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Getting the best from the book

Welcome to *Collins Cambridge IGCSE Physics*.

This textbook has been designed to help you understand all of the requirements needed to succeed in the Cambridge IGCSE Physics course. Just as there are five sections in the Cambridge syllabus, there are five sections in the textbook: General physics, Thermal physics, Properties of waves - including light and sound, Electricity and magnetism and Atomic physics.

Each section is split into topics. Each topic in the textbook covers the essential knowledge and skills you need. The textbook also has some very useful features which have been designed to really help you understand all the aspects of Physics which you will need to know for this syllabus.

SAFETY IN THE SCIENCE LESSON

This book is a textbook, not a laboratory or practical manual. As such, you should not interpret any information in this book that related to practical work as including comprehensive safety instructions. Your teachers will provide full guidance for practical work and cover rules that are specific to your school.

A brief introduction to the section to give context to the science covered in the section.

Starting points will help you to revise previous learning and see what you already know about the ideas to be covered in the section.

The section contents shows the separate topics to be studied matching the syllabus order.

You will probably have experienced magnetism in simple toys and in bar magnets. The magnetic field around a bar magnet, when plotted, looks very similar to the one around the Earth. However, it is the existence of electromagnetism that really makes a difference to your life.

Without electromagnetism, the generation of electricity would not happen in the way that it does. Without electromagnetism, the high voltages transmitted down power lines could not be transformed into the lower voltages that you need in your home. Electricity is something that many people use every day – for lighting, heating, cooking and to power many different items of equipment. However, it can be dangerous.

You will already have explored different models to explain current and the transfer of electrical energy, and you will have evaluated these models. You will also have investigated current and voltage in circuits and drawn conclusions from data. You should be able to explain, using data and a simple model, the differences between series and parallel circuits.

STARTING POINTS

1. How can electromagnets be made stronger?
2. Describe some similarities and differences between magnets and electromagnets.
3. Describe the form of the electromagnetic field around the Earth.
4. What is the difference between a magnetically 'hard' and a magnetically 'soft' material?
5. How could you investigate the magnetic field pattern for: a) a permanent bar magnet; b) the field between two bar magnets?
6. What is an electric circuit?
7. What is a solenoid?

CONTENTS

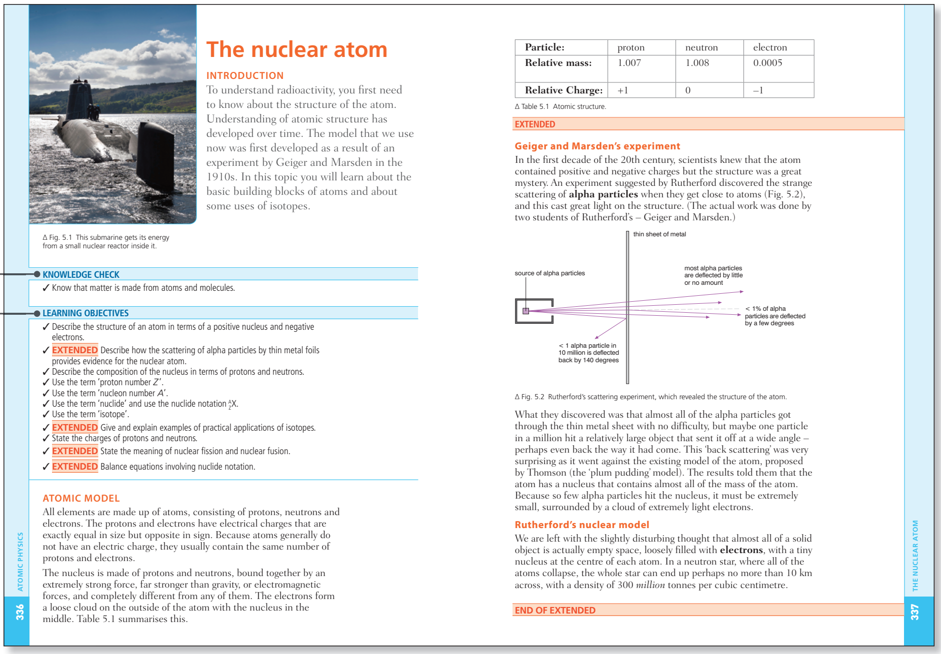
a) Simple phenomena of magnetism
b) Electrical quantities
c) Electric circuits
d) Dangers of electricity
e) Electromagnetic effects
f) Exam-style questions

4 Electricity and magnetism

△ Electricity is an essential part of our lives – we rely on it to operate many devices.

Knowledge check shows the ideas you should have already encountered in previous work before starting the topic.

Learning objectives cover what you need to learn in this topic.



The nuclear atom

INTRODUCTION

To understand radioactivity, you first need to know about the structure of the atom. Understanding of atomic structure has developed over time. The model that we use now was first developed as a result of an experiment by Geiger and Marsden in the 1910s. In this topic you will learn about the basic building blocks of atoms and about some uses of isotopes.

Δ Fig. 5.1 This submarine gets its energy from a small nuclear reactor inside it.

KNOWLEDGE CHECK

✓ Know that matter is made from atoms and molecules.

LEARNING OBJECTIVES

✓ Describe the structure of an atom in terms of a positive nucleus and negative electrons.
✓ EXTENDED Describe how the scattering of alpha particles by thin metal foils provides evidence for the nuclear atom.
✓ Describe the composition of the nucleus in terms of protons and neutrons.
✓ Use the term 'proton number *Z*'.
✓ Use the term 'nucleon number *A*'.
✓ Use the term 'nuclide' and use the nuclide notation $^{A}_{Z}X$.
✓ Use the term 'isotope'.
✓ EXTENDED Give and explain examples of practical applications of isotopes.
✓ State the charges of protons and neutrons.
✓ EXTENDED State the meaning of nuclear fission and nuclear fusion.
✓ EXTENDED Balance equations involving nuclide notation.

ATOMIC MODEL

All elements are made up of atoms, consisting of protons, neutrons and electrons. The protons and electrons have electrical charges that are exactly equal in size but opposite in sign. Because atoms generally do not have an electric charge, they usually contain the same number of protons and electrons.

The nucleus is made of protons and neutrons, bound together by an extremely strong force, far stronger than gravity, or electromagnetic forces, and completely different from any of them. The electrons form a loose cloud on the outside of the atom with the nucleus in the middle. Table 5.1 summarises this.

ATOMIC PHYSICS 336

Particle:	proton	neutron	electron
Relative mass:	1.007	1.008	0.0005
Relative Charge:	+1	0	–1

Δ Table 5.1 Atomic structure.

EXTENDED

Geiger and Marsden's experiment

In the first decade of the 20th century, scientists knew that the atom contained positive and negative charges but the structure was a great mystery. An experiment suggested by Rutherford discovered the strange scattering of **alpha particles** when they get close to atoms (Fig. 5.2), and this cast great light on the structure. (The actual work was done by two students of Rutherford's – Geiger and Marsden.)

Δ Fig. 5.2 Rutherford's scattering experiment, which revealed the structure of the atom.

What they discovered was that almost all of the alpha particles got through the thin metal sheet with no difficulty, but maybe one particle in a million hit a relatively large object that sent it off at a wide angle – perhaps even back the way it had come. This 'back scattering' was very surprising as it went against the existing model of the atom, proposed by Thomson (the 'plum pudding' model). The results told them that the atom has a nucleus that contains almost all of the mass of the atom. Because so few alpha particles hit the nucleus, it must be extremely small, surrounded by a cloud of extremely light electrons.

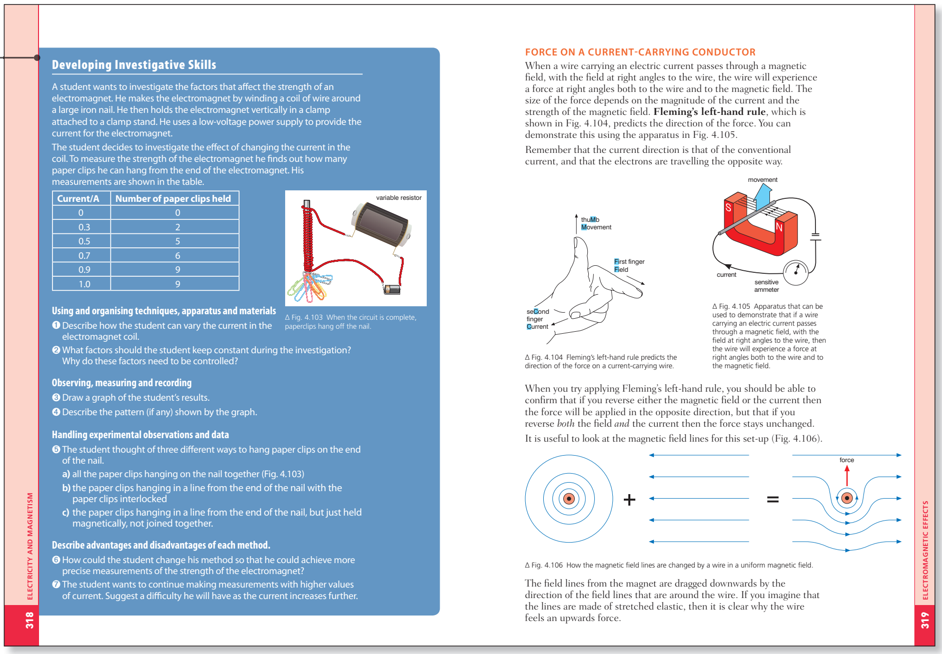
Rutherford's nuclear model

We are left with the slightly disturbing thought that almost all of a solid object is actually empty space, loosely filled with **electrons**, with a tiny nucleus at the centre of each atom. In a neutron star, where all of the atoms collapse, the whole star can end up perhaps no more than 10 km across, with a density of 300 *million* tonnes per cubic centimetre.

END OF EXTENDED

THE NUCLEAR ATOM 337

Examples of investigations are included with questions matched to the investigative skills you will need to learn.



Developing Investigative Skills

A student wants to investigate the factors that affect the strength of an electromagnet. He makes the electromagnet by winding a coil of wire around a large iron nail. He then holds the electromagnet vertically in a clamp attached to a clamp stand. He uses a low-voltage power supply to provide the current for the electromagnet.

The student decides to investigate the effect of changing the current in the coil. To measure the strength of the electromagnet he finds out how many paper clips he can hang from the end of the electromagnet. His measurements are shown in the table.

Current/A	Number of paper clips held
0	0
0.3	2
0.5	5
0.7	6
0.9	9
1.0	9

Δ Fig. 4.103 When the circuit is complete, paperclips hang off the nail.

Using and organising techniques, apparatus and materials

❶ Describe how the student can vary the current in the electromagnet coil.
❷ What factors should the student keep constant during the investigation? Why do these factors need to be controlled?

Observing, measuring and recording

❸ Draw a graph of the student's results.
❹ Describe the pattern (if any) shown by the graph.

Handling experimental observations and data

❺ The student thought of three different ways to hang paper clips on the end of the nail.
a) all the paper clips hanging on the nail together (Fig. 4.103)
b) the paper clips hanging in a line from the end of the nail with the paper clips interlocked
c) the paper clips hanging in a line from the end of the nail, but just held magnetically, not joined together.

Describe advantages and disadvantages of each method.

❻ How could the student change his method so that he could achieve more precise measurements of the strength of the electromagnet?
❼ The student wants to continue making measurements with higher values of current. Suggest a difficulty he will have as the current increases further.

ELECTRICITY AND MAGNETISM 318

FORCE ON A CURRENT-CARRYING CONDUCTOR

When a wire carrying an electric current passes through a magnetic field, with the field at right angles to the wire, the wire will experience a force at right angles both to the wire and to the magnetic field. The size of the force depends on the magnitude of the current and the strength of the magnetic field. **Fleming's left-hand rule**, which is shown in Fig. 4.104, predicts the direction of the force. You can demonstrate this using the apparatus in Fig. 4.105.

Remember that the current direction is that of the conventional current, and that the electrons are travelling the opposite way.

Δ Fig. 4.104 Fleming's left-hand rule predicts the direction of the force on a current-carrying wire.

Δ Fig. 4.105 Apparatus that can be used to demonstrate that if a wire carrying an electric current passes through a magnetic field, with the field at right angles to the wire, then the wire will experience a force at right angles both to the wire and to the magnetic field.

When you try applying Fleming's left-hand rule, you should be able to confirm that if you reverse either the magnetic field or the current then the force will be applied in the opposite direction, but that if you reverse *both* the field *and* the current then the force stays unchanged.

It is useful to look at the magnetic field lines for this set-up (Fig. 4.106).

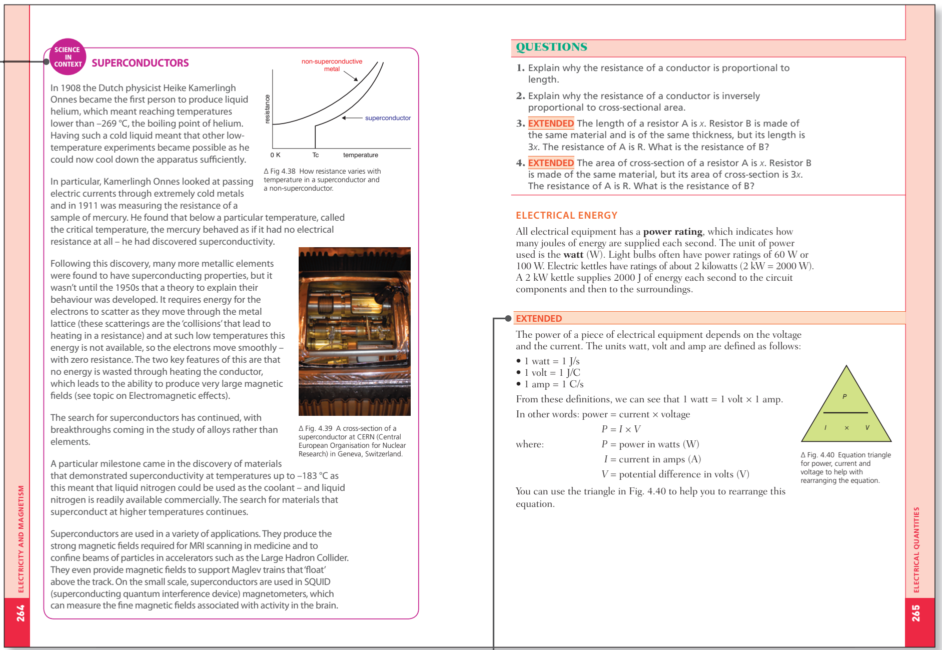
Δ Fig. 4.106 How the magnetic field lines are changed by a wire in a uniform magnetic field.

The field lines from the magnet are dragged downwards by the direction of the field lines that are around the wire. If you imagine that the lines are made of stretched elastic, then it is clear why the wire feels an upwards force.

ELECTROMAGNETIC EFFECTS 319

Getting the best from the book *continued*

Science in context boxes put the ideas you are learning into real-life context. It is not necessary for you to learn the content of these boxes as they do not form part of the syllabus. However, they do provide interesting examples of scientific application that are designed to enhance your understanding.



SCIENCE IN CONTEXT

SUPERCONDUCTORS

In 1908 the Dutch physicist Heike Kamerlingh Onnes became the first person to produce liquid helium, which meant reaching temperatures lower than –269 °C, the boiling point of helium. Having such a cold liquid meant that other low-temperature experiments became possible as he could now cool down the apparatus sufficiently.

Δ Fig 4.38 How resistance varies with temperature in a superconductor and a non-superconductor.

In particular, Kamerlingh Onnes looked at passing electric currents through extremely cold metals and in 1911 was measuring the resistance of a sample of mercury. He found that below a particular temperature, called the critical temperature, the mercury behaved as if it had no electrical resistance at all – he had discovered superconductivity.

Following this discovery, many more metallic elements were found to have superconducting properties, but it wasn't until the 1950s that a theory to explain their behaviour was developed. It requires energy for the electrons to scatter as they move through the metal lattice (these scatterings are the 'collisions' that lead to heating in a resistance) and at such low temperatures this energy is not available, so the electrons move smoothly – with zero resistance. The two key features of this are that no energy is wasted through heating the conductor, which leads to the ability to produce very large magnetic fields (see topic on Electromagnetic effects).

The search for superconductors has continued, with breakthroughs coming in the study of alloys rather than elements.

Δ Fig. 4.39 A cross-section of a superconductor at CERN (Central European Organisation for Nuclear Research) in Geneva, Switzerland.

A particular milestone came in the discovery of materials that demonstrated superconductivity at temperatures up to –183 °C as this meant that liquid nitrogen could be used as the coolant – and liquid nitrogen is readily available commercially. The search for materials that superconduct at higher temperatures continues.

Superconductors are used in a variety of applications. They produce the strong magnetic fields required for MRI scanning in medicine and to confine beams of particles in accelerators such as the Large Hadron Collider. They even provide magnetic fields to support Maglev trains that 'float' above the track. On the small scale, superconductors are used in SQUID (superconducting quantum interference device) magnetometers, which can measure the fine magnetic fields associated with activity in the brain.

264 ELECTRICITY AND MAGNETISM

QUESTIONS

1. Explain why the resistance of a conductor is proportional to length.
2. Explain why the resistance of a conductor is inversely proportional to cross-sectional area.
3. EXTENDED The length of a resistor A is *x*. Resistor B is made of the same material and is of the same thickness, but its length is 3*x*. The resistance of A is R. What is the resistance of B?
4. EXTENDED The area of cross-section of a resistor A is *x*. Resistor B is made of the same material, but its area of cross-section is 3*x*. The resistance of A is R. What is the resistance of B?

ELECTRICAL ENERGY

All electrical equipment has a **power rating**, which indicates how many joules of energy are supplied each second. The unit of power used is the **watt** (W). Light bulbs often have power ratings of 60 W or 100 W. Electric kettles have ratings of about 2 kilowatts (2 kW = 2000 W). A 2 kW kettle supplies 2000 J of energy each second to the circuit components and then to the surroundings.

EXTENDED

The power of a piece of electrical equipment depends on the voltage and the current. The units watt, volt and amp are defined as follows:

- 1 watt = 1 J/s
- 1 volt = 1 J/C
- 1 amp = 1 C/s

From these definitions, we can see that 1 watt = 1 volt × 1 amp.

In other words: power = current × voltage

$P = I \times V$

where: P = power in watts (W)
I = current in amps (A)
V = potential difference in volts (V)

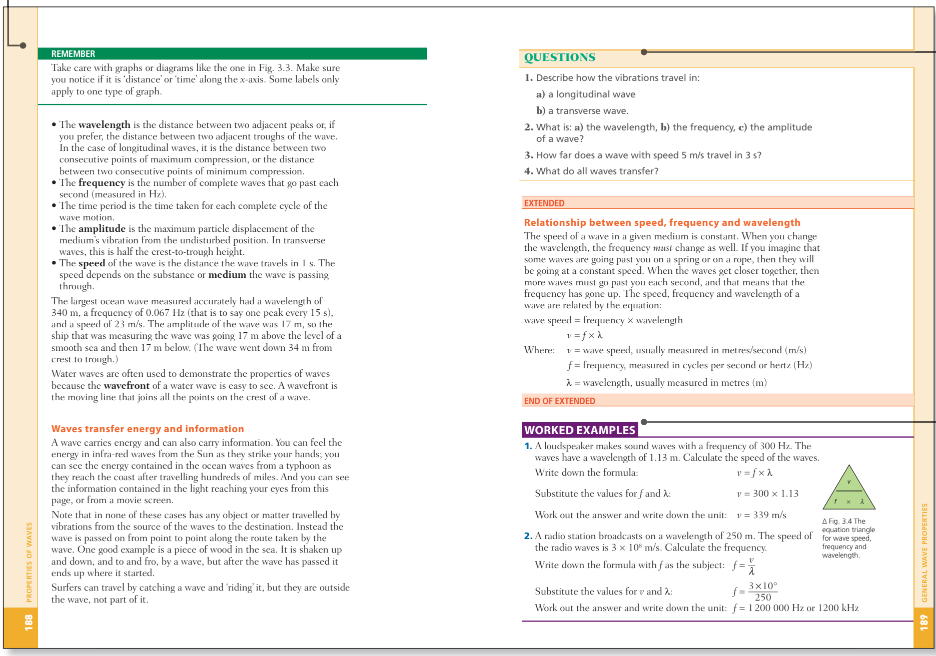
You can use the triangle in Fig. 4.40 to help you to rearrange this equation.

Δ Fig. 4.40 Equation triangle for power, current and voltage to help with rearranging the equation.

265 ELECTRICAL QUANTITIES

Clearly differentiated extended material takes your learning even further.

Remember boxes provide tips and guidance to help you during your course and to prepare for examination.



REMEMBER

Take care with graphs or diagrams like the one in Fig. 3.3. Make sure you notice if it is 'distance' or 'time' along the *x*-axis. Some labels only apply to one type of graph.

- The **wavelength** is the distance between two adjacent peaks or, if you prefer, the distance between two adjacent troughs of the wave. In the case of longitudinal waves, it is the distance between two consecutive points of maximum compression, or the distance between two consecutive points of minimum compression.
- The **frequency** is the number of complete waves that go past each second (measured in Hz).
- The time period is the time taken for each complete cycle of the wave motion.
- The **amplitude** is the maximum particle displacement of the medium's vibration from the undisturbed position. In transverse waves, this is half the crest-to-trough height.
- The **speed** of the wave is the distance the wave travels in 1 s. The speed depends on the substance or **medium** the wave is passing through.

The largest ocean wave measured accurately had a wavelength of 340 m, a frequency of 0.067 Hz (that is to say one peak every 15 s), and a speed of 23 m/s. The amplitude of the wave was 17 m, so the ship that was measuring the wave was going 17 m above the level of a smooth sea and then 17 m below. (The wave went down 34 m from crest to trough.)

Water waves are often used to demonstrate the properties of waves because the **wavefront** of a water wave is easy to see. A wavefront is the moving line that joins all the points on the crest of a wave.

Waves transfer energy and information

A wave carries energy and can also carry information. You can feel the energy in infra-red waves from the Sun as they strike your hands; you can see the energy contained in the ocean waves from a typhoon as they reach the coast after travelling hundreds of miles. And you can see the information contained in the light reaching your eyes from this page, or from a movie screen.

Note that in none of these cases has any object or matter travelled by vibrations from the source of the waves to the destination. Instead the wave is passed on from point to point along the route taken by the wave. One good example is a piece of wood in the sea. It is shaken up and down, and to and fro, by a wave, but after the wave has passed it ends up where it started.

Surfers can travel by catching a wave and 'riding' it, but they are outside the wave, not part of it.

188 PROPERTIES OF WAVES

QUESTIONS

1. Describe how the vibrations travel in:
   a) a longitudinal wave
   b) a transverse wave.
2. What is: a) the wavelength, b) the frequency, c) the amplitude of a wave?
3. How far does a wave with speed 5 m/s travel in 3 s?
4. What do all waves transfer?

EXTENDED

Relationship between speed, frequency and wavelength

The speed of a wave in a given medium is constant. When you change the wavelength, the frequency *must* change as well. If you imagine that some waves are going past you on a spring or on a rope, then they will be going at a constant speed. When the waves get closer together, then more waves must go past you each second, and that means that the frequency has gone up. The speed, frequency and wavelength of a wave are related by the equation:

wave speed = frequency × wavelength

$v = f \times \lambda$

Where: v = wave speed, usually measured in metres/second (m/s)
f = frequency, measured in cycles per second or hertz (Hz)
λ = wavelength, usually measured in metres (m)

END OF EXTENDED

WORKED EXAMPLES

1. A loudspeaker makes sound waves with a frequency of 300 Hz. The waves have a wavelength of 1.13 m. Calculate the speed of the waves.
   Write down the formula: $v = f \times \lambda$
   Substitute the values for f and λ: $v = 300 \times 1.13$
   Work out the answer and write down the unit: $v = 339$ m/s
2. A radio station broadcasts on a wavelength of 250 m. The speed of the radio waves is 3×10^8 m/s. Calculate the frequency.
   Write down the formula with f as the subject: $f = \frac{v}{\lambda}$
   Substitute the values for v and λ: $f = \frac{3 \times 10^8}{250}$
   Work out the answer and write down the unit: f = 1 200 000 Hz or 1200 kHz

Δ Fig. 3.4 The equation triangle for wave speed, frequency and wavelength.

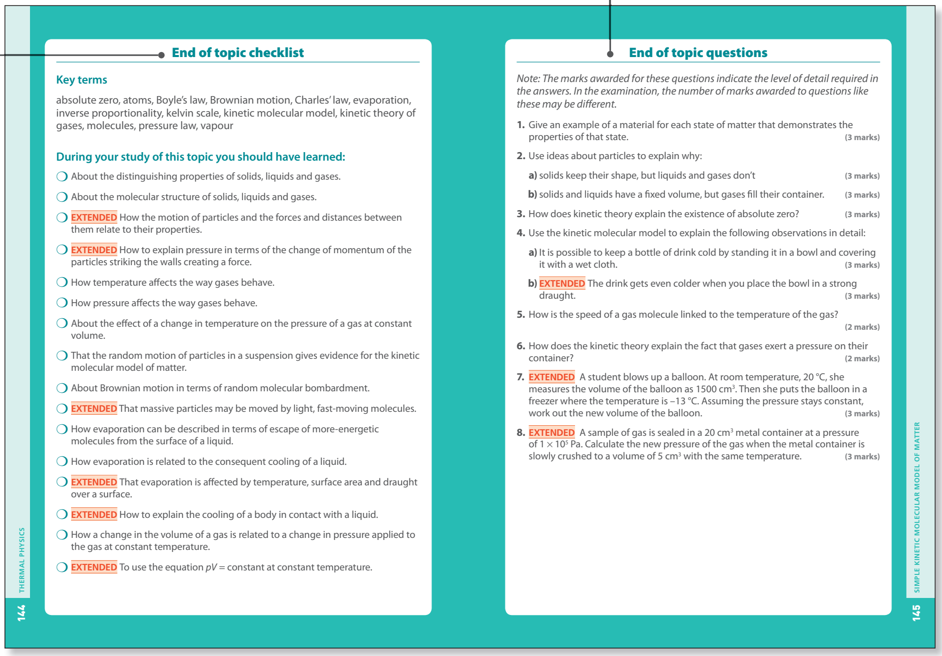
189 GENERAL WAVE PROPERTIES

Questions to check your understanding.

Learn to apply formulae through worked examples.

End of topic questions allow you to apply the knowledge and understanding you have learned in the topic to answer the questions.

A full checklist of all the information you need to cover the complete syllabus requirements for each topic.



THERMAL PHYSICS

144

End of topic checklist

Key terms

absolute zero, atoms, Boyle's law, Brownian motion, Charles' law, evaporation, inverse proportionality, kelvin scale, kinetic molecular model, kinetic theory of gases, molecules, pressure law, vapour

During your study of this topic you should have learned:

- ○ About the distinguishing properties of solids, liquids and gases.
- ○ About the molecular structure of solids, liquids and gases.
- ○ EXTENDED How the motion of particles and the forces and distances between them relate to their properties.
- ○ EXTENDED How to explain pressure in terms of the change of momentum of the particles striking the walls creating a force.
- ○ How temperature affects the way gases behave.
- ○ How pressure affects the way gases behave.
- ○ About the effect of a change in temperature on the pressure of a gas at constant volume.
- ○ That the random motion of particles in a suspension gives evidence for the kinetic molecular model of matter.
- ○ About Brownian motion in terms of random molecular bombardment.
- ○ EXTENDED That massive particles may be moved by light, fast-moving molecules.
- ○ How evaporation can be described in terms of escape of more-energetic molecules from the surface of a liquid.
- ○ How evaporation is related to the consequent cooling of a liquid.
- ○ EXTENDED That evaporation is affected by temperature, surface area and draught over a surface.
- ○ EXTENDED How to explain the cooling of a body in contact with a liquid.
- ○ How a change in the volume of a gas is related to a change in pressure applied to the gas at constant temperature.
- ○ EXTENDED To use the equation pV = constant at constant temperature.

End of topic questions

Note: The marks awarded for these questions indicate the level of detail required in the answers. In the examination, the number of marks awarded to questions like these may be different.

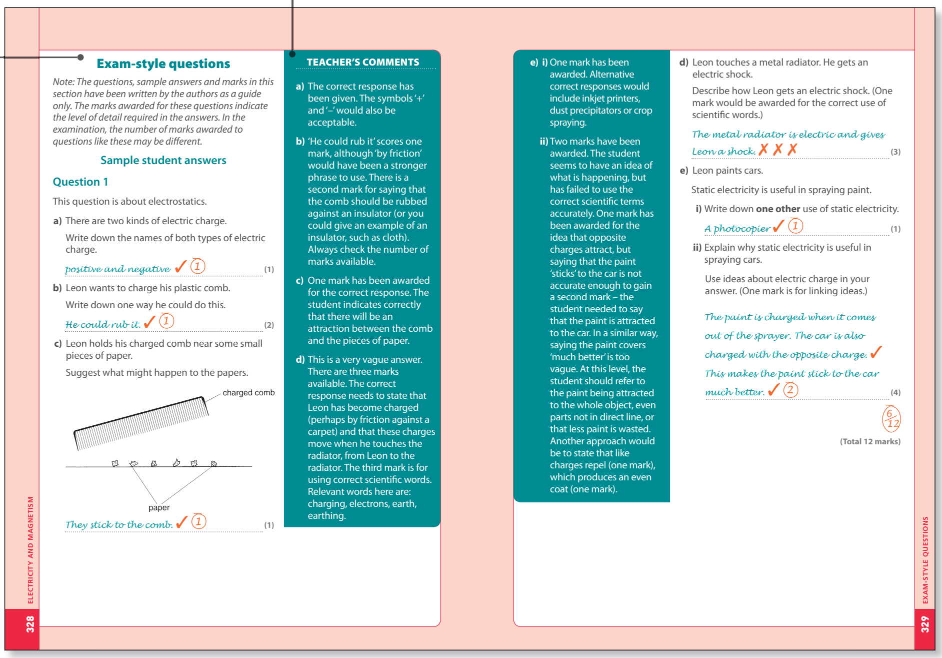
1. Give an example of a material for each state of matter that demonstrates the properties of that state. **(3 marks)**
2. Use ideas about particles to explain why:
   a) solids keep their shape, but liquids and gases don't **(3 marks)**
   b) solids and liquids have a fixed volume, but gases fill their container. **(3 marks)**
3. How does kinetic theory explain the existence of absolute zero? **(3 marks)**
4. Use the kinetic molecular model to explain the following observations in detail:
   a) It is possible to keep a bottle of drink cold by standing it in a bowl and covering it with a wet cloth. **(3 marks)**
   b) EXTENDED The drink gets even colder when you place the bowl in a strong draught. **(3 marks)**
5. How is the speed of a gas molecule linked to the temperature of the gas? **(2 marks)**
6. How does the kinetic theory explain the fact that gases exert a pressure on their container? **(2 marks)**
7. EXTENDED A student blows up a balloon. At room temperature, 20 °C, she measures the volume of the balloon as 1500 cm^3. Then she puts the balloon in a freezer where the temperature is –13 °C. Assuming the pressure stays constant, work out the new volume of the balloon. **(3 marks)**
8. EXTENDED A sample of gas is sealed in a 20 cm^3 metal container at a pressure of 1×10^5 Pa. Calculate the new pressure of the gas when the metal container is slowly crushed to a volume of 5 cm^3 with the same temperature. **(3 marks)**

SIMPLE KINETIC MOLECULAR MODEL OF MATTER

145

The first question is a student sample with teacher's comments to show best practice.

Each section includes exam-style questions to help you prepare for your exam in a focussed way and get the best results.



ELECTRICITY AND MAGNETISM

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Exam-style questions

Note: The questions, sample answers and marks in this section have been written by the authors as a guide only. The marks awarded for these questions indicate the level of detail required in the answers. In the examination, the number of marks awarded to questions like these may be different.

Sample student answers

Question 1

This question is about electrostatics.

a) There are two kinds of electric charge.

Write down the names of both types of electric charge.

positive and negative ✓ 1 (1)

b) Leon wants to charge his plastic comb.

Write down one way he could do this.

He could rub it. ✓ 1 (2)

c) Leon holds his charged comb near some small pieces of paper.

Suggest what might happen to the papers.

charged comb

paper

They stick to the comb. ✓ 1 (1)

TEACHER'S COMMENTS

a) The correct response has been given. The symbols '+' and '–' would also be acceptable.

b) 'He could rub it' scores one mark, although 'by friction' would have been a stronger phrase to use. There is a second mark for saying that the comb should be rubbed against an insulator (or you could give an example of an insulator, such as cloth). Always check the number of marks available.

c) One mark has been awarded for the correct response. The student indicates correctly that there will be an attraction between the comb and the pieces of paper.

d) This is a very vague answer. There are three marks available. The correct response needs to state that Leon has become charged (perhaps by friction against a carpet) and that these charges move when he touches the radiator, from Leon to the radiator. The third mark is for using correct scientific words. Relevant words here are: charging, electrons, earth, earthing.

e) i) One mark has been awarded. Alternative correct responses would include inkjet printers, dust precipitators or crop spraying.

ii) Two marks have been awarded. The student seems to have an idea of what is happening, but has failed to use the correct scientific terms accurately. One mark has been awarded for the idea that opposite charges attract, but saying that the paint 'sticks' to the car is not accurate enough to gain a second mark – the student needed to say that the paint is attracted to the car. In a similar way, saying the paint covers 'much better' is too vague. At this level, the student should refer to the paint being attracted to the whole object, even parts not in direct line, or that less paint is wasted. Another approach would be to state that like charges repel (one mark), which produces an even coat (one mark).

d) Leon touches a metal radiator. He gets an electric shock.

Describe how Leon gets an electric shock. (One mark would be awarded for the correct use of scientific words.)

The metal radiator is electric and gives Leon a shock. ✗ ✗ ✗ (3)

e) Leon paints cars.

Static electricity is useful in spraying paint.

i) Write down **one other** use of static electricity.

A photocopier ✓ 1 (1)

ii) Explain why static electricity is useful in spraying cars.

Use ideas about electric charge in your answer. (One mark is for linking ideas.)

The paint is charged when it comes out of the sprayer. The car is also charged with the opposite charge. ✓ *This makes the paint stick to the car much better.* ✓ 2 (4)

6/12

(Total 12 marks)

EXAM-STYLE QUESTIONS

329

Most things in the world are either a solid, a liquid or a gas. These are the three main states of matter. Substances can change from a solid to a liquid in a process called melting, and from liquid to gas in a process called evaporation. Gases change to liquids by condensation and liquids change to solids in solidification.

You are probably most familiar with these changes for water. It is possible for the states to exist at the same time: for example, there is a temperature at which ice, water and steam are all present. This is called the triple point of water and is used to define the kelvin scale of temperature, which you will meet later in this section.

STARTING POINTS

1. Describe how particles are arranged in: a) a solid; b) a liquid; and c) a gas.
2. What happens to the particles when a solid melts?
3. Explain what happens when a solid dissolves in a liquid.
4. Are evaporation and boiling the same thing? Give a reason for your answer.
5. What happens to the speed of gas molecules as temperature increases?

CONTENTS

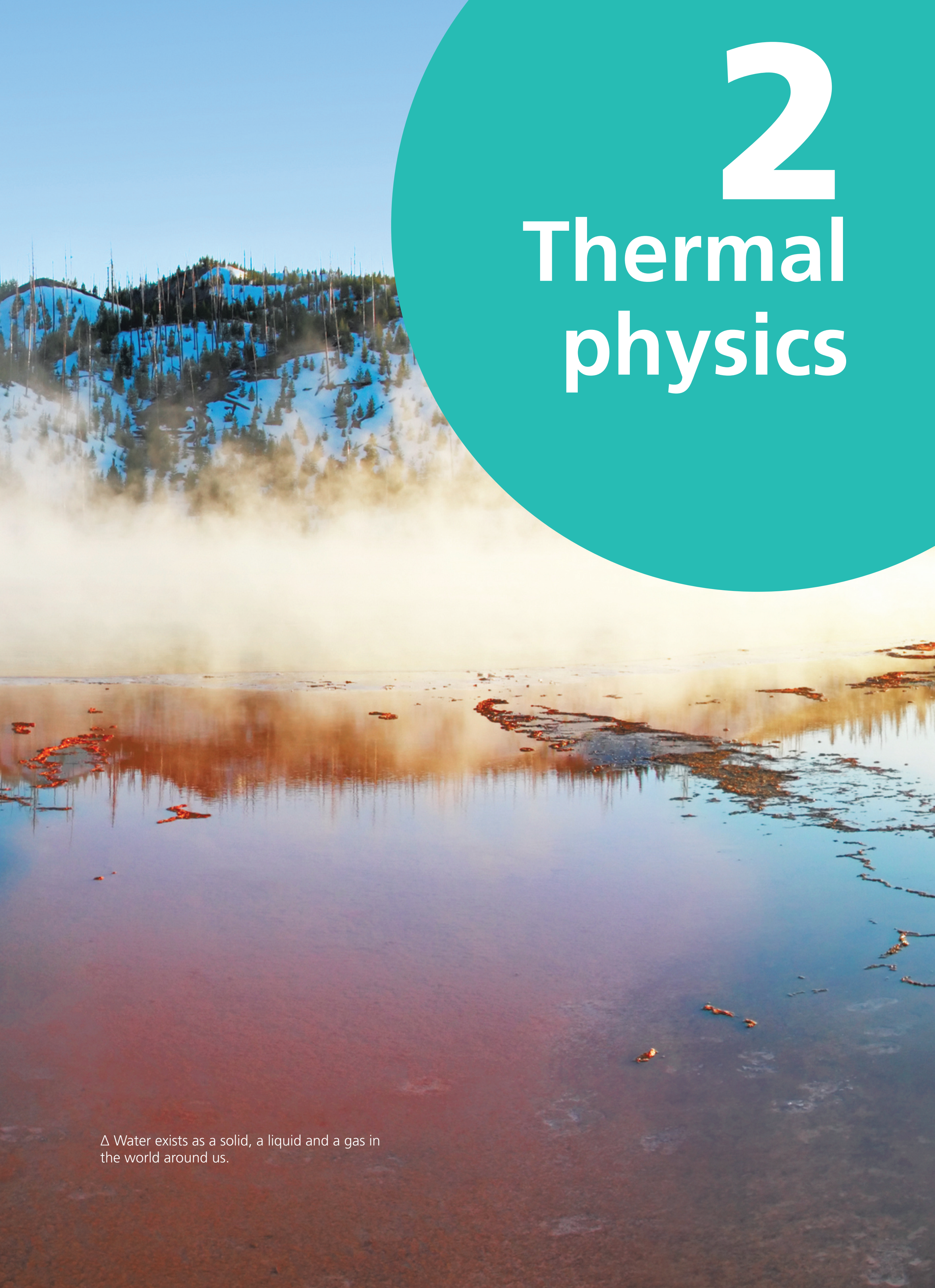
a) Simple kinetic molecular model of matter

b) Thermal properties

c) Thermal processes

d) Exam-style questions

2 Thermal physics



Δ Water exists as a solid, a liquid and a gas in the world around us.

∆ Fig. 2.1 Water in all three states of matter.

Simple kinetic molecular model of matter

INTRODUCTION

Almost all matter can be classified as a solid, a liquid or a gas. These are called the three states of matter.

The fourth state of matter is called 'plasma'. It only exists at high temperatures seldom seen on Earth, so we won't consider it further here, even though most of the matter in the Universe and most stars are made of plasma.

KNOWLEDGE CHECK

✓ Know what happens when you heat a solid, liquid or gas.
✓ Know what happens when you cool down a solid, liquid or gas.
✓ Know that matter is made of tiny particles called atoms.
✓ Know how to define and calculate pressure.
✓ Know some everyday properties of gases – for example that they expand when heated and they exert a pressure on container walls.

LEARNING OBJECTIVES

✓ State the distinguishing properties of solids, liquids and gases.
✓ Be able to describe qualitatively the molecular structure of solids, liquids and gases.
✓ Be able to interpret the temperature of a gas in terms of the motion of its molecules.
✓ Be able to describe qualitatively the effect of a change of temperature on the pressure of a gas at constant volume.
✓ Show an understanding of the random motion of particles in a suspension as evidence for the kinetic molecular model of matter.
✓ Be able to describe this motion (sometimes known as Brownian motion) in terms of random molecular bombardment.
✓ **EXTENDED** Relate the properties of solids, liquids and gases to the forces and distances between molecules and to the motion of the molecules.
✓ **EXTENDED** Explain pressure in terms of the change of momentum of the particles striking the walls creating a force.
✓ **EXTENDED** Show an appreciation that massive particles may be moved by light, fast-moving molecules.
✓ Be able to describe evaporation in terms of the escape of more-energetic molecules from the surface of a liquid.
✓ Relate evaporation to consequent cooling of the liquid.
✓ **EXTENDED** Demonstrate an understanding of how temperature, surface area and draught over a surface influence evaporation.
✓ **EXTENDED** Explain the cooling of a body in contact with an evaporating liquid.

✓ Describe qualitatively, in terms of molecules, the effect on the pressure of a gas of: a change of temperature at constant volume and a change of volume at constant temperature.

✓ **EXTENDED** Recall and use the equation pV = constant for a fixed mass of gas at constant temperature.

STATES OF MATTER

The three states of matter each have different properties:

- A solid has a fixed volume and shape, is not easily compressed (squashed) and does not flow easily.
- A liquid assumes the shape of the part of the container that it occupies, usually occupying the lowest level, is not easily compressed and flows easily.
- A gas assumes the shape and volume of its container, occupying the whole volume, can be compressed and flows easily.

MOLECULAR MODEL

In this topic, these properties of matter are explained in terms of the molecular structure of the three states.

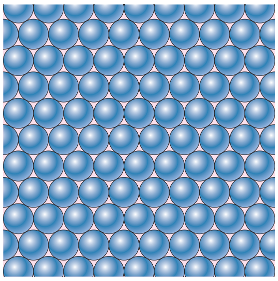
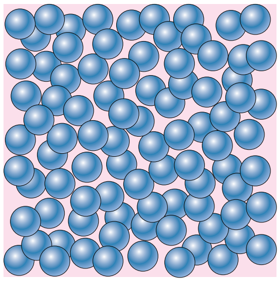
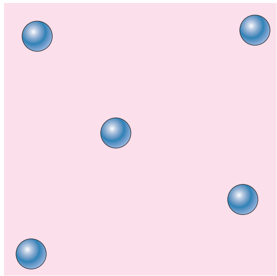
◁ Fig. 2.2 The main body of this rocket is filled with liquid oxygen and liquid hydrogen, which have to be kept at extremely low temperatures to prevent them from heating up and turning back into gas. If the fuel were made colder it would turn into a solid.

We now know that all materials are made of tiny particles called **atoms** that can attract each other. The atoms in a solid are locked together by the forces between them. However, even in a solid, the particles are not completely still. They vibrate constantly about their fixed positions. When the material is heated, it is given more internal energy, and the particles vibrate faster and further.

When the temperature is increased more, the vibrations of the particles increase to the point at which the forces are no longer strong enough to hold the structure together in the rigid order of a solid. The forces can no longer prevent the atoms moving around, but they do prevent them from flying apart from each other. This is what makes a liquid. The volume of the liquid is the volume occupied by the particles from which it is made.

Δ Fig. 2.3 The molten iron can be poured into a mould before it cools down and turns back into a solid.

When the temperature is increased even more, then the particles do fly apart. They now form a gas. The particles fly around at high speed – several hundred kilometres per hour. If they are in a container, they travel all over it, bouncing off the walls. The volume of a gas is not fixed; it just depends on the size of the container that the gas is put into. We use the **kinetic molecular model** to explain the behaviour of solids, liquids and gases. Table 2.1 summarises this model.

	Solid	**Liquid**	**Gas**
Arrangement of particles	Regular pattern, closely packed together, particles held in place	Irregular, closely packed together, particles able to move past each other	Irregular, widely spaced, particles able to move freely
Diagram			
Motion of particles	Vibrate in place within the structure	'Slide' over each other in a random motion	Random motion, faster movement than the other states

∆ Table 2.1 The kinetic molecular model of matter.

The kinetic molecular model uses this idea that all materials are made up of atoms that behave rather like tiny balls. When the model is used to try to explain the behaviour of gases it is often called the **kinetic theory of gases**.

EXTENDED

The arrangement of atoms can be used to explain the properties of solids, liquids and gases that you met earlier.

Solids:

- retain a fixed shape and volume because the particles are locked into place in the lattice
- are not easily compressed because there is little free space between the particles
- do not flow easily because the particles cannot move/slide past one another.

Liquids:

- assume the shape of the part of the container that they occupy because the particles can move/slide past one another
- are not easily compressed because there is little free space between the particles
- flow easily because the particles can move/slide past one another.

Gases:

- assume the shape and volume of their container because the particles move past one another continuously
- are compressible because there is lots of free space between the particles
- flow easily because the particles can move past one another.

END OF EXTENDED

QUESTIONS

1. What happens to the motion of atoms as the temperature increases?
2. Explain why it is easier to compress a gas than a liquid.
3. Describe the arrangement of particles in: a) a solid; b) a liquid; c) a gas.
4. What does the volume of a gas depend on?

What are molecules?

In Table 2.1, you can see that the particles in the liquid and the gas consist of single atoms. There are materials like this – elements such as helium and neon. In most materials, though, the particles that move around in the liquid or the gaseous state are groups of atoms called **molecules**. A water molecule is H_2O and a nitrogen molecule is N_2. This means that the particles moving around in liquid or gaseous water each consist of two hydrogen atoms and one oxygen atom. In liquid nitrogen or in nitrogen gas, the particles each consist of two nitrogen atoms.

Δ Fig. 2.4 This balloon rises because the gas inside it is less dense than the surrounding area.

Taking the idea of particles one step further, you can start to apply your knowledge of forces and motion to the molecules of a gas. This step is building up a theory – the kinetic theory of gases – to see if the predictions that come from our ideas match what happens when we experiment with gases.

It is quite a simple theory to begin with. We only look at gases where the particles are generally separated from each other and the maths is not too difficult. However, the ideas have proved to be remarkably successful in describing the behaviour of materials.

The kinetic theory of gases builds up a set of ideas from the basic idea that a gas is made of many tiny particles called molecules. These ideas give a picture of what happens inside a gas (Table 2.2).

Observed feature of a gas	Related ideas from the kinetic theory
Gases have a mass that can be measured	The total mass of a gas is the sum of the masses of the individual molecules.
Gases have a temperature that can be measured	The individual molecules are always moving. The faster they move (the more kinetic energy they have), the higher the temperature of the gas.
Gases have a pressure that can be measured	When the molecules hit the walls of the container they exert a force on it. It is this force, divided by the surface area of the container, that we observe when measuring pressure. EXTENDED As molecules strike the walls of a container, their momentum changes. As momentum changes, a force is created $Ft = m(v–u)$.
Gases have a volume that can be measured	Although the volume of each molecule is only tiny, they are always moving about and spread out throughout the container.
Temperature has an absolute zero	As the temperature falls, the speed of the molecules (and their kinetic energy) becomes less. At absolute zero the molecules would have stopped moving.

∆ Table 2.2 What happens inside a gas.

These ideas help to explain Boyle's law.

Boyle's law states that when the temperature of the gas stays constant, the volume of the gas is inversely proportional to the pressure. The link to kinetic theory is as follows. The temperature stays constant, so the average speed of the molecules stays constant. If the volume of the gas is reduced by half, then the molecules make the same number of collisions with half the surface area of wall, so the pressure (= force/area) must be doubled. This is **inverse proportionality.**

Gases only follow Boyle's law if the mass of the gas remains constant (that is, no particles move in or out of the system) and the gases are ideal, that is they do not liquefy or solidify.

QUESTIONS

1. How does the kinetic theory explain the measurable volume of a gas?
2. A fixed mass of gas is at a constant temperature. What happens to the volume when you increase the pressure?
3. What conditions must be met for gases to follow Boyle's law?

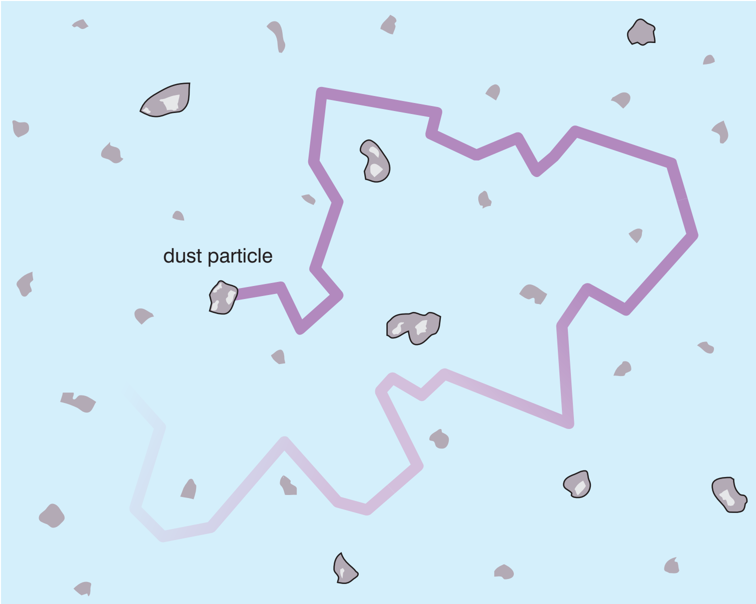
Brownian motion

Evidence for the molecular model of matter comes from observations such as **Brownian motion**. When viewed under a microscope, small particles (such as pollen grains or fine smoke particles) can be seen moving in a random way. The explanation is that the particles are constantly being hit by even smaller particles, which are too small to see (such as water molecules or air molecules).

EXTENDED

Massive particles may be moved by light, fast-moving particles.

END OF EXTENDED

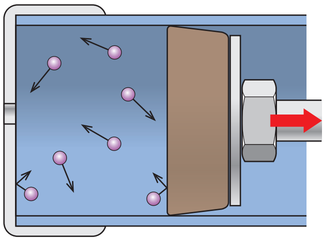


Δ Fig. 2.5 Brownian motion as seen in dust particles.

Molecules in a gas

The molecular model says that the pressure on the walls of a container is caused by the collisions made by the speeding gas molecules. You can feel this pressure if you try to hold a bicycle pump in the pushed-in position while blocking the air outlet with your finger as shown in Fig. 2.6. (If the pump is broken and allows the air to escape, this does not work.)

In Fig. 2.6 the piston is not moving. However, there is a force trying to push it out. It is clear that if the molecules travel faster then they will hit the piston in the pump more often and harder. The pressure on the piston and on the walls will go up. This is exactly what will happen when the air gets hotter.



Δ Fig. 2.6 The molecules of the gas are colliding with the piston and trying to push it out.

Note that the molecules will also hit each other as well as the walls of the container. At normal pressures they travel a lot less than 1 mm between collisions. This does not affect the way that the model works.

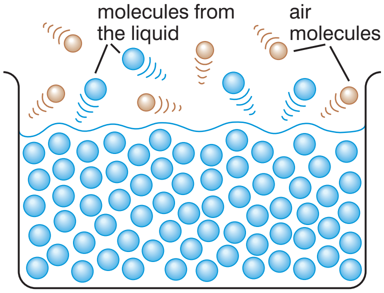
◁ Fig. 2.7 The inner tube from a tyre has been pumped up with air to use as a toboggan. It is the pressure caused by the movement of the air molecules inside that keeps it inflated. Because the temperature is low, the inner tube will need a lot of air to provide a high enough pressure. On a hot day this tube could burst.

QUESTIONS

1. What is Brownian motion?
2. How does the kinetic theory explain Brownian motion?
3. How does the model explain pressure on the walls of a container?
4. Why does the pressure in a pump increase when the molecules move faster?

EVAPORATION

When particles break away from the surface of a liquid and form a **vapour**, this is known as **evaporation**. The more energetic molecules of the liquid escape from the surface as shown in Fig. 2.8. This reduces the average energy of the molecules remaining in the liquid, and so the temperature of the liquid falls.



Δ Fig. 2.8 Evaporation.

Therefore, evaporation causes cooling. The evaporation of sweat helps to keep your body cool in hot weather. The more energetic molecules of liquid sweat escape from the surface of your skin and so the average energy and therefore temperature of the remaining molecules falls and your skin cools down. This is what happens when any body is in contact with an evaporating liquid. The body cools down. The cooling in a refrigerator is also due to evaporation of a special liquid inside the freezing compartment at the top of the refrigerator. The vapour is collected and compressed back into liquid inside the condenser behind the refrigerator. The liquid is circulated by a pump and recycled.

EXTENDED

The rate of evaporation is increased at higher temperatures. It is also increased by a strong flow of air across the surface of the liquid, as in this way the evaporating molecules are carried away quickly. A certain amount of water will also evaporate more quickly when you increase its surface area. Tea or coffee in a shallow, wide cup cools down much more quickly than in a tall, narrow mug because the large surface area of the cup allows more evaporation.

Imagine you are a particle that has experienced evaporation. Write a letter to your friend describing the experience. Your letter should answer the following questions.

1. What change of state did you go through?

2. How close to your neighbours were you in your original state?

3. What was given to you to make you change state?

4. How did you change state?

END OF EXTENDED

QUESTIONS

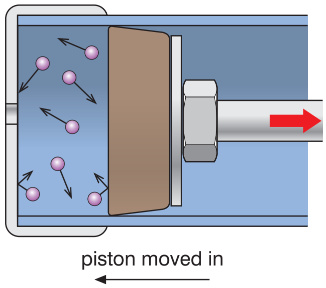
1. What factors increase the rate of evaporation?
2. Why does tea in a narrow mug cool down more slowly than tea in a wide mug?

PRESSURE CHANGES

Pressure and volume

When the piston of a bicycle pump is pushed in with the air outlet blocked, then the more you push it in, the harder and harder it gets to push it further. This is because the pressure in the container goes up.

The molecular model says that there is the same number of molecules in the container travelling at the same speed. However, because the molecules are now packed in more densely, there will be more collisions with the walls (and with the piston) per second. When the volume is halved, then the number of collisions per second with the walls and with the piston will double, and the pressure on the piston will double. This law is often called Boyle's law. It only applies when the temperature of the air does not change.



△ Fig. 2.9 The pressure increases when the volume is reduced.

Temperature at constant volume

You have already seen that the individual molecules of a gas are always moving. The higher the temperature of the gas, the faster they move (the more kinetic energy they have).

Although all of the molecules in a constant volume of gas are travelling at different speeds, it is possible to calculate the average speed of the molecules and hence their average kinetic energy. We know that the average kinetic energy of the molecules will increase as the temperature increases, but it is perhaps surprising to discover that the average kinetic energy is exactly proportional to the temperature of the gas in kelvin. So, for example, if the temperature of a gas is doubled from 273 K to 546 K, then the average kinetic energy of the molecules will exactly double as well.

EXTENDED

A fixed amount of gas in a sealed container at constant temperature obeys the following equation:

pressure × volume = constant

pV = constant

Where: p = pressure in Pa (or N/m^2)

V = volume in m^3

Pascals and newtons per square metre are the same thing. When using this equation, you can use whichever units you like so long as you continue to use the same ones.

The constant will be a constant for a particular sample of gas in a particular container. So, in an experiment (or an exam question) you can write that the initial values of pressure and volume multiplied together, $p_1 \times V_1$ are constant.

The final values of pressure and volume multiplied together, $p_2 \times V_2$, are also constant.

This is the same constant in both cases. So:

p_1V_1 = constant = p_2V_2

or

$p_1V_1 = p_2V_2$

This equation, representing Boyle's law, only applies if the temperature stays constant.

WORKED EXAMPLE

A bicycle pump contains 400 cm^3 of air at atmospheric pressure. The air is compressed slowly. What is the pressure when the volume of the air is compressed to 125 cm^3? What would happen to the pressure if the air were compressed quickly? (Remember that atmospheric pressure = 100 kPa.)

Write down equation: $p_1V_1 = p_2V_2$

Substitute values into the equation: $100 \times 400 = p_2 \times 125$

$p_2 \times 125 = 40\,000$

Rearrange the equation to find p_2: $p_2 = 40\,000 / 125$

Work out the answer and write down the unit: $p_2 = 320$ kPa

If the air were compressed quickly, it would also heat up to a higher temperature. This would mean that the final pressure will be greater than 320 kPa. Because the temperature had changed, $p_1V_1 = p_2V_2$ could not then be used.

END OF EXTENDED

QUESTIONS

1. Describe the link between the pressure of a gas and its volume at constant temperature (this is Boyle's law).

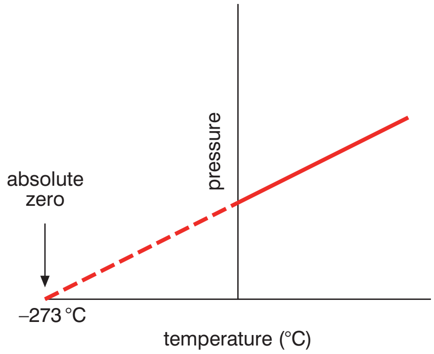
2. What factors must remain constant for the law to apply?

3. EXTENDED An aerosol has a volume of 150 cm^3. It contains gas at a pressure of 350 kPa. When the temperature stays constant, what will be the volume of gas if it is allowed to expand at a pressure of 101 kPa?

SCIENCE IN CONTEXT

ABSOLUTE ZERO AND THE KELVIN SCALE OF TEMPERATURE

As a gas is cooled down, its molecules have less energy and move round more slowly. If you kept cooling the gas down, it would eventually reach a temperature so low that all movement of the molecules would have stopped. This temperature is the lowest that can be reached. It is known as **absolute zero**, and it has been shown to be at a temperature of –273 °C. There can be no lower temperature, as clearly the molecules cannot do less than not move!



Δ Fig. 2.10 Absolute zero is the lowest possible temperature.

Because there is an absolute zero, a system of measuring temperature has been set up in which the temperature at absolute zero is given the number 0. All other temperatures are then higher than this. The steps are the same size as in the Celsius scale: you have to go up 273 degrees to reach the melting point of ice, and another 100 degrees to reach the boiling point of water. This scale is known as the kelvin scale of temperature.

Table 2.3 shows how the two temperature scales work.

Scale	Absolute zero	Melting point of ice	Boiling point of water	Melting point of gold
Celsius (°C)	–273	0	100	1064
kelvin (K)	0	273	373	1337

Δ Table 2.3 The Celsius and kelvin scales compared.

- To convert a temperature in degrees Celsius to kelvin, you add 273.
- To convert a temperature in kelvin to degrees Celsius, you subtract 273.

Note that the unit for the Celsius scale is always called 'degree Celsius' and written as °C, though you will sometimes see 'deg C'. The unit for the kelvin scale is kelvin and is always written as K.

End of topic checklist

Key terms

absolute zero, atoms, Boyle's law, Brownian motion, Charles' law, evaporation, inverse proportionality, kelvin scale, kinetic molecular model, kinetic theory of gases, molecules, pressure law, vapour

During your study of this topic you should have learned:

- ❍ About the distinguishing properties of solids, liquids and gases.
- ❍ About the molecular structure of solids, liquids and gases.
- ❍ **EXTENDED** How the motion of particles and the forces and distances between them relate to their properties.
- ❍ **EXTENDED** How to explain pressure in terms of the change of momentum of the particles striking the walls creating a force.
- ❍ How temperature affects the way gases behave.
- ❍ How pressure affects the way gases behave.
- ❍ About the effect of a change in temperature on the pressure of a gas at constant volume.
- ❍ That the random motion of particles in a suspension gives evidence for the kinetic molecular model of matter.
- ❍ About Brownian motion in terms of random molecular bombardment.
- ❍ **EXTENDED** That massive particles may be moved by light, fast-moving molecules.
- ❍ How evaporation can be described in terms of escape of more-energetic molecules from the surface of a liquid.
- ❍ How evaporation is related to the consequent cooling of a liquid.
- ❍ **EXTENDED** That evaporation is affected by temperature, surface area and draught over a surface.
- ❍ **EXTENDED** How to explain the cooling of a body in contact with a liquid.
- ❍ How a change in the volume of a gas is related to a change in pressure applied to the gas at constant temperature.
- ❍ **EXTENDED** To use the equation $pV =$ constant at constant temperature.

End of topic questions

Note: The marks awarded for these questions indicate the level of detail required in the answers. In the examination, the number of marks awarded to questions like these may be different.

1. Give an example of a material for each state of matter that demonstrates the properties of that state. **(3 marks)**

2. Use ideas about particles to explain why:

a) solids keep their shape, but liquids and gases don't **(3 marks)**

b) solids and liquids have a fixed volume, but gases fill their container. **(3 marks)**

3. How does kinetic theory explain the existence of absolute zero? **(3 marks)**

4. Use the kinetic molecular model to explain the following observations in detail:

a) It is possible to keep a bottle of drink cold by standing it in a bowl and covering it with a wet cloth. **(3 marks)**

b) EXTENDED The drink gets even colder when you place the bowl in a strong draught. **(3 marks)**

5. How is the speed of a gas molecule linked to the temperature of the gas? **(2 marks)**

6. How does the kinetic theory explain the fact that gases exert a pressure on their container? **(2 marks)**

7. EXTENDED A student blows up a balloon. At room temperature, 20 °C, she measures the volume of the balloon as 1500 cm^3. Then she puts the balloon in a freezer where the temperature is –13 °C. Assuming the pressure stays constant, work out the new volume of the balloon. **(3 marks)**

8. EXTENDED A sample of gas is sealed in a 20 cm^3 metal container at a pressure of 1×10^5 Pa. Calculate the new pressure of the gas when the metal container is slowly crushed to a volume of 5 cm^3 with the same temperature. **(3 marks)**

End of topic questions continued

9. **EXTENDED** The volume of a cylinder is 0.05 m^3. 1.4 m^3 of air at atmospheric pressure (1×10^5 Pa) is pumped into the tyre. What is the pressure in the cylinder? Assume that the temperature remains constant. **(3 marks)**

10. **EXTENDED** A gas cylinder contains gas at a pressure of 1.5×10^6 Pa. What volume of gas would be released from the cylinder at a pressure of 1×10^5 Pa? (Hint: remember that some of the gas will remain in the cylinder.) Assume the temperature does not change. **(3 marks)**

11. **EXTENDED** The correct pressure in a tyre should be 2.4×10^5 Pa. A driver has checked the pressure and it is 1.5×10^5 Pa. What volume of air at atmospheric pressure (1×10^5 Pa) should the driver pump into the tyre to increase it to the correct pressure? The volume of the tyre is 0.013 m^3. **(4 marks)**

12. **EXTENDED** A cylinder with a volume of 0.17 m^3 containing 20 kg of compressed air is stored at a temperature of 7 °C. The pressure of the gas in the cylinder is 950 kPa. The compressed air is used in a process in which the air at a temperature of 7 °C has to be supplied from the cylinder at a pressure of 150 kPa and at a rate of 1000 cm^3 per minute.

a) What volume would the gas occupy at a pressure of 150 kPa at 7 °C? **(3 marks)**

b) What volume of air can one cylinder supply to the process? **(1 mark)**

c) For what length of time can one cylinder supply the process? **(3 marks)**