11.1 States of Matter and the Kinetic Molecular Theory

Section Preview/ Specific Expectations

In this section, you will

- **explain** states of matter in terms of intermolecular forces and the motion of particles
- **perform** an ExpressLab to determine if gases occupy space
- **describe** a gas using the kinetic molecular theory
- **communicate** your understanding of the following terms and concepts: *condensation, kinetic molecular theory of gases, ideal gas*

Most of the universe is composed of plasma, a state of matter that exists at incredibly high temperatures (>5000˚C). Under normal conditions, matter on Earth can only exist in the other three physical states, namely, the solid, liquid, or gaseous states. As you learned in an earlier course, the particle theory describes matter in all states as being composed of tiny invisible particles, which can be atoms, ions, or molecules. In this section, you will learn how these particles behave in each state. You will also learn about the forces that cause their behaviour.

Solids and Liquids

In previous courses, you learned about the properties of the different states of matter. You may recall that both solids and liquids are incompressible. That is, the particles cannot squeeze closer together, or compress. The incompressible nature of solids and liquids is not due to the fact that particles are touching. On the contrary, the particle theory states that there is empty space between all particles of matter. The incompressibility of solids and liquids arises instead from the fact that these particles cannot move independently of each other. That is, the movement of one particle affects the movement of other particles, or is restricted by them.

This is especially true for solids. The particles of a solid are held together in a framework, called a crystal lattice. In a crystal lattice, the positions of solid particles are relatively fixed. This explains why solids have definite shapes: the particles are unable to slip past each other and thus change the shape of the solid.

Like solids, liquid particles cannot move independently of one another. They can slip past each other enough, however, to flow and change shape.

Another property of states of matter is their motion. According to the particle theory, all particles that make up matter are in constant motion. In solids, the range of motion of the particles is the most restricted. Each particle of a solid is only able to vibrate around a fixed point in the lattice (see Figure 11.2). This is called *vibrational motion*. Since solid particles are fixed in space, the degree of disorder is very low.

Figure 11.2 The arrangement of particles in a solid. Particles vibrate in a fixed position relative to one another. They are unable to move past each other.

Particles in the liquid state can move more freely than particles in the solid state, although not entirely independently. Liquid particles move with *rotational motion* as well as vibrational motion. This means that the particles can rotate and change position. It explains why liquids are able to flow and change shape, but keep the same volume. Since liquid particles move around more than solid particles, the liquid state has a higher degree of disorder, as shown in Figure 11.3.

To summarise the discussion, particles in solids and liquids are incompressible and thus have definite volumes. The particles in each state cannot move independently of each other. Therefore they are relatively restricted in their motion. How are the properties of gases different from those of solids and liquids?

The Gas State

Unlike solids and liquids, particles in the gaseous state are able to move independently of one another. Gas particles are able to move from one point in space to another. This is called *translational motion*. Thus, gas particles move with all three types of motion: vibrational, rotational, and translational. Gas particles move through space in random fashion. However, they do travel in straight lines until their course is altered by collisions with other particles. Because gas particles move freely, there is a high degree of disorder in a gaseous state.

Gas particles move much faster than liquid particles. Liquids always flow to the lowest point because they are still greatly influenced by gravity. Because gas particles move so quickly, gravity does not affect them as much. Gases flow in all directions, including upward against gravity, until all of the available empty space is occupied. This is why gases expand to fill a container. (See Figure 11.4.)

Gases can be compressed, unlike both solids and liquids. What is different about their particle arrangement that allows for this? The space between gas particles is much larger than the space between liquid or solid particles. Even if gas particles are moved closer together through compression, the distance between each particle is still very large. The particles remain in the gaseous state. When gas molecules are compressed further, eventually the forces between molecules become strong enough to hold the gas molecules together. At this point, the gas changes to the liquid state. This is known as **condensation**.

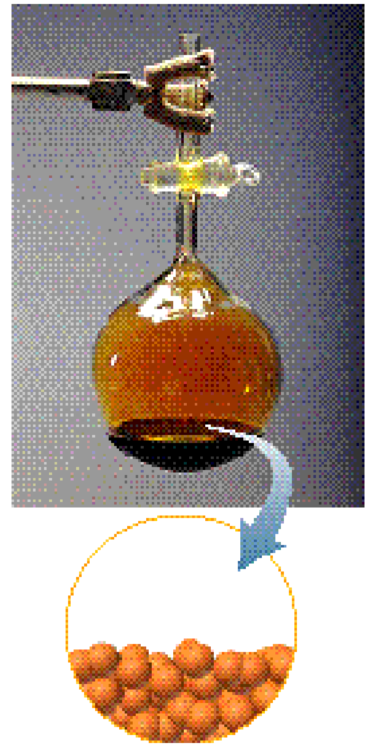


Figure 11.3 **Particles in liquids are not held in a fixed position relative to other particles. They can slide over and past one another.**

Forces Between Particles

You have examined some properties of solids, liquids, and gases. You have seen how the motion of the particles affects these properties. Now you will examine how the particles affect each other.

The particle theory states that there are attractive forces between particles. The weaker the attractive force is between particles, the freer the particles are to move. Therefore, attractive forces between particles are at their strongest in the solid state. Attractive forces are at their weakest in the gaseous state.

The strength of attractive forces between particles in any physical state depends on two major factors: type of force and temperature. The effect of temperature, or kinetic energy, on the state of a substance will be covered in greater detail later on in this section.

Attractions Between Charged Particles

What types of attractive forces exist between particles? In Chapter 3, you learned that oppositely charged particles attract each other due to *electrostatic attraction*. Ionic bonding is one example of electrostatic attraction. A positive ion (an atom or molecule that has lost electrons) is attracted to a negative ion (an atom or molecule that has gained electrons). Ions form very strong *ionic bonds*. Since these attractive forces are so strong, ionic compounds usually exist in nature as solids. For example, table salt (sodium chloride, NaCl) is a solid crystalline substance. It has a high melting point and a high boiling point.

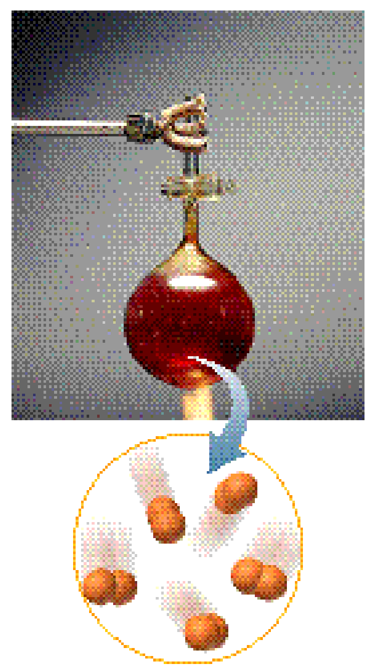


Figure 11.4 **Gas particles move freely in all directions, bouncing off each other as well as off the walls of their container.**

CHECKPOINT

What is a dipole? Go back to Chapter 3 or Chapter 8 to refresh your memory.

Attractions Between Polar Molecules

Not all particles are charged, but attractions can still form between them. You learned about *intermolecular forces* in Chapter 3. Intermolecular forces are forces that exist between neutral molecules, or between molecules and ions.

You know that some molecules are polar due to their asymmetrical shapes. Sulfur dioxide (SO_2) is one example of a polar molecule. These molecules have a permanent dipole effect. This means that one end of the molecule is more positive, and the other end is more negative.

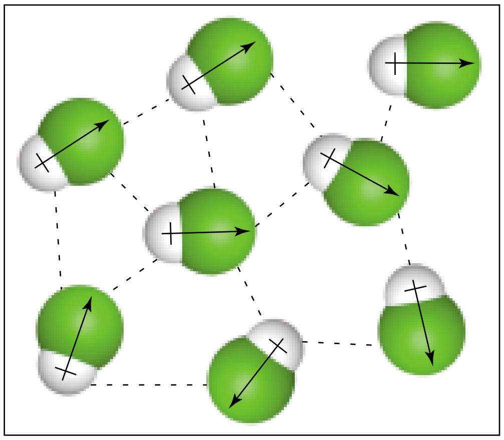


Figure 11.5 **Dipole–dipole interactions between polar HCl molecules**

Polar molecules attract ions and other polar molecules. The partially positive end of one molecule is attracted to the partially negative end of another molecule. This pattern continues throughout the substance. These *dipole–dipole* forces of attraction are not as strong as ionic bonds. Thus substances made up of polar molecules can exist as liquids and gases. For example, ethanol (CH_3CH_2OH) is polar, and exists as a liquid. You know this liquid as rubbing alcohol. Hydrogen chloride (HCl) is also polar. It is a gas under normal conditions as shown in Figure 11.5.

Attractions Between Non-Polar Molecules

What about substances made of non-polar molecules? You learned in Chapter 3 that *weak dispersion forces* form between non-polar molecules. As temporary dipoles form, they cause molecules to move closer together. However, these attractions are temporary and weak. Thus, most small non-polar molecules do not hold together long enough to maintain their solid or liquid forms. As a result, most small non-polar molecules exist as gases at room temperature. For example, carbon dioxide (CO_2) is a gas at normal temperatures.

CHECKPOINT

Hydrogen bonding is a very strong type of dipole-dipole interaction. Go back to Chapter 8 to review how this type of intermolecular force works.

The Relationship Between Size and State

Dispersion forces are also the primary forces of attraction between large non-polar molecules. However, as these molecules increase in size, their melting and boiling points rise. For example, methane (CH_4) is a small non-polar molecule. It has a very low boiling point and exists as a gas at room temperature. Pentane (C_5H_{12}) is a larger non-polar molecule. It has a higher boiling point, so it exists as a liquid at room temperature. Pentane has more sites along its length than methane does where temporary dipoles can form. The dispersion forces add up, so that it takes more energy overall to separate the molecules. This leads to a higher boiling point.

Electronic Learning Partner

If you are having difficulty visualizing molecules in the different states of matter, go to the Chemistry 11 Electronic Learning Partner.

To summarize, the state of a substance depends on the forces between the particles of that substance. If the forces are very strong, that substance is likely to exist as a solid. If the forces are weaker, that substance will exist as a liquid, or as a gas. The state of a non-polar substance also depends on the size of the molecule. Smaller non-polar molecules are more likely to be gases. Larger non-polar molecules will probably exist as liquids or even solids. Table 11.1 shows the forces discussed in this section ranked in order of strength.

Table 11.1 Attractive Forces

strong forces ← weak forces

Force	Ionic	Polar (dipole–dipole)	Dispersion
Type of force	between ions (intramolecular)	between molecules (intermolecular)	between molecules (intermolecular)
State	usually solid	liquid or gas (can also be solid)	liquid or gas
Example	$NaCl_{(s)}$	$CH_3CH_2OH_{(\ell)}$, $HCl_{(g)}$	$C_5H_{12(\ell)}$, $CH_{4(g)}$, $CO_{2(g)}$

The Effect of Kinetic Energy on the State of a Substance

There is one more factor that affects the state of a substance: temperature, which is related to kinetic energy. A hotter substance with high kinetic energy is more likely to overcome attractive forces between molecules, and exist as a gas. A cooler substance with low kinetic energy is more likely to be a solid or a liquid. This explains why heating a substance causes a change in state. When a solid is heated, it gains kinetic energy. Eventually it will melt, and become a liquid. When you add kinetic energy by heating a liquid, it will boil and become a gas. Earlier in this section, you learned that gases move much more quickly than liquids or solids. This is because gases have high kinetic energy.

CHECKPOINT

What kind of molecular forces would you expect for KI, SCl_6, and SiO_2? Use diagrams to explain your answer. Compare their melting and boiling points.

Kinetic Molecular Theory of Gases

The particle theory of matter does not discuss the kinetic energy of particles. Kinetic energy is important, however, when describing the unique properties of gases.

The **kinetic molecular theory of gases** makes the following assumptions:

- The volume of an individual gas molecule is negligible compared to the volume of the container holding the gas. This means that individual gas molecules, with virtually no volume of their own, are extremely far apart and most of the container is “empty” space.
- There are neither attractive nor repulsive forces between gas molecules,
- Gas molecules have high translational energy. They move randomly in all directions, in straight lines. (See Figure 11.6, on page 423.)
- When gas molecules collide with each other or with a container wall, the collisions are perfectly elastic. This means that when gas molecules collide, somewhat like billiard balls, there is no loss of kinetic energy.
- The average kinetic energy of gas molecules is directly related to the temperature. The greater the temperature, the greater the average motion of the molecules and the greater their average kinetic energy.

The kinetic molecular theory describes a hypothetical gas called an **ideal gas**. In an ideal gas, the gas particles take up hardly any space. Also, the particles of an ideal gas do not attract each other.

ExpressLab Do Gases Take Up Space?

Not everything can be seen with the unaided eye. Looking at a solid or a liquid, it is easy to see that they have mass and volume. Most gases are colourless. How can we "see" the volume of a gas?

Materials

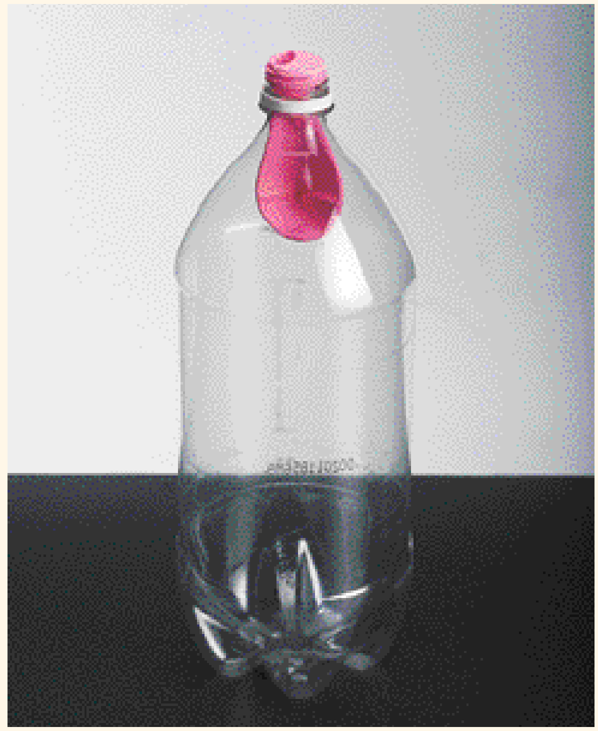
1 L or 2 L clean plastic soft drink or juice bottle
round balloon
pointed scissors

Safety Precautions

Be careful with the sharp point of the scissors when piercing the plastic bottle.

Procedure

1. Insert the balloon into the bottle, holding the open end. Stretch the open end of the balloon over the lip of the bottle.
2. Step 3 will ask you to inflate the balloon as large as you can. Before you do Step 3, predict how much you will be able to inflate the balloon. Record your prediction in your notebook.
3. Inflate the balloon inside the bottle. How large did it get? Record your observations in your notebook.
4. Using the sharp end of a pair of scissors, puncture a hole in the middle of the bottom of the plastic bottle. Inflate the balloon again. Record your observations in your notebook.



Analysis

1. Was your prediction in Step 2 verified in Step 3? If you had problems inflating the balloon in Step 3, explain why.
2. Was there a difference in how much you were able to inflate the balloon after you punctured a hole in the bottle? If there was, explain why.
3. From your observations in this activity, do gases take up space? Explain your answer.

Why Use the Kinetic Molecular Theory?

How and why did scientists formulate the kinetic molecular theory? Experiments into gas behaviour demonstrate that, under normal temperatures and pressures, nearly all gases behave in similar and predictable ways. The properties and behaviours of real gases can be generalized into a theory of an ideal gas. This generalization makes it possible for us to calculate mathematically, with a high degree of accuracy, how real gases will behave under varying conditions.

Of course, no gas is really "ideal." The ideal gas theory ignores certain facts about real gases. For example, an ideal gas particle does not take up any space. In fact, you know that all particles of matter must take up space. Gas particles are small and far apart, however. Thus the space occupied by the particles is insignificant compared to the total volume of the container. You will learn more about the behaviour of real gases in Chapter 12.

Figure 11.6 **This diagram shows the possible path of one gas molecule inside a volleyball. In a sample of gas, there are countless molecules moving in straight lines. They rebound off each other and the inner wall of the volleyball.**

Section Wrap-up

The molecular-level interpretation of gas behaviour given by the kinetic molecular theory helps to explain the macroscopic, or "larger picture," properties of gases in the real world. One of the most important properties of gases is their compressibility—how they react to the application of an external force. In the next section, you will observe how gases behave under pressure. Later in this chapter, you will learn about some interesting applications of pressurized gases.

CHEM FACT

Oxygen molecules in the atmosphere, at room temperature, travel at an average speed of 443 m/s. This is approximately 1600 km/h!

Section Review

1. K/U Using the kinetic molecular theory of matter, explain each of the following observations.
   - **(a)** Gases are more compressible than liquids.
   - **(b)** The density of gases is less than that of solids.
2. K/U In your own words, describe the characteristics of an ideal gas.
3. MC Using your knowledge of intermolecular forces, predict the state of each substance at room temperature. Explain your answer.
   - **(a)** hexane (C_6H_{14})
   - **(b)** hydrogen fluoride (HF)
   - **(c)** potassium chloride (KCl)
4. I Explain each of the following observations.
   - **(a)** Metals expand when heated, yet contract in cold weather.
   - **(b)** Gases have no fixed volume.
   - **(c)** A certain amount of moles of water occupies much more space as a gas than as a liquid.
5. C How does the degree of disorder of a gas compare to that of a liquid or a solid? Explain your answer.
6. K/U Describe the motion of a gas particle.
7. K/U What effect does heating have on the particles of a liquid?
8. **(a)** C Draw five boxes in your notebook. Inside them, illustrate the motion of gas particles according to the kinetic molecular theory.
   - **(b)** Draw another five boxes underneath the five boxes in (a). Illustrate how you think the molecules of a real gas might move in comparison.