-2</sup> **B**  $4\pi$  m s<sup>-2</sup> **C**  $\pi^2$  m s<sup>-2</sup> **D**  $4\pi^2$  m s<sup>-2</sup>

- 8 A lorry driver notices that the image in the rear-view mirror is blurred when the engine runs slowly and becomes clear as the engine speed is increased. This is an example of
  - A superposition
  - **B** resonance
  - C polarisation
  - **D** coherence
- **9** Figure 4.15 shows how the displacement x of a particle in a progressive wave varies with time t.

Which of the following gives the values of the amplitude and frequency of the vibration of the particle?

- **A** Amplitude = 2 mm and frequency = 25 kHz
- **B** Amplitude = 2 mm and frequency = 50 kHz
- C Amplitude = 4 mm and frequency = 25 kHz
- **D** Amplitude = 4 mm and frequency = 50 kHz
- 10 Which of the following describes the type of wave produced on a stretched guitar string after it has been plucked?
  - A Progressive, longitudinal, electromagnetic
  - **B** Progressive, transverse, mechanical
  - C Stationary, longitudinal, electromagnetic
  - **D** Stationary, transverse, mechanical
- 11 Which of the following phenomena cannot be demonstrated using sound waves?
  - A Diffraction
  - **B** Polarisation
  - C Reflection
  - **D** Superposition
- 12 Yellow light (1), radiowaves (2), blue light (3), X-rays (4) and infrared (5) are all electromagnetic waves. Which of the following places them in order of increasing frequency?
  - A 2, 5, 1, 3, 4
  - **B** 2, 5, 3, 1, 4
  - C 4, 1, 3, 5, 2
  - **D** 4, 3, 1, 5, 2
- 13 Which of the following forms of electromagnetic waves is associated with a wave of frequency 10<sup>15</sup> Hz? (Speed of electromagnetic radiation in vacuum is  $3.0 \times 10^8$  m s<sup>-1</sup>.)
  - A Infrared
  - **B** Ultraviolet
  - **C** Visible light
  - **D** X-rays
- 14 Figure 4.16 shows two idealised wave pulses moving towards one another on a spring.

The pulses travel at the same speed. As they pass through each other, the pulses superpose. The diagrams in Figure 4.17 show the result of this superposition at four successive instants during their interaction. Which of these idealised drawings is NOT correct?

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notion, the displacement x from time t as shown in Figure 4,14. **15** Which of the following is a correct statement with regard to a two-slit experiment to produce fringes for the measurement of the wavelength of light?

- **A** A dark fringe occurs when the path difference between the two beams is zero
- **B** The distance between the slits is equal to the distance between adjacent bright (or dark) fringes
- **C** The overlapping beams are a result of diffraction at the two slits
- **D** The two slits act as incoherent sources
- **16** When a two-slit arrangement was set up to produce a superposition pattern on a screen using a monochromatic source of green light, the fringes were found to be too close together for accurate observation. It would be possible to increase the separation of the fringes by
  - A replacing the light source with a monochromatic source of red light
  - **B** increasing the distance between the source and the slits
  - **C** decreasing the distance between the slits and the screen
  - **D** increasing the distance between the two slits
- **17** Two sources emit coherent radiation of wavelength 3 mm. The superposition pattern at a distance of 2 m from the sources consists of fringes that are 5 cm apart. The separation of the sources is

	A 0.12 m	<b>B</b> 0.30 m	<b>C</b> 0.33 m	<b>D</b> 0.75 m
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- **18** The following statements each make a comparison of progressive and stationary waves. Which comparison is NOT correct?
  - A Energy is continually transferred along a progressive wave whereas there is no transfer of energy along a stationary wave
  - **B** Progressive waves can be polarised whereas stationary waves cannot be polarised
  - **C** Amplitude is either constant or gradually declines along a progressive wave whereas amplitude depends on position along a stationary wave
  - **D** A progressive wave has no nodes or antinodes whereas a stationary wave has definite positions for nodes and antinodes
- **19** A taut wire is fixed at one end whilst the other end is attached to a small vibration generator. The wire is set vibrating so that there are nodes at both ends and a single node along the wire at its centre. Which of the following statements is NOT correct?
  - **A** All points of the wire on one side of the centre vibrate in phase with each other
  - **B** The wavelength of the waves on the wire equals the length of the wire
  - **C** Two points on the wire at equal distances from the centre have the same amplitude
  - **D** Any two points on either side of the centre vibrate with a phase difference of 90°
- **20** Two waves of equal amplitude and frequency are travelling in opposite directions along the same path with speeds of 75 m s<sup>-1</sup>. Their frequency is 50 Hz. The distance between adjacent nodes of the resulting stationary wave is

<b>A</b> 0.33 m <b>B</b>	0.67 m	<b>C</b> 0.75 m	<b>D</b> 1.50 m
--------------------------	--------	-----------------	-----------------

#### Worked examples

Study the following worked examples on oscillations and waves carefully. Make sure you fully understand their answers before attempting the practice assessment questions.

Worked example 1

The following statements apply to a body orbiting a planet at constant speed and at a constant height.

- The body is travelling at constant velocity.
- (ii) The body is in equilibrium because the centripetal force is equal and opposite to the weight.

State and explain whether each statement is true or false.

(Total 4 marks)

(Edexcel Module Test PH1, January 1999, Q. 1 (part))

#### Answer:

- (i) false
- Velocity is a vector and its direction continually changes (ii) false V
  - Centripetal force is the resultant force producing circular motion/weight is the centripetal force 🗸

Worked example 2

Figure 4.18 shows a method for determining the mass of small animals orbiting the Earth in a space station. The animal is securely strapped into a tray attached to the end of a spring. The tray will oscillate with simple harmonic motion when displaced as shown and released.

#### Define simple harmonic motion.

The tray has a mass of 0.400 kg. When it contains a mass of 1.00 kg, it oscillates with a period of 1.22 s. Calculate the spring constant k. [3] The 1.00 kg mass is removed and a small animal is now strapped into the tray. The new period is 1.48 s. Calculate the mass of the animal. [3] The astronauts suggest that the calibration experiment with the 1.00 kg mass could have been carried out on Earth before take off. If a similar experiment were conducted on Earth would the time period be greater than, less than, or equal to 1.22 s? Explain your answer. [3] (Total 11 marks) (Edexcel Module Test PH2, June 1998, Q. 5)

Answer:

Motion where the acceleration is directly proportional to the displacement from a fixed point 🗸

and always directed towards that point

Total mass m = 0.400 kg + 1.00 kg = 1.40 kgUsing  $T = 2\pi \sqrt{(m/k)}$  or  $T^2 = 4\pi^2 m/k$  $k = 4\pi^2 m/T^2 = 4 \times \pi^2 \times 1.40 \text{ kg}/(1.22 \text{ s})^2$  $= 37.1 \text{ N m}^{-1} (\text{or kg s}^{-2})$  🗸

Side of Trav Skylab 0000 Displacement Stran Small animal Spring

Fig 4.18

[2.2]

[2]

#### WAVES AND OUR UNIVERSE

on oscillations and waves carefully. nswers before attempting the

Helpful hint

Don't fall for the trap here, the intensity will only fall and rise if the incident light is already polarised

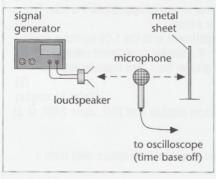


Fig 4.19

 $m = kT^2/4\pi^2 = 37.1 \text{ N m}^{-1} \times (1.48 \text{ s})^2/(4 \times \pi^2)$ = 2.06 kg 🗸 Mass of small(ish) animal = 2.06 kg - 0.400 kg = 1.66 kg

The period would be equal to 1.22 s on Earth  $\checkmark$ Period depends on  $\sqrt{(m/k)}$  and mass is the same everywhere  $\checkmark$ and *k* is a constant for any given spring system  $\checkmark$ 

Worked example 3-

A 60 W filament lamp transfers electrical energy to light with an efficiency of 12%. Calculate the light intensity produced by the lamp at a point 3.5 m from the filament

The lamp is observed through a sheet of Polaroid. Describe and explain the effect of this on the intensity of the light. [3]

The sheet of Polaroid is now slowly rotated in a plane perpendicular to the direction of propagation of the light. What effect does this have on the intensity of the light?[1] (Total 7 marks)

(Edexcel Module Test PH2, January 2001, Q. 5)

[3]

Answer: Light output =  $0.12 \times 60 \text{ W} = 7.2 \text{ W}$   $\checkmark$ Intensity  $I = P/4\pi r^2 = 7.2 \text{ W}/[4 \times \pi \times (3.5 \text{ m})^2]$  $= 0.047 \text{ W m}^{-2} \checkmark$ 

Intensity is reduced  $\checkmark$ Light from lamp is unpolarised with vibrations in many planes Polaroid removes all but one plane of vibrations  $\checkmark$ 

Rotating the Polaroid has no effect 🗸

Worked example 4

Figure 4.19 shows a loudspeaker that sends a note of constant frequency towards a vertical metal sheet.

As the microphone is moved between the loudspeaker and the metal sheet the amplitude of the vertical trace on the oscilloscope continually changes several times between maximum and minimum values. This shows that a stationary wave has been set up in the space between the loudspeaker and the metal sheet. How has the stationary wave been produced? [3]

State how the stationary wave pattern changes when the frequency of the signal generator is doubled. Explain your answer. [2]

What measurements would you take, and how would you use them, to calculate the speed of sound in air? [4]

Suggest why the minima detected near the sheet are much smaller than those detected near the loudspeaker. [3]

(Total 12 marks)

(Edexcel Module Test PH2, January 1996, Q. 4)

Answer:

Metal sheet reflects the sound waves Stationary wave is a result of the superposition between waves of the same frequency moving in opposite directions OSCILLATIONS AND WAVES

Answers to these questions, together with explanations, are in the Answers section which follows Chapter 6.

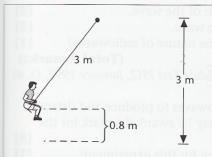


Fig 4.20

through a vertical height of 0.80 m (Figure 4.20). Calculate the speed of the child at a moment when the child is moving through the lowest position.

[3] Calculate the force exerted on the child by the seat of the swing at the same moment. [4]

2 A child of mass 21 kg sits on a swing of length 3.0 m and swings

(Total 7 marks)

(Edexcel Module Test PH1, January 1998, Q. 6 (part))

3 Fill in the gaps in the following sentences. A body oscillates with simple harmonic motion when the resultant force F acting on it and its displacement x are related by the expression .....

The acceleration of such a body is always directed ..... The acceleration of the body is a maximum when its displacement is ..... and its velocity is ..... when its displacement is zero.

[4]

A mass of 0.80 kg suspended from a vertical spring oscillates with a period of 1.5 s. Calculate the force (spring) constant of the spring.

#### [2] (Total 6 marks)

(Edexcel Module Test PH2, June 2000, Q. 4)

91

Max 4

Nodes and antinodes are twice as close together </ since the wavelength halves when the frequency doubles

Measure total distance between several nodes 🗸 Calculate distance between adjacent nodes 🗸 Read frequency off signal generator/use a frequency meter Wavelength =  $2 \times$  distance between adjacent nodes  $\checkmark$ Speed  $v = f\lambda$   $\checkmark$ 

Near the sheet there is almost complete cancellation 🗸 Incident and reflected waves have the same amplitude (as they've travelled roughly the same distance) 🗸 Near loudspeaker, reflected waves have travelled a lot further so their amplitude is much less 🗸

#### **Practice** questions

The following are typical assessment questions on oscillations and waves. Attempt these questions under similar conditions to those in which you will sit your actual test.

1 The period of the Earth about the Sun is approximately 365 days. Use this value to calculate the angular speed of the Earth about the Sun in rad s<sup>-1</sup>. [2]

The mass of the Earth is  $5.98 \times 10^{24}$  kg and its average distance from the Sun is  $1.50 \times 10^{11}$  m. Calculate the centripetal force acting on the Earth.

What provides this centripetal force?

(Total 6 marks)

(Edexcel Module Test PH1, June 1997, Q. 8)

[3] [1]

[2]

[2]

[2]

[4]

[3]

[2]

[3]

[2]

[2]

[1]

[5]

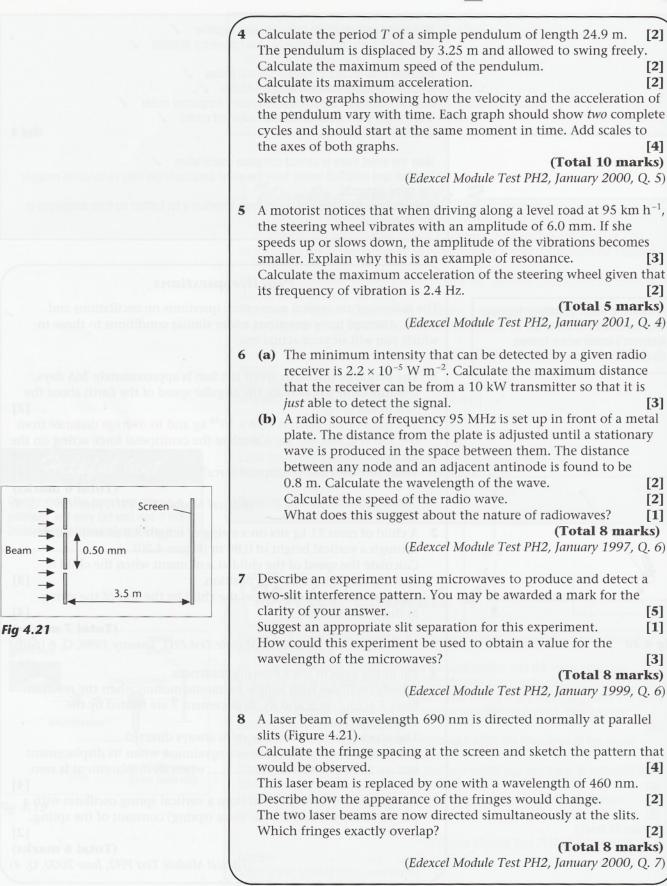
[1]

[3]

[4]

[2]

[2]





## Quantum phenomena and the expanding universe

## Introduction

The photoelectric effect occurs when electrons are released from a metal when electromagnetic radiation with a sufficiently high frequency is shone on it. The photoelectric effect cannot be explained in terms of the wave behaviour of light. It is a quantum phenomenon and a photon model has to be used to explain it. In this section, you learn that a photon is the smallest possible packet of light energy at a given frequency. You find that all particles have the dualistic property of behaving like either a particle or a wave disturbance with the particle nature of the photon being used to explain the photoelectric effect and the wave characteristics of the photon being used to explain superposition and diffraction. You observe the wave characteristics of electrons as they pass through layers of graphite and diffract. You learn that an atom emits a photon during a transition from a higher to a lower energy state and how all the different transitions produce a characteristic spectrum. You find that such emission spectra are important in analysing the composition of stars and learn how they can be used to find the speeds at which galaxies are moving. You find that the universe is expanding and attempt to predict what will happen to it in the future.

## F Things to understand

#### Photons

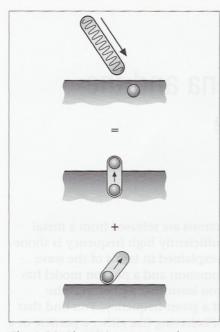
- electromagnetic radiation consists of small packets of energy (photons)
- energy of a photon depends only on the frequency of the radiation
- increasing the frequency of a beam, increases the energy of each photon (E = hf)
- ultraviolet photons are more energetic than infrared photons
- increasing the intensity of a beam, increases the number of photons but not their energy
- a bright blue beam contains more photons, all of the same energy, than a dim blue beam

#### **Photoelectric effect**

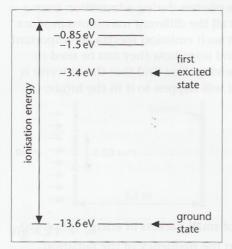
- energy has to be supplied to remove electrons from a metal
- surface electrons are the easiest to release
- different metals require different amounts of energy (work functions) to release their surface electrons
- a photon can release a surface electron only if it has sufficient energy

- hotoelectric effect, particularly nd its independence of intensity to éxplain all of its probedies
- diffraction pattern is produced
  - peeded to explain all of its





**Fig 4.22** Photon energy = work function + electron kinetic energy



**Fig 4.23** Energy level diagram for a hydrogen atom

- photon frequency must be above a minimum threshold value to release electrons
- if photon energy is less than the work function (frequency below threshold value) then electrons will not be released
- if photon energy is greater than the work function (frequency above threshold value), electrons are released and the excess energy is the kinetic energy of the released electron (Figure 4.22)
- the kinetic energy of a released electron can be measured by finding the potential difference needed to stop it moving (stopping potential)
- the electronvolt is a unit of energy

#### **Emission spectra**

- electrons within an atom have only a limited number of possible energies
- an energy level diagram shows the possible energies for an electron in a given atom
- usually an electron lies in the lowest energy level, known as the ground state
- a precise amount of energy is needed to move an electron up a level
- an atom with one or more electrons in raised energy levels is excited
- when an electron moves back down, the same precise amount of energy is released as a photon of frequency *f* where  $hf = \Delta E$
- if an electron gains sufficient energy to reach the highest energy level it can leave the atom so the atom is then ionised
- an electron in the highest energy level has (by definition) zero energy and so all other electron energy levels are negative (Figure 4.23)
- free electrons only have kinetic energy and therefore their total energy is always positive
- in a gas discharge tube, atoms are continually being excited/ionised by electrons colliding with them and photons are continually released as electrons fall back down to a lower level
- the irregular spacing of the energy levels means that photons with different energies and, therefore, frequencies are released
- viewing light emitted from a gas discharge tube through a diffraction grating produces a line emission spectrum, where each line is one of the emitted discrete frequencies
- the atoms of each element have a characteristic set of energy levels and so give out a set of frequencies from which they can be identified

#### **Wave-particle duality**

- most properties of light, such as diffraction and superposition, are explained by considering it to be a wave
- a wave theory is unable to explain the photoelectric effect, particularly the existence of a threshold frequency and its independence of intensity
- a wave/photon model of light is needed to explain all of its properties
- electrons are very small, negatively charged particles
- when electrons are fired at graphite, a diffraction pattern is produced allowing the wavelength of the electrons to be calculated
- a particle/wave model of an electron is needed to explain all of its behaviour

WAVES AND OUR UNIVERSE

#### QUANTUM PHENOMENA AND THE EXPANDING UNIVERSE

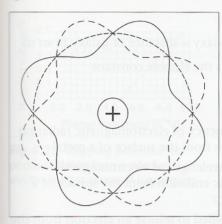
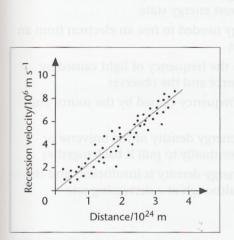


Fig 4.24 A possible electron stationary wave in an atom

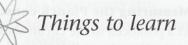


**Fig 4.25** Despite the uncertainty in measuring astronomical distances, the data suggests that v = Hd

- de Broglie's equation relates a particle's wavelength to its momentum,  $\lambda = h/p$
- all particles have an associated wavelength, although for most particles the wavelength is so small that that any wave effects are unobservable
- atomic energy levels can be explained by the electrons behaving like stationary waves within the atom (Figure 4.24)
- only certain patterns of stationary wave fit and each of these corresponds to one of the fixed energy states of the atom

#### The expanding universe

- a star's spectrum can be produced using a diffraction grating
- dark lines across the spectrum denote certain frequencies that have been absorbed by atoms in the outer layers of the star
- these absorption lines give evidence of the elements that are present in the star
- when compared to laboratory spectra, those from distant galaxies appear to be Doppler shifted towards the red end of the spectrum
- red-shift occurs as a result of the galaxies moving away from us and indicates that the universe is expanding
- the amount of shift depends on speed and allows the recession velocities of galaxies to be measured
- the further a galaxy is from us, the greater is its recession velocity (Figure 4.25)
- dividing a galaxy's distance by its recession velocity gives the same expansion time for every galaxy
- all galaxies have been spreading out since they were formed during the Big Bang about 10<sup>10</sup> years ago
- astronomical distances are often measured in light years, the distance travelled by light in one year
- the rate of expansion of the universe is probably slowly decreasing as a result of the gravitational force of attraction between the masses of the galaxies
- the fate of the universe depends on the average mass-energy density of the universe
- if this is large enough, the universe is closed and will eventually stop expanding and begin to collapse inwards, producing a Big Crunch
- if the average mass-energy density is insufficient, the universe is open and will go on expanding for ever but at a slower and slower rate



You should learn the following for your Unit PHY4 Test. Remember that it may also test your understanding of the 'general requirements' (see Appendix 1).

#### Equations that will not be given to you in the test

wave speed = frequency × wavelength

 $v = f\lambda$ 

 $\lambda$  = wavelength

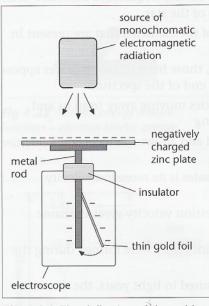
#### Laws

Hubble's law: recession velocity of galaxy  $\propto$  distance of galaxy from us

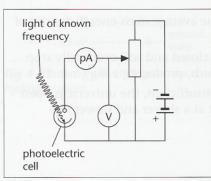
v = Hd where *H* is the Hubble constant

#### Helpful hint

1 eV =  $1.6 \times 10^{-19}$  J is given in the data at the end of your test paper (see Appendix 2)



**Fig 4.26** The deflection of the gold leaf is a measure of the charge stored on the zinc plate



**Fig 4.27** Measuring the energy of the photoelectrons



This apparatus can be used to show how photocurrent varies with potential difference across the photocell

#### **General definitions**

- threshold frequency: minimum frequency of electromagnetic radiation that will cause photoelectric emission from the surface of a metal
- threshold wavelength: maximum wavelength of electromagnetic radiation that will cause photoelectric emission from the surface of a metal
- work function: amount of energy needed to release an electron from the surface of a metal
- electronvolt: energy transferred to an electron charge when it moves through a potential difference of 1 V
- excitation energy: minimum energy needed to raise an electron within an atom to a position above its lowest energy state
- ionisation energy: minimum energy needed to free an electron from an atom, leaving behind a positive ion
- Doppler effect: apparent change in the frequency of light caused by relative movement between the source and the observer
- red-shift: an apparent decrease in frequency caused by the source and the observer moving apart
- closed universe: the average mass-energy density of the universe is sufficient for gravitational forces eventually to pull it back together
- open universe: the average mass-energy density is insufficient and the universe will continue to expand, although at a decreasing rate

#### Experiments

#### 1. Simple demonstration of the photoelectric effect

Remove the oxide layer from the surface of a zinc plate. Put the zinc plate on the cap of a gold-leaf electroscope.

Give the electroscope a negative charge so that the gold leaf deflects. Observe what happens to the gold leaf when first red and then ultraviolet light is shone onto the zinc plate (Figure 4.26).

The gold leaf remains deflected when red light is used.

The gold leaf gradually falls back down when ultraviolet light is used. If the electroscope is charged positively, the gold leaf remains deflected whatever radiation is used.

#### **2.** Measuring the Planck constant

Connect a photocell to the circuit shown in Figure 4.27.

Set the potentiometer so that the voltmeter reads zero.

Shine light of known frequency onto the emitting electrode and observe the current flowing in the picoammeter.

Slowly increase the potential difference across the cell until the current decreases to zero.

Record the stopping potential from the voltmeter.

Repeat for a range of frequencies.

Plot a graph of stopping voltage against frequency (Figure 4.28).

2.0	2				
	voltage/				
5 1.2	offe				
- 0.8	> 0				
E 0.4	opping				
	do				
0.0 2.0 4.0 6.0 8.0 10.0	35				
Photon frequency/10 <sup>14</sup> Hz					

Fig 4.28 Stopping potential for photoelectrons from a caesium electrode for a range of frequencies Photon energy = work function + maximum kinetic energy

= work function + (electronic charge × stopping potential)

 $hf = \varphi + eV_s$   $V_s = (h/e) \times f - \varphi/e$ Comparing this with y = mx + cGradient = h/eSo  $h = e \times$  gradient

Checklist

Before attempting the following questions on quantum phenomena and the expanding universe, check that you:

- know that all electromagnetic radiation consists of small packets of energy called photons
- can use the equations E = hf and  $E = hc/\lambda$  to calculate the energy of a photon
- understand that an intense beam has more photons than a dim beam
- appreciate that if the photon energy is less than the work function, no photoelectrons will be released whatever the intensity of the incident beam
- know that even a dim beam will release photoelectrons when its photon energy is more than the work function
- have learnt a description of an experiment to demonstrate the photoelectric effect using a zinc plate and a golf-leaf electroscope
- can calculate the maximum speed of photoelectrons emitted from a given surface by a known frequency (or wavelength) of incident radiation
- know how to convert between electronvolts and joules
- appreciate how stopping potential is used to measure the maximum kinetic energy of photoelectrons
- have learnt a description of an experiment to measure the Planck constant
- know that an atom has a limited number of fixed energy states and that these are best displayed on an energy level diagram
- appreciate why all energy levels are negative
- understand the difference between excitation and ionisation energies
- can calculate the frequency of the photon emitted when an atom moves to a lower energy state
- know how a diffraction grating can be used to observe line emission spectra
- appreciate that each element has its own characteristic emission spectrum
- understand the need for a wave-particle model
- know that fast-moving electrons behave like waves and produce a diffraction pattern after passing through layers of graphite
- know that the fixed energy states of an atom can be explained in terms of stationary electron waves
- can calculate the de Broglie wavelength of a moving particle

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- appreciate how the absorption spectra of the light from stars gives information about their chemical compositions
- know that relative movement between source and observer produces an apparent change in the frequency of light received
- can calculate speed from the amount of Doppler shift
- understand that red shift of light from galaxies suggests the expansion of the universe
- have learnt a statement of Hubble's law
- can use the Hubble constant to calculate the approximate age of the universe
- appreciate the reasons for this being only an approximate value
- know that the expanding universe results from a Big Bang origin
- understand how the fate of the universe will be determined by its average mass-energy density and appreciate that the actual value of this is unknown
- are familiar with the 'general requirements' (see Appendix 1) and how they apply to the topic of quantum phenomena and the expanding universe

Testing your knowledge and understanding

#### Quick test

Select the correct answer to each of the following questions from the four answers supplied. In each case only one of the four answers is correct. Allow about 30 minutes for the 15 questions.

**1** The unit for the Planck constant *h* may be written as

**A**  $J s^{-1}$  **B** N m s **C** kg m<sup>2</sup> s **D** N m s<sup>-1</sup>

- **2** To which of the following forms of electromagnetic radiation does a photon with energy  $3 \times 10^{-19}$  J belong?
  - A Microwaves
  - **B** Infrared
  - **C** Visible light
  - **D** Ultraviolet
- **3** A laser emits monochromatic light of wavelength  $\lambda$  at a constant power *P*. If *h* is the Planck constant and *c* is the speed of light in a vacuum, the number of photons emitted per second by the laser is given by

**A**  $Pc/h\lambda$  **B**  $\lambda c/Ph$  **C**  $P/hc\lambda$  **D**  $P\lambda/hc$ 

- **4** An ultraviolet light source causes the emission of photoelectrons from a zinc plate. A more intense light source of the same wavelength would give
  - A the same number of photoelectrons each second with the same maximum energy
  - **B** the same number of photoelectrons each second with a greater maximum energy
  - **C** more photoelectrons each second with the same maximum energy
  - **D** more photoelectrons each second with a greater maximum energy

Answers to these questions, together with explanations, are in the Answers section which follows Chapter 6.

#### 2 QUANTUM PHENOMENA AND THE EXPANDING UNIVERSE

**Jnit** 4

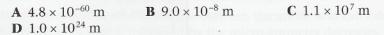
- **5** The maximum speed of photoelectrons emitted from a metal surface by electromagnetic radiation depends upon
  - A the frequency of the radiation only
  - **B** the intensity and the frequency of the radiation
  - C the intensity of the radiation and the work function of the metal
  - **D** the frequency of the radiation and the work function of the metal
- **6** Which of the following statements best describes the work function of a metal?
  - A A measure of the maximum kinetic energy of photoelectrons
  - **B** The energy of any photon that causes emission of a photoelectron
  - **C** A measure of the minimum kinetic energy of photoelectrons
  - **D** The minimum energy required to remove a photoelectron from the metal
- 7 The threshold frequency for a certain metal surface is  $5.0 \times 10^{14}$  Hz. The surface is illuminated with light of frequency  $7.0 \times 10^{14}$  Hz. The maximum kinetic energy of photoelectrons released from the surface is

**A**  $1.3 \times 10^{-19}$  J **B**  $3.2 \times 10^{-19}$  J **C**  $4.6 \times 10^{-19}$  J **D**  $4.6 \times 10^{49}$  J

- **8** Which of the following is evidence for the existence of discrete electron energy levels in atoms?
  - A The spectrum of a tungsten filament lamp
  - **B** The spectrum of a mercury discharge lamp
  - **C** The photoelectric effect
  - **D** The Doppler effect
- **9** When an electron falls from an energy level of energy  $E_1$  to one of energy  $E_2$ , radiation of frequency f and wavelength  $\lambda$  is emitted. If h is the Planck constant and c is the speed of light,  $E_1 E_2$  is equal to

**A** hf **B** 
$$h\lambda$$
 **C** hf/c **D**  $h\lambda/c$ 

**10** The ionisation energy of hydrogen is  $2.2 \times 10^{-18}$  J. The minimum wavelength of radiation emitted when a proton combines with an electron to form a hydrogen atom is



- **11** Figure 4.29 shows five energy levels of an atom. Five transitions between the energy levels are indicated, each of which will produce a photon of definite energy and frequency. Which of the four spectra shown best corresponds to these transitions?
- **12** The de Broglie wavelength of an electron moving at  $3.0 \times 10^7$  m s<sup>-1</sup> is
  - **A**  $2.7 \times 10^{-23}$  m **B**  $2.4 \times 10^{-11}$  m **C**  $4.1 \times 10^{10}$  m **D**  $3.7 \times 10^{22}$  m
- **13** In which of the following situations, would the Doppler effect not be observed?
  - A Source and observer moving with the same velocity
  - **B** Source and observer moving with opposite velocities
  - C Source moving towards a stationary observer
  - **D** Observer moving towards a stationary source

 E2
 Image: frequency (high)

 E1
 Image: frequency (high)

 A
 Image: frequency (high)

 B
 Image: frequency (high)

 C
 Image: frequency (high)

 D
 Image: frequency (high)

 Fig 4.29
 Fig 4.29

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14 When observed from the Earth, the light from a particular galaxy contains a wavelength of  $6.105 \times 10^{-7}$  m. The same spectral line when measured from a laboratory source has a wavelength of  $5.893 \times 10^{-7}$  m. The reason for this apparent change in wavelength is that the galaxy is

- **A** moving away from the Earth at  $1.04 \times 10^7$  m s<sup>-1</sup>
- **B** moving towards the Earth at  $1.04 \times 10^7$  m s<sup>-1</sup>
- **C** moving away from the Earth at  $1.08 \times 10^7$  m s<sup>-1</sup>
- **D** moving towards the Earth at  $1.08 \times 10^7$  m s<sup>-1</sup>

**15** Which of the following statements about the possible fates of the universe is not correct?

- **A** If the average mass-energy density is above a critical value then the universe is closed
- **B** If the universe is open then it will continue to expand but at a decreasing rate
- **C** If the universe is closed then it will continue to expand but at an increasing rate
- **D** If the average mass-energy density is below a critical value then the universe is open

#### Worked examples

Study the following worked examples on quantum phenomena carefully. Make sure you fully understand their answers before attempting the practice assessment questions.

Worked example 1.

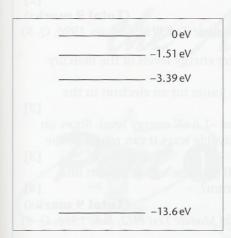
Ultraviolet light of wavelength 12.2 nm is shone on to a metal surface. The work function of the metal is 6.20 eV. Calculate the maximum kinetic energy of the emitted photoelectrons. [4] Show that the maximum speed of these photoelectrons is approximately  $6 \times 10^{6} \text{ m s}^{-1}$ . [2] Calculate the de Broglie wavelength of photoelectrons with this speed. [2] Explain why these photoelectrons would be suitable for studying the crystal structure of a molecular compound. [2] (Total 10 marks) (Edexcel Module Test PH2, January 2001, Q. 3) Answer: Work function =  $6.20 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1} = 9.92 \times 10^{-19} \text{ J}$ photon energy =  $hf = hc/\lambda = 6.63 \times 10^{-34} \text{ J s} \times 3.00 \times 10^8 \text{ m s}^{-1}/(12.2 \times 10^{-9} \text{ m})$  $= 1.63 \times 10^{-17} \text{ J}$   $\checkmark$ 

Kinetic energy =  $1.63 \times 10^{-17} \text{ J} - 9.92 \times 10^{-19} \text{ J} = 1.53 \times 10^{-17} \text{ J}$ 

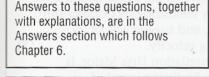
 $\frac{1}{2}mv^{2} = \frac{1}{2} \times 9.11 \times 10^{-31} \text{ kg} \times v^{2} = 1.53 \times 10^{-17} \text{ J} \quad \checkmark$   $v^{2} = 2 \times 1.53 \times 10^{-17} \text{ J}/(9.11 \times 10^{-31} \text{ kg})$  $v = \sqrt{(3.36 \times 10^{13} \text{ m}^{2} \text{ s}^{-2})} = 5.8 \times 10^{6} \text{ m s}^{-1} \quad \checkmark$ 

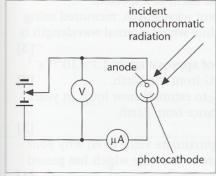
Momentum  $p = mv = 9.11 \times 10^{-31} \text{ kg} \times 5.8 \times 10^6 \text{ m s}^{-1} = 5.3 \times 10^{-24} \text{ kg m s}^{-1}$   $\lambda = h/p = 6.63 \times 10^{-34} \text{ J s}/(5.3 \times 10^{-24} \text{ kg m s}^{-1}) = 1.26 \times 10^{-10} \text{ m}$ 

Diffraction would occur ✓ as wavelength is similar to the spacing/size of atoms/molecules ✓











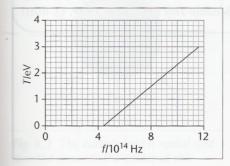






 Figure 4.30 shows some of the energy levels for atomic hydrogen.

 Add arrows to the diagram showing all the single transitions that could ionise the atom.

 Why is the level labelled -13.6 eV called the ground state?

 Identify the transition that would result in the emission of light of wavelength 660 nm.

 (Total 7 marks)

(Edexcel Module Test PH2, June 2000, Q. 9)

#### Answer:

Arrows added to diagram showing: a transition from – 13.6 eV up to 0 eV  $\checkmark$  transitions from – 3.39 eV up to 0 eV and from –1.51 eV up to 0 eV  $\checkmark$ 

Ground state: lowest energy state of the atom 🗸

Photon energy =  $hc/\lambda = 6.63 \times 10^{-34} \text{ J s} \times 3.00 \times 10^8 \text{ m s}^{-1}/(660 \times 10^{-9} \text{ m})$  =  $3.01 \times 10^{-19} \text{ J}/(1.6 \times 10^{-19} \text{ J eV}^{-1})$  = 1.88 eV so need a downward transition between levels with an energy difference of 1.88 eV

so need a downward transition between levels with an energy difference of 1.88 eV transition is from -1.51 eV down to -3.39 eV  $\checkmark$ 

## Unit 4

#### **Practice** questions

The following are typical assessment questions on quantum phenomena and the expanding universe. Attempt these questions under similar conditions to those in which you will sit your actual test.

**1** Figure 4.31 shows monochromatic light falling on a photocell.

As the reverse potential difference between the anode and cathode is increased, the current measured by the micro-ammeter decreases. When the potential difference reaches a value  $V_s$ , called the stopping potential, the current is zero. Explain these observations. [5] What would be the effect on the stopping potential of

- (i) increasing only the intensity of the incident radiation,
- (ii) increasing only the frequency of the incident radiation?

(Total 7 marks)

[2]

(Edexcel Module Test PH2, June 1998, Q. 7)

**2** The graph in Figure 4.32 shows how the maximum kinetic energy T of photoelectrons emitted from the surface of sodium metal varies with the frequency f of the incident radiation.

Why are no photoelectrons emitted at frequencies below[1] $4.4 \times 10^{14}$  Hz?[1]Calculate the work function  $\phi$  of sodium in electronvolts.[3]Explain how the graph supports the photoelectric equation $hf = T + \phi$ [2]

How could the graph be used to find a value for the Planck constant? [1]

WAVES AND OUR UNIVERSE

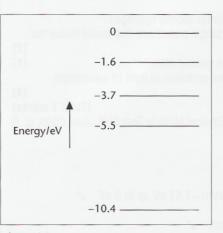


Fig 4.33



uons on quantum paenomeni e questions under signifat our actual test.

tween the anode and cathode is the micro-ammeter decreases, a value V<sub>0</sub> called the stopping these observations. [5]

the incident radiation, the incident radiation? [2] (Total 7 marks)

the maximum kinetic energy T surface of sodium metal varies Add a line to the graph to show the maximum kinetic energy of the photoelectrons emitted from a metal which has a greater work function than sodium. [2]

#### (Total 9 marks)

(Edexcel Module Test PH2, January 1996, Q. 8)

- **3** Figure 4.33 shows some of the outer energy levels of the mercury atom.
  - Calculate the ionisation energy in joules for an electron in the -10.4 eV level.

An electron has been excited to the -1.6 eV energy level. Show on the energy level diagram all the possible ways it can return to the -10.4 eV level. [3]

Which change in energy levels will give rise to a yellowish line  $(\lambda \approx 600 \text{ nm})$  in the mercury spectrum?

[2]

[4]

(Edexcel Module Test PH2, June 1996, Q. 8)

4In a nuclear reaction, neutrons are emitted each with a kinetic<br/>energy of  $8.0 \times 10^{-21}$  J. The mass of a neutron is 1.0087 u. Calculate<br/>the momentum of one of these neutrons.[4]Show that the de Broglie wavelength of these neutrons is<br/>approximately  $10^{-10}$  m.[1]

Would neutrons of this de Broglie wavelength be suitable for diffraction studies of molecular structure? Explain your answer. [2]

(Total 7 marks)

(Edexcel Module Test PH2, January 1999, Q. 8)

5 An astronomical body is moving relative to the Earth. Information about its velocity may be obtained by measuring its Doppler shift. Outline the principle of this method, and suggest one of its limitations as a means of determining velocity. [3]

A certain galaxy G, visible in the constellation Ursa Major, is thought to be moving away from the Earth at a speed of  $1.5 \times 10^7$  m s<sup>-1</sup>. Calculate the apparent wavelength, measured using light from this galaxy, of a spectral line whose normal wavelength is 396.8 nm. [3]

The Hubble constant *H* has a value of approximately  $1.7 \times 10^{-18}$  s<sup>-1</sup>. Estimate the distance of the galaxy G from the Earth. [2] Use the information about galaxy G to estimate how long, in years,

it has taken to reach its present distance from Earth. (1 year =  $3.2 \times 10^7$  s)

Give one reason (other than the approximate value of *H*) why your answer may not be a reliable estimate of the time which has passed since the Big Bang. [1]

#### (Total 12 marks)

[3]

(Edexcel Module Test PH2, June 1999, Q. 8(a))

<sup>(</sup>Total 9 marks)

5 Fields and forces and the A2 practical test

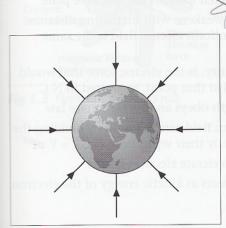
Fields and forces

### $\gtrless$ Introduction

Fields are used to interpret interactions between particles, a field being a region within which a force can be experienced. Gravitational, electric and magnetic interactions all have fields associated with them. As you study fields and forces, you learn about uniform and radial fields and the similarities and differences between gravitational and electric fields. You find that radial gravitational forces are responsible for the orbit of the planets around the Sun and learn how to calculate the period of an artificial satellite in orbit around the Earth. You find that uniform electric forces accelerate electrons towards the screen of your television and learn how to calculate the electrons' speed. You discover that a 'pulse' of current flows in a circuit in which there is a capacitor, a component containing an insulator, and find that capacitors can store energy. You investigate the magnetic fields resulting from permanent magnets and from currents flowing in wires, and discover how, when these are combined, they produce a force. You learn that whenever there is relative movement between a conductor and a magnetic field, an electromotive force is produced and how this is used to generate and to transform electricity.

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Unit



**Fig 5.1** The Earth's field is radial and directed towards the centre of the Earth

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Things to understand

#### Gravitational fields

- mass is the amount of matter in a body and, for a given body, remains the same everywhere
- all masses attract, exerting equal and opposite gravitational forces on each other
- gravitational forces are very small unless at least one of the masses involved is extremely large
- the region surrounding a mass in which another mass experiences a gravitational force of attraction is called a gravitational field
- field lines are used to show the shape and direction of a gravitational field (Figure 5.1)
- the strength of a radial gravitational field weakens with increasing