1 States of matter

FOCUS POINTS

★ What is the structure of matter?
★ What are the three states of matter?
★ How does kinetic particle theory help us understand how matter behaves?

In this first chapter, you will look at the three states of matter: solids, liquids and gases. The structure of these states of matter and how the structures can be changed from one to another is key to understanding the states of matter.

You will use the kinetic particle theory to help explain how matter behaves, so you can understand the difference in the properties of the three states of matter and how the properties are linked to the strength of bonds between the particles they contain. Why, for example, can you compress gases but cannot compress a solid? By the end of this chapter, you should be able to answer this question and use the ideas involved to help you to understand many everyday observations, such as why car windows mist up on a cold morning or why dew forms on grass at night.

1.1 Solids, liquids and gases

Chemistry is about what **matter** is like and how it behaves, and our explanations and predictions of its behaviour. What is matter? This word is used to cover all the substances and materials from which the physical universe is composed. There are many millions of different substances known, and all of them can be categorised as solids, liquids or gases (Figure 1.1). These are what we call the three states of matter.

a Solid

b Liquid

c Gas

▲ **Figure 1.1** Water in three different states

A **solid**, at a given temperature, has a definite volume and shape which may be affected by changes in temperature. Solids usually increase slightly in size when heated, called **expansion** (Figure 1.2), and usually decrease in size if cooled, called **contraction**.

A **liquid**, at a given temperature, has a fixed volume and will take up the shape of any container into which it is poured. Like a solid, a liquid's volume is slightly affected by changes in temperature.

A **gas**, at a given temperature, has neither a definite shape nor a definite volume. It will take up the shape of any container into which it is placed and will spread out evenly within it. Unlike solids and liquids, the volumes of gases are affected greatly by changes in temperature.

Liquids and gases, unlike solids, are compressible. This means that their volume can be reduced by the application of pressure. Gases are much more compressible than liquids.

▲ **Figure 1.2** Without expansion gaps between the rails, the track would buckle in hot weather

1.2 The kinetic particle theory of matter

The **kinetic particle theory** helps to explain the way that matter behaves. It is based on the idea that all matter is made up of tiny particles. This theory explains the physical properties of matter in terms of the movement of the particles from which it is made.

The main points of the theory are:

- All matter is made up of tiny, moving particles, invisible to your eye. Different substances have different types of particles (atoms, molecules or ions) of varying sizes.
- The particles move all the time. The higher the temperature, the faster they move on average.
- Heavier particles move more slowly than lighter ones at a given temperature.

The kinetic particle theory can be used as a scientific model to explain how the arrangement of particles relates to the properties of the three states of matter.

Explaining the states of matter

In a solid, the particles attract one another. There are attractive forces between the particles which hold them close together. The particles have little freedom of movement and can only vibrate about a fixed position. They are arranged in a regular manner, which explains why many solids form **crystals**.

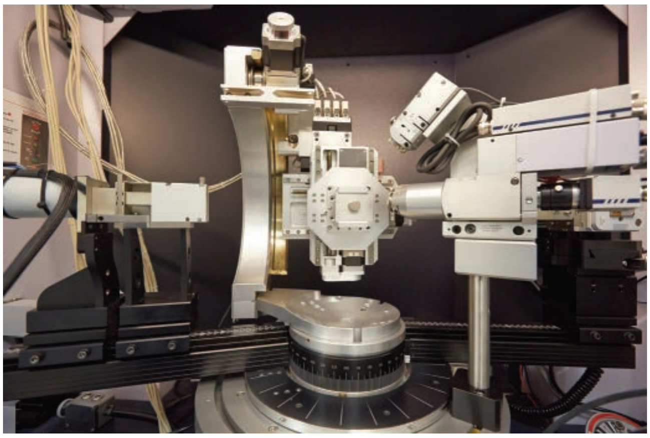
It is possible to model such crystals by using spheres to represent the particles. For example, Figure 1.3a shows spheres built up in a regular way to represent the structure of a chrome alum crystal. The shape is very similar to that of a part of an actual chrome alum crystal (Figure 1.3b).

a A model of a chrome alum crystal

b An actual chrome alum crystal

▲ **Figure 1.3**

Studies using X-ray crystallography (Figure 1.4) have confirmed how particles are arranged in crystal structures. When crystals of a pure substance form under a given set of conditions, the particles are always arranged (or packed) in the same way. However, the particles may be packed in different ways in crystals of different substances. For example, common salt (sodium chloride) has its particles arranged to give cubic crystals as shown in Figure 1.5.



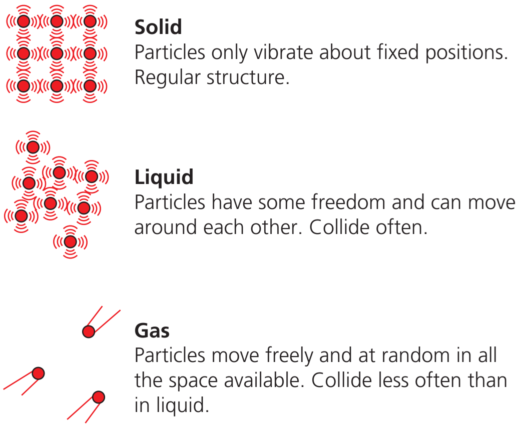
▲ **Figure 1.4** A modern X-ray crystallography instrument used for studying crystal structure

▲ **Figure 1.5** Sodium chloride crystals

In a liquid, the particles are still close together but they move around in a random way and often collide with one another. The forces of attraction between the particles in a liquid are weaker than those in a solid. Particles in the liquid form of a substance have more energy on average than the particles in the solid form of the same substance.

In a gas, the particles are relatively far apart. They are free to move anywhere within the container in which they are held. They move randomly at very high velocities, much more rapidly than those in a liquid. They collide with each other, but less often than in a liquid, and they also collide with the walls of the container. They exert virtually no forces of attraction on each other because they are relatively far apart. Such forces, however, are very significant. If they did not exist, we could not have solids or liquids (see Changes of state, p. 4).

The arrangement of particles in solids, liquids and gases is shown in Figure 1.6.



▲ **Figure 1.6** The arrangement of particles in solids, liquids and gases

Test yourself

1 When a metal (such as copper) is heated, it expands. Explain what happens to the metal particles as the solid metal expands.

1.3 Changes of state

The kinetic particle theory model can be used to explain how a substance changes from one state to another. If a solid is heated, the particles vibrate faster as they gain energy. This makes them 'push' their neighbouring particles further away. This causes an increase in the volume of the solid, such that the solid expands, and we can say that expansion has taken place.

Eventually, the heat energy causes the forces of attraction to weaken. The regular pattern of the structure breaks down, and the particles can now move around each other. The solid has melted. The temperature at which this takes place is called the **melting point** of the substance. The temperature of a melting pure solid will not rise until it has all melted. When the substance has become a liquid, there are still very significant forces of attraction between the particles, which is why the substance is a liquid and not a gas.

Solids which have high melting points have stronger forces of attraction between their particles than those which have low melting points. A list of some substances with their corresponding melting and boiling points is shown in Table 1.1.

▼ **Table 1.1** Melting points and boiling points of substances

Substance	Melting point/°C	Boiling point/°C
Aluminium	661	2467
Ethanol	–117	79
Magnesium oxide	827	3627
Mercury	–30	357
Methane	–182	–164
Oxygen	–218	–183
Sodium chloride	801	1413
Sulfur	113	445
Water	0	100

If a liquid is heated, the average energy of the particles increases and the particles will move around even faster. Some particles at the surface of the liquid have enough energy to overcome the forces of attraction between themselves and the other particles in the liquid and they escape to form a gas. The liquid begins to **evaporate** as a gas is formed.

Eventually, a temperature is reached at which the particles are trying to escape from the liquid so quickly that bubbles of gas actually start to form inside the liquid. This temperature is called the **boiling point** of the substance. At the boiling point, the pressure of the gas created above the liquid equals that of the air, which is **atmospheric pressure**.

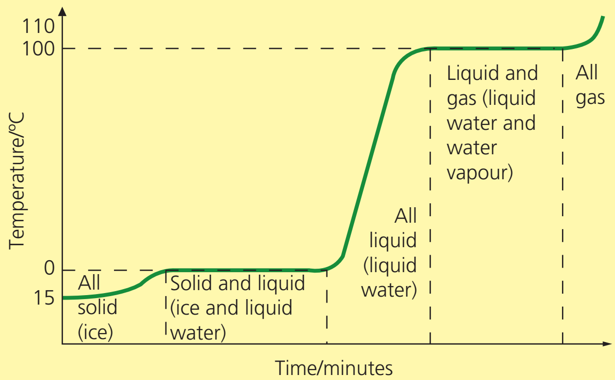
Liquids with high boiling points have stronger forces between their particles than liquids with low boiling points.

When a gas is cooled, the average energy of the particles decreases and the particles move closer together. The forces of attraction between the particles now become significant and cause the gas to **condense** into a liquid. When a liquid is cooled, it freezes to form a solid. Energy is released in each of these changes.

Changes of state are examples of physical changes. Whenever a physical change of state occurs, the temperature remains constant during the change. During a physical change, no new substance is formed.

Heating and cooling curves

The graph shown in Figure 1.7 was drawn by plotting the temperature of water as it was heated steadily from –15°C to 110°C. You can see from the curve that changes of state have taken place. When the temperature was first measured, only ice was present. After a short time, the curve flattens showing that even though heat energy is being put in, the temperature remains constant.



▲ **Figure 1.7** Graph of temperature against time for the change from ice at –15°C to water to steam

Practical skills

Changes of state

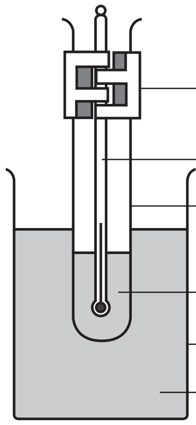
For safe experiments/demonstrations which are related to this chapter, please refer to the *Cambridge IGCSE Chemistry Practical Skills Workbook*, which is also part of this series.

Safety

- Eye protection must be worn.
- Take care when handling and using hot water.

The apparatus on the right was set up to obtain a cooling curve for stearic acid. The stearic acid was placed into a boiling tube which was then placed in a beaker of water that was heated to 80°C, which is above the melting point of stearic acid.

The boiling tube was then removed from the beaker and the temperature of the stearic acid was recorded every minute for 12 minutes using the thermometer to stir the stearic acid while it was a liquid.



1 Why was it important to remove the boiling tube with the stearic acid from the water?
2 Why was the stearic acid stirred with the thermometer?
3 Why were temperature readings taken every minute for 12 minutes?

The following data was obtained from the experiment:

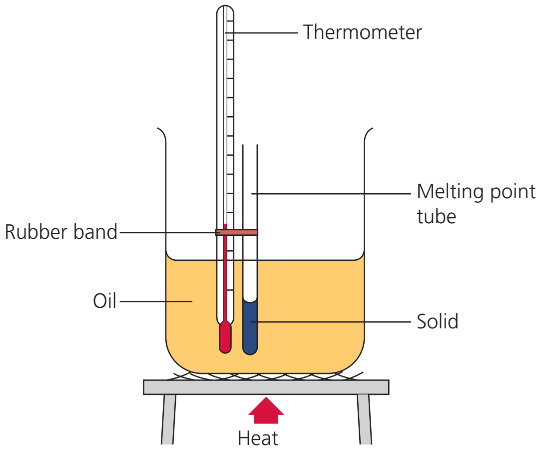
Time/mins	0	1	2	3	4	5	6	7	8	9	10	11	12
Temperature/°C	79	76	73	70	69	69	69	69	69	67	64	62	60

4 Draw and label axes for plotting this data.
5 Plot the points and draw a line of best fit.
6 **a** At what temperature did the stearic acid begin to change state?
b How could you tell this from your graph?
c Explain what is happening at this temperature.

In ice, the particles of water are close together and are attracted to one another. For ice to melt, the particles must obtain sufficient energy to overcome the forces of attraction between the water particles, so that relative movement can take place. The heat energy is being used to overcome these forces.

The temperature will begin to rise again only after all the ice has melted. Generally, the heating curve for a pure solid always stops rising at its melting point and gives rise to a sharp melting point. A sharp melting point therefore indicates that it is a pure sample. The addition or presence of impurities lowers the melting point.

You can find the melting point of a substance using the apparatus shown in Figure 1.8. The addition or presence of impurities lowers the melting point. A mixture of substances also has a lower melting point than a pure substance, and the melting point will be over a range of temperatures and not sharp.



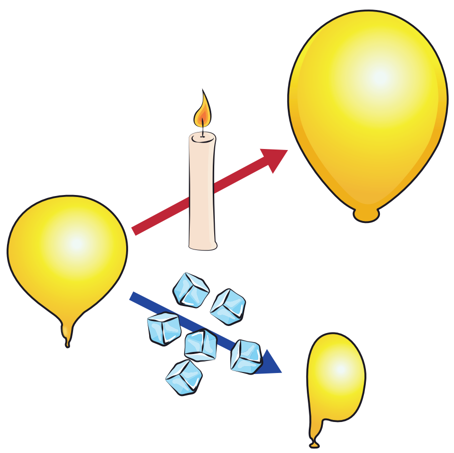
▲ **Figure 1.8** If a substance, such as the solid in the melting point tube, is heated slowly, this apparatus can be used to find the melting point of the substance

In the same way, if you want to boil a liquid, such as water, you have to give it some extra energy. This can be seen on the graph in Figure 1.7, where the curve levels out at 100°C – the boiling point of water.

Solids and liquids can be identified from their characteristic melting and boiling points.

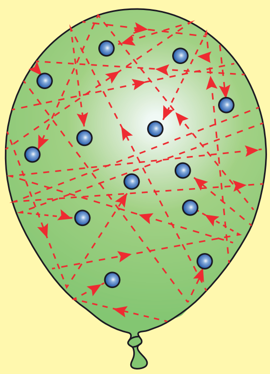
The reverse processes of condensing and freezing occur when a substance is cooled. Energy is given out when the gas condenses to the liquid and the liquid freezes to give the solid.

1.4 The effects of temperature and pressure on the volume of a gas



▲ **Figure 1.9** Temperature changes the volume of the air in a balloon. Higher temperatures increase the volume of the balloon and cold temperatures reduce its volume.

What do you think has caused the difference between the balloons in Figure 1.9? The pressure inside a balloon is caused by the gas particles striking the inside surface of the balloon. At a higher temperature, there is an increased pressure inside the balloon (Figure 1.10). This is due to the gas particles having more energy and therefore moving around faster, which results in the particles striking the inside surface of the balloon more frequently, which leads to an increase in pressure.



▲ **Figure 1.10** The gas particles striking the surface create the pressure

Since the balloon is made from an elastic material, the increased pressure causes the balloon to stretch and the volume increases. An increase in volume of a gas with increased temperature is a property of all gases. French scientist J.A.C. Charles made an observation like this in 1781 and concluded that when the temperature of a gas increased, the volume also increased at a fixed pressure. We can extend this idea to suggest that changing the pressure of a fixed volume of a gas must have an effect on the temperature of the gas. If you have ever used a bicycle pump to blow up a bicycle tyre then you may have felt the pump get hotter the more you used it. As you use the pump you increase pressure on the air in the pump. Such an increase in pressure causes the gas molecules to move closer together so the molecules to collide more frequently and more frictional forces come into play, which causes the temperature to rise. In addition, as the molecules are forced closer to one another, intermolecular bonds form, again increasing the temperature of the gas. As the temperature of the gas increases, this also causes the molecules to move faster, causing even more collisions.

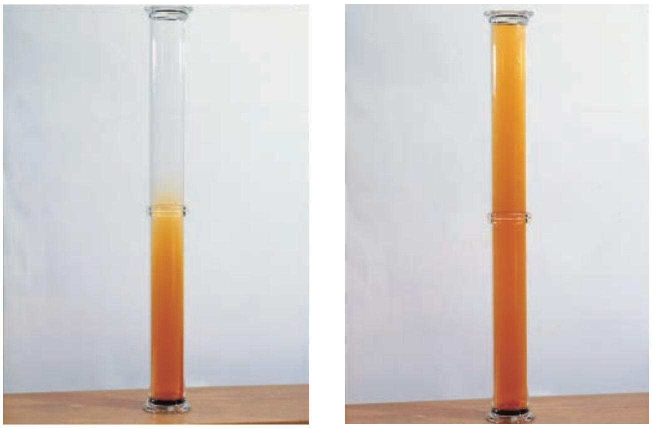
Test yourself

2 Why do gases expand more than solids for the same increase in temperature?
3 Ice on a car windscreen will disappear as you drive along, even without the heater on. Explain why this happens.
4 When salt is placed on ice, the ice melts. Explain why this happens.
5 Draw and label a graph of water at 100°C being allowed to cool to –5°C.

1.5 Diffusion

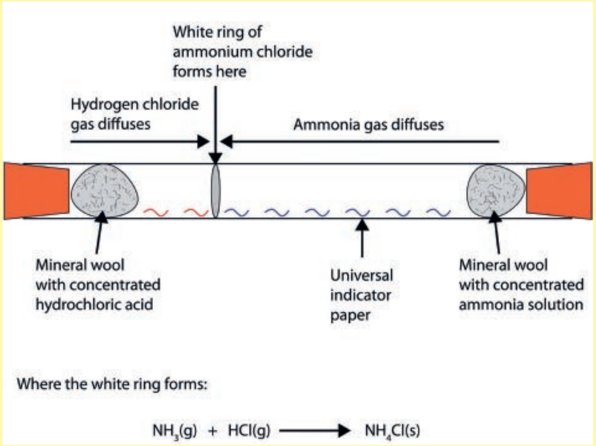
When you go through the door of a restaurant, you can often smell the food being cooked. For this to happen, gas particles must be leaving the pans the food is being cooked in and be spreading out through the air in the restaurant. This spreading out of a gas is called **diffusion** and it takes place in a haphazard and random way.

All gases diffuse to fill the space available. Figure 1.11 shows two gas jars on top of each other. Liquid bromine has been placed in the bottom gas jar (left photo) and then left for a day (right photo). The brown-red fumes are gaseous bromine that has spread evenly throughout both the gas jars from the liquid present in the lower gas jar.



▲ **Figure 1.11** After 24 hours the bromine fumes have diffused throughout both gas jars

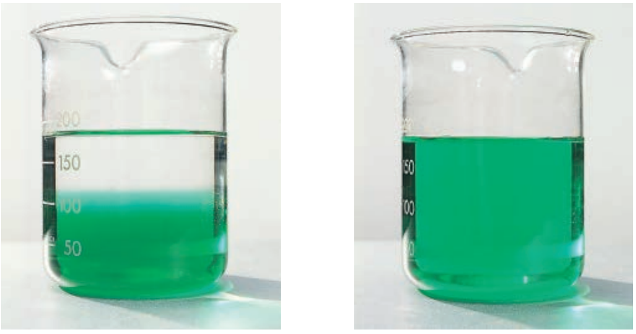
Diffusion can be explained by the **kinetic particle theory**. This theory states that all matter is made up of many small particles which are constantly moving. In a solid, as we have seen, the particles simply vibrate about a fixed point. However, in a gas, the particles move randomly past one another, colliding with each other.



▲ **Figure 1.12** Hydrochloric acid (left) and ammonia (right) diffuse at different rates

Gases diffuse at different rates. If one piece of cotton wool is soaked in concentrated ammonia solution and another is soaked in concentrated hydrochloric acid and these are put at opposite ends of a dry glass tube, then after a few minutes a white cloud of ammonium chloride appears. Figure 1.12 shows the position at which the two gases meet and react. The white cloud forms in the position shown because the ammonia particles are lighter; they have a smaller relative molecular mass (Chapter 4, p. 54) than the hydrogen chloride particles (released from the hydrochloric acid) and so move faster, such that the gas diffuses more quickly. (See *Chemistry Practical Skills Workbook* for more detail of this experiment.) This experiment is a teacher demonstration only, which must be carried out in a fume cupboard. If considering carrying out this practical, teachers should refer to the *Practical Skills Workbook* for full guidance and safety notes.

Diffusion also takes place in liquids (Figure 1.13) but it is a much slower process than in gases. This is because the particles of a liquid move much more slowly.



▲ **Figure 1.13** Diffusion of green food colouring can take days to reach the stage shown on the right

When diffusion takes place between a liquid and a gas, it is known as intimate mixing. Kinetic particle theory can be used to explain this process. It states that collisions are taking place randomly between particles in a liquid or a gas and that there is sufficient space between the particles of one substance for the particles of the other substance to move into.

Test yourself

6 When a jar of coffee is opened, people can often smell it from anywhere in the room. Use the kinetic particle theory to explain how this happens.

7 Describe, with the aid of diagrams, the diffusion of a drop of green food colouring added to the bottom of a beaker.

8 Explain why diffusion is faster in gases than in liquids.

9 Explain why a gas with a low relative molecular mass can diffuse faster than a gas with a high relative molecular mass at the same temperature.

Revision checklist

After studying Chapter 1 you should be able to:

- ✔ State the three states of matter and describe the structure arrangement of the particles in each.
- ✔ Explain the properties of the three states of matter using ideas about the separation and movement of particles.
- ✔ Name the changes of state and describe what happens to the particles in a substance when they occur.
- ✔ Explain what is happening when a substance changes state.
- ✔ Describe what happens to a given amount of gas when temperature and/or pressure decreases and increases.
- ✔ Use the kinetic particle theory to explain the effects of pressure and temperature on the volume of a gas.
- ✔ Describe the process of diffusion and explain why gases diffuse.
- ✔ Describe and explain the rate of diffusion of a gas in terms of its relative molecular mass.

Exam-style questions

1 **a** Sketch diagrams to show the arrangement of particles in:
- **i** solid oxygen [1]
- **ii** liquid oxygen [1]
- **iii** oxygen gas. [1]

b Describe how the particles move in these three states of matter. [3]

c Explain, using the kinetic particle theory, what happens to the particles in oxygen as it is cooled down. [3]

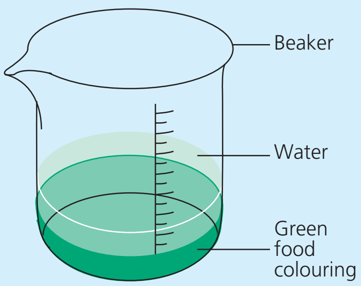
2 Explain the meaning of each of the following terms. In your answer include an example to help with your explanation.
- **a** expansion [2]
- **b** contraction [2]
- **c** physical change [2]
- **d** diffusion [2]
- **e** random motion [2]

3 **a** Explain why solids do not diffuse. [2]

b Give two examples of diffusion of gases and liquids found in your house. [2]

4 Explain the following, using the ideas you have learned about the kinetic particle theory:
- **a** When you take a block of butter out of the fridge, it is quite hard. However, after 15 minutes it is soft enough to spread. [2]
- **b** When you come home from school and open the door, you can smell food being cooked. [2]
- **c** A football is blown up until it is hard on a hot summer's day. In the evening the football feels softer. [2]
- **d** When a person wearing perfume enters a room, it takes several minutes for the smell to reach the back of the room. [2]

5 Some green food colouring was carefully added to the bottom of a beaker of water using a syringe. The beaker was then covered and left for several days.

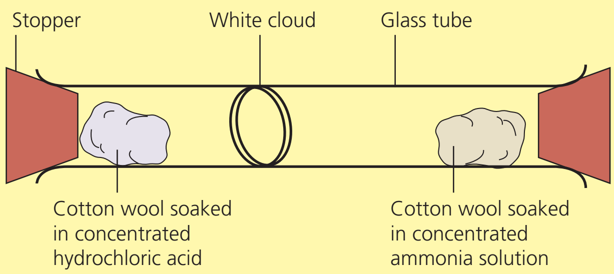


a Describe what you would observe after:
- **i** a few hours [1]
- **ii** several days. [1]

b Explain your answer to Question 5a using your ideas of the kinetic particle theory. [2]

c State the physical process that takes place in this experiment. [1]

6 The apparatus shown below was set up.



When this apparatus is used, the following things are observed. Explain why each of these is observed.
- **a** A white cloud is formed. [1]
- **b** It took a few minutes before the white cloud formed. [1]
- **c** The white cloud formed further from the cotton wool soaked in ammonia than that soaked in hydrochloric acid. [2]
- **d** Cooling the concentrated ammonia and hydrochloric acid before carrying out the experiment increased the time taken for the white cloud to form. [1]