CHEMISTRY

10

PECTAA

Transformation, Innovation & Excellence

PUNJAB EDUCATION, CURRICULUM, TRAINING & ASSESSMENT AUTHORITY

Ahsan Publishers
Lahore-Pakistan

This textbook is prepared in accordance with Updated / Revised National Curriculum of Pakistan-2023

Authors

Prof. Dr. Abid Zia
(PhD Organic Chemistry)
University of East Anglia Norwich, United Kingdom

External Review Committee Members

- Dr. Muhammad Monim-ul-Mehboob
  Professor of Chemistry, Govt. Graduate College of Science, Wahdat Road, Lahore
- Dr. Azmat Mehmood Asim
  Assistant Professor, Govt. Islamia Associate College, Lahore Cantt.
- Hafiza Samreen Kousar
  Assistant Education Officer(AEO), Lahore
- Ms. Samina Gull
  Assistant Director Curriculum Science, PECTAA

Apex Review Committee Members

- Dr. Iftikhar Hussain
  Associate Prof. (Chem.) Govt. Graduate College of Science, Wahdat Road, Lahore
- Dr. Tariq Mahmood
  Assistant Prof. (Chem.) Govt. Graduate College of Science, Wahdat Road, Lahore
- Dr. Rubina Munir
  Assistant Prof. (Chem.) Kinnaird College for Women, Lahore

Director Curriculum & Compliance
Mr. Aamir Riaz

Dy. Director (Compliance-Sciences)
Syed Saghir-ul-Hassnain Tirmizi

Incharge Artcell
Ms. Aisha Sadiq

Coordinator
Ms. Samina Gull
AD (C-Sc)

Design & Layout
Mr. Aleem Ur Rehman

Prepared by: Ahsan Publishers, Lahore

Experimental Edition

Contents

Chapter 14

States of Matter and Phase Changes

Student Learning Outcomes

After studying this chapter, students will be able to:

- Explain changes of state and internal energy with change in temperature (melting, boiling, freezing, condensation, sublimation and deposition) in terms of kinetic particle theory.
- Distinguish between evaporation and boiling.
- Interpret heating and cooling curves in terms of kinetic theory
- Interpret in terms of kinetic particle theory the effects of changing pressure, temperature and volume of a gas on the other two with regards to Boyle's law, Charles' Law, and Avogadro's Law.
- Explain qualitatively the effect of external pressure on rate of boiling and evaporation
- Explain diffusion of gases in terms of kinetic particle theory.
- Examine qualitatively the effect of molecular mass and temperature on the rate of diffusion
- Discuss applications of sublimation around us.
- {Examples may include: solid air fresheners and 3D printing}
- Explain, with the help of kinetic particle theory, the importance of rates of diffusion of medicines in the body

Matter in this world exists in four physical states namely gas, liquid, solid and plasma. Out of these four states the properties of gases were studied first. It was suggested that physical properties of gases such as their ability to compress or expand, or diffuse could be understood by assuming that these gases consist of particles which are continuously moving randomly. This idea then led to formulation of kinetic particle theory for gases.

Kinetic particle theory not only explains all the laws which govern the behaviour of gases, it also explains the composition of liquid and solid states of matter and the interconversion of all the three states. This is natural because all the three physical states are distinct in their physical properties only while their chemical nature remains the same. For example, water in all its three physical states remains chemically the same compound.

According to kinetic particle theory gases are composed of particles which are in a continuous state of random motion in all the possible directions. The pressure exerted by a gas is due to the collisions of its particles with the walls of the container. Since the pressure of a gas in a container does not change with time at constant temperature, it is assumed that the collisions between its particles do not involve any loss or gain of energy due to friction. The attractive forces between the particles of a gas are assumed as negligible since the particles are widely apart at low pressure. The average kinetic energy of the particles is directly proportional to the temperature measured on kelvin scale. The average kinetic energy is the same for all gases at the same temperature.

According to kinetic theory, the particles in a liquid are quite close to one another. They are also moving in all possible directions. As a result the particles of a liquid do not have any fixed position and shape. Owing to the presence of inter-particle forces, however, a liquid has a fixed volume and it keeps its level as well. In a liquid, the particles show all the three types of movements.

Solid substances may consist of ions, atoms and molecules. According to kinetic particle theory the inter-particle forces in the solid substances are so strong that they keep their particles arranged in a fixed position.

THINGS TO KNOW

Molecules present in a gas and a liquid show all the three types of movements simultaneously namely, translational, rotational and vibrational.

These particles possess vibrational motion only. These restricted movements force solid substances to have a fixed shape and a fixed volume.

14.1 Internal Energy

The internal energy of a substance is the total energy it contains. It includes the kinetic energy of its particles and the potential energy due to bonding between them. Heat increases the internal energy of a system.

14.1 Quick Check!
1. What is translational motion?
2. Is the average kinetic energy possessed by the particles of a gas and a liquid, same at the same temperature?

14.2 Interconversion of Physical States

Conversion of a Solid into a Liquid (Melting)

The physical state of a solid substance can be changed by simple heating. Heat increases the kinetic energy of the particles and they start vibrating at a higher frequency. At a particular temperature their vibrational motion becomes so fast that it overcomes the cohesive forces. As a result the solid starts melting and this temperature is called the **melting point** of the solid. At the melting point, the particles of a solid not only lose their mean positions but the arrangement as well. The solid collapses and turns to a liquid (Figure 14.1).

Heating a solid below its melting point increases its kinetic energy and temperature that weakens the force of attraction between its particles. Further heating the solid after it has started melting does not increase its temperature. Instead, all the heat energy provided at this moment is utilized to convert the solid into its liquid.


Figure 14.1: Melting of ice

Conversion of a Liquid into a Gas (Boiling)

The molecules of a liquid keep on coming out from the surface of a liquid at all temperatures and such an escape of molecules from surface is called **Evaporation**. Heating a liquid increases the kinetic energy of its molecules and so does the process of evaporation. Heating the liquid further, increases the kinetic energy so much that the inter-particle forces are weakened to a large extent. At this point the bubbles start coming out of the liquid at a rapid pace. At this stage if the vapour pressure of the liquid becomes equal to the external pressure, the liquid starts boiling. The temperature of a liquid at which its vapour pressure becomes equal to the atmospheric or external pressure is called its **boiling point**.

At the boiling point, the heat provided to the liquid is used to convert it into gaseous form and during this its temperature remains constant. In other words, the heat provided is used only to break the forces of attraction between its particles.

Conversion of a Gas into its Liquid (Condensation)

When a gas is cooled, the kinetic energy of its molecules decreases, as a result the molecules come closer with a significant force of attraction between them. At a suitable lower temperature the increased attractions bring the molecules so close that they are changed into a liquid form. This is called **condensation**. During this transition the temperature of the gas remains constant until all the gas is changed into its liquid.

14.3 Heating and Cooling Curves

Interconversion of physical states can also be understood with the help of a graph drawn between the internal energy and the temperature of a system. Such a graph is also called a heating or cooling curve. Figure 14.2 shows such a curve when a substance is heated or cooled.

When a solid substance at a point A is heated, its temperature increases. On attaining a specific temperature, it melts as shown by the point B in the Figure 14.2. This point represents the melting point of the given solid. Further heating does not increase the temperature because the heat provided here is being utilized to melt all the solid substance as represented by the line B to C. When all the solid converts into the liquid the temperature starts rising again as shown in the graph for the points

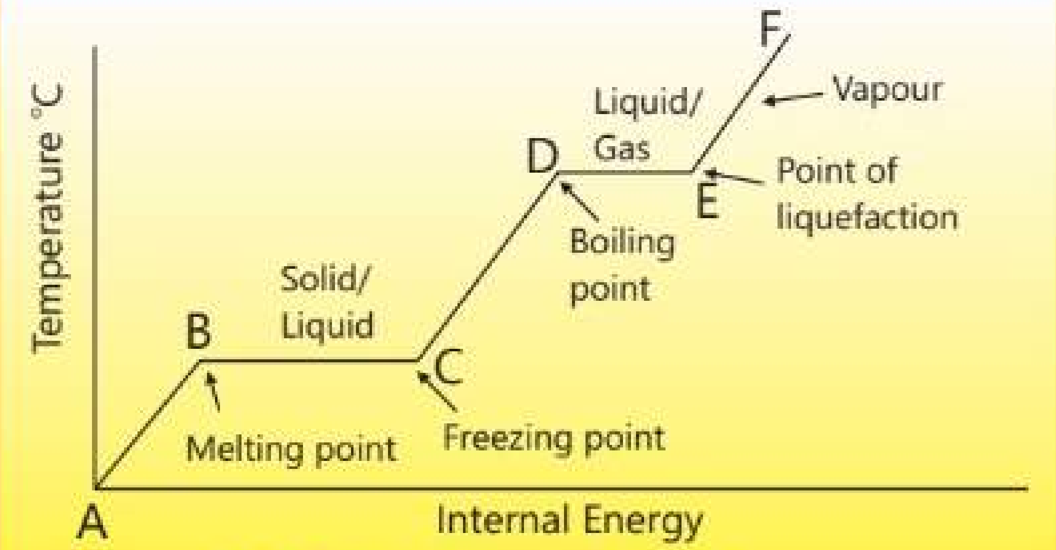

Figure 14.2: Heating and cooling curves

C to D. At the temperature corresponding to point D the liquid starts boiling. This represents the boiling point of the liquid. Again, further heating does not increase the temperature till the whole liquid is converted into gas. A line D to E in the figure shows no further rise in the temperature. The temperature again starts rising after the point E. This curve represented by the steps from A to F is called a heating curve.

Interesting Information

Phase change materials are used in thermal regulation, such as in clothing or building insulation, to store and release thermal energy.

The same graph in the Figure 14.2 can be studied in the reverse direction from the point F to A. It is called a cooling curve. When the gas present at the point F is cooled its temperature starts decreasing. At the point E it starts converting into a liquid. This is called the condensation point or liquefaction point and it represents the same temperature as the boiling point. The temperature will however remain constant during this process of condensation or liquefaction. Further cooling will convert the liquid into solid at the point C which is called the freezing point and it represents the same temperature as the melting point. The line C to B shows that the process of cooling is converting all the liquid into solid state at constant temperature.

For water, a heating curve will show the rise of temperature of ice until it reaches 0 °C (melting point), then it remains constant while the ice melts into liquid water. Further heating will increase the temperature again until it reaches 100 °C (boiling point). At this point it remains constant while the liquid water is converted into steam. A cooling

14.2 Quick Check!

1. Why do water vapour at 100 °C cause more severe burns as compared to liquid water at the same temperature?
2. Why do we feel comfortable wearing cotton clothes in summer?

Did you know?

Interconversion of physical states of matter may not be brought about by changing the temperature only. Sometimes their interconversion may be affected more conveniently by changing both the temperature and pressure at the same time or by varying the pressure only at constant temperature. For example, ice melts from pressure in the hands of a snowball maker. Ammonia gas can be liquefied at atmospheric pressure and at a temperature of -34° C. Alternatively, it can also be liquified by exerting a pressure 1MPa and at room temperature (25° C).

curve for water will show the temperature of the steam decreasing until it reaches 100 °C, it then remains constant while the steam condenses into liquid water. The temperature decreases again until it reaches 0 °C. Finally it remains constant while the liquid water changes to ice. Lines B to C and D to E show that here the given energy is being utilized to change the phase from solid to liquid and from liquid to gas respectively.

14.4 Evaporation and Boiling

When water is taken in an open container at normal external pressure, vapours start coming out of its surface silently and steadily. It is shown by the decrease in the level of water surface in the open container. It is called evaporation and it is known to occur at all temperatures.

Increasing the temperature of water increases the rate of evaporation because the number of water molecules escaping the surface also increases. The temperature will keep on increasing until a stage will come at which the water molecules acquire the maximum value of kinetic energy while in a liquid state. The heat which is provided at this stage will be utilized to change the liquid water into gaseous water while keeping the temperature of water constant. This stage is called boiling. The whole process is being carried out at constant atmospheric pressure.

Difference between Evaporation and Boiling

Evaporation	Boiling
1. It is a surface phenomenon. It occurs slowly and only at the surface of the liquid.	1. A phase change when a liquid turns into a gas throughout the entire liquid forming bubbles, at a definite external atmospheric pressure.
2. It occurs at all temperatures but below the boiling point. It increases with increase in temperature and vice versa.	2. It occurs at a specific temperature at normal pressure and called the boiling point.
3. It produces cooling.	3. It does not result in cooling.
4. It requires a smaller amount of energy which is provided from inside the liquid.	4. It requires an external energy source.

Effect of External Pressure on the Rates of Evaporation and Boiling

Rates of both evaporation and boiling are affected by the variation in the external pressure to which the liquid is subjected.

Rate of evaporation tends to increase by the decrease in external pressure and vice versa. If a liquid is in an open container, most of the molecules that escape into the vapour phase will not return to the liquid phase. Instead, they will diffuse through the atmosphere away from the container. Increasing the external pressure will force these molecules to return back to the liquid surface making evaporation difficult.

When a liquid boils, bubbles are formed inside the container, which then rise to the surface. At this stage, the temperature of the liquid remains constant till all the liquid boils over. This temperature is called the boiling point. If you measure the boiling point of water at Karachi it will be 100°C. However, if you will measure this boiling point at Murree it will be 98 °C. The atmospheric pressure at Murree is lower than that in Karachi, so we find that the boiling point has decreased at lower atmospheric pressure.

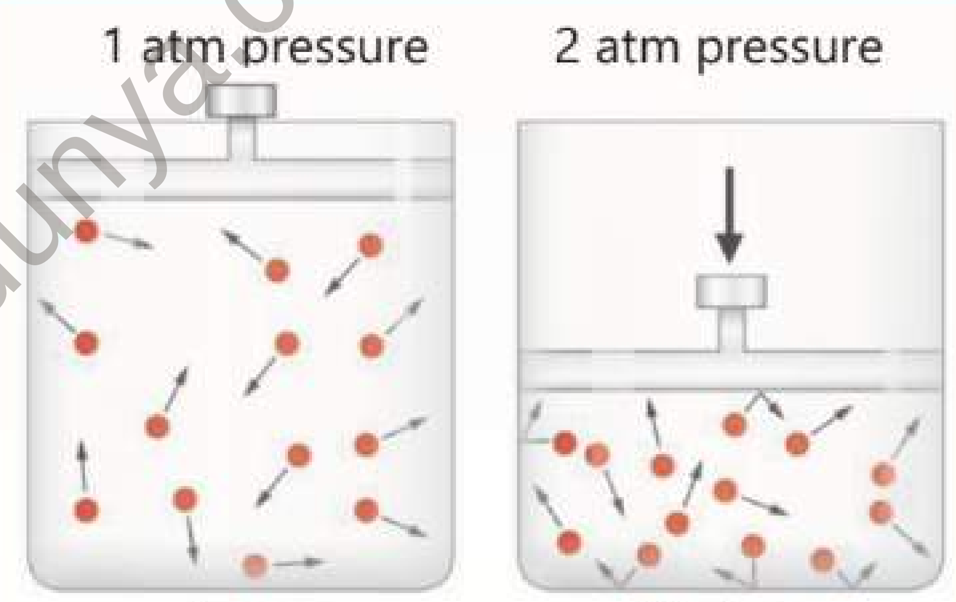

Figure 14.3

14.5 Sublimation

The direct conversion of a solid to vapours without melting is called sublimation. For example, solid carbon dioxide which is also called dry ice, changes directly to gaseous carbon dioxide at room temperature without first melting to liquid state. Another common example of sublimation is the disappearance of naphthalene balls which are used to keep the insects away from the woolen clothes. Just like evaporation, the energy needed for sublimation also comes from within the substance which then absorbs energy from the surrounding. This energy is sufficient to overcome the attractive forces of the neighbouring molecules which then escape into the vapour phase.

Deposition

The process reverse to sublimation is called deposition where a gas changes directly to a solid without going into the liquid state. Formation of frost in winter season is an example of deposition.

14.3 Quick Check!

1. Does the change in temperature occur during the process of evaporation?
2. Does ice sublime?
3. Give one example each for sublimation and deposition other than mentioned in the text.

14.6 Applications of Sublimation

(a) Solid air fresheners

The process of sublimation is used in the working of air fresheners. Solid air fresheners contain a scented substance which may evaporate with or without heating. The scented substance undergoes sublimation and disperse scented vapours throughout the room and mask unpleasant odours.

When a solid air freshener is exposed to the atmosphere or heated in the air, its solid particles gain enough energy to overcome the attractive forces holding them together in the solid state. These particles then spread in the nearby atmosphere in the form of sweet smelling vapours.

(b) Sublimation Printing

When the process of sublimation is used to print a design into a material or fabric, it is called sublimation printing. Essentially the process involves printing that transfers a design into a fabric using ink and heat.

In sublimation printing the first step is to print a design onto a special paper using sublimation inks. The printed paper is then placed onto a fabric and heat and pressure are applied. The inks used are converted into vapour. The printing is permanent which does not fade away with time because the ink is embedded in the fabric rather than simple attaching with the top of the fabric in a normal printing. The heat supplied during the process opens up the pores present in the fabric, the ink enters into these pores under applied pressure, cools down and returns to a solid form. The method is popular for print on demand t-shirts and it is also available on ceramic, wood and metal that have a special coating on to receive the inks which are sublimed.

14.7 Kinetic Theory and The Gas Laws

Pressure –Volume Relationship (Boyle's Law)

According to Kinetic Theory, the pressure exerted by the gas in a container is caused by the collisions of its molecules with the walls of the container. The pressure changes directly with the number of molecules colliding with the wall per unit of time. When the pressure on the given mass of a gas is increased at constant temperature it will decrease the distance between its molecules and the volume of gas will also decrease. If the volume of the gas will be reduced to one half of its original volume, it will double the number of molecules per unit of volume. Hence the number of collisions per unit of time on the same area of the surface will also be doubled. As a consequence of these collisions, the pressure of the gas will also be doubled. These observations form the basis of pressure-volume relationship first observed by an Irish chemist, Robert Boyle, and is called Boyle's law. The law states that the volume of a given mass of a gas is inversely proportional to its pressure at constant temperature.

Mathematically Boyle's law is written as:

$$V \propto \frac{1}{P}$$ (V is the volume of given mass of gas and P is its absolute pressure)

Activity 14.1 Experimental verification of Boyle's law

Robert Boyle proved this pressure-volume relationship by performing a simple experiment. He used a simple J shaped tube and sealed its shorter limb as shown in the Figure 14.4. He then poured a small amount of mercury through its open end until it just trapped the air in the sealed end. Since he used a small amount of mercury it did not squeeze the air inside the limb and it was now at atmospheric pressure (760 mm Hg). Boyle then added more mercury until the difference in the height of the two columns of mercury was close to 760mm. This mercury exerted the extra pressure on the entrapped

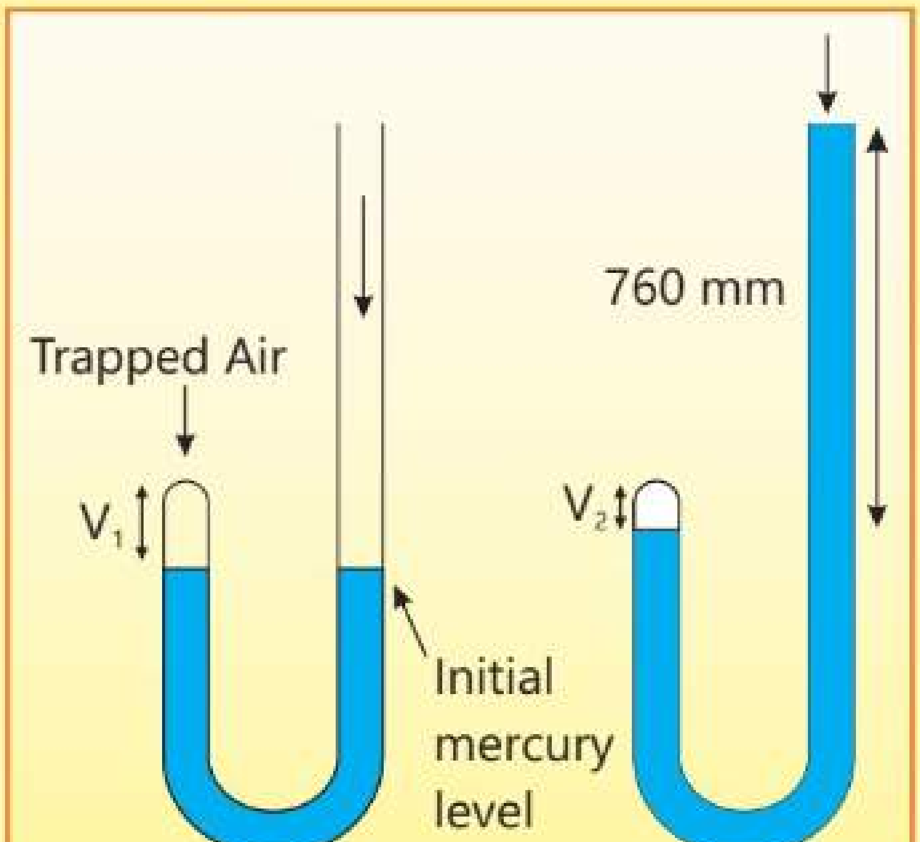

Figure 14.4: Verification of Boyle's law

air which was now about 2 atmosphere (2 x 760 mm). When he read the new volume of the entrapped air it was one half of the initial volume. During the experiment the mass of the gas remained fixed and the temperature also did not change. By doubling the pressure, Boyle had reduced the volume by one half.

Temperature – Volume Relationship – Charles' law

According to kinetic theory, if temperature of a gas increases, it increases the average speed and kinetic energy of its molecules. An increase in average speed results in more frequent and harder collisions with the walls of the container and hence its pressure increases. If the pressure of the gas is kept constant, the increase in the temperature must increase the volume of the gas. This may be visualized easily if a gas is taken in a cylinder to which a piston is attached. When the gas is heated the piston must move up to increase the volume if the pressure is to remain constant Figure 14.5.

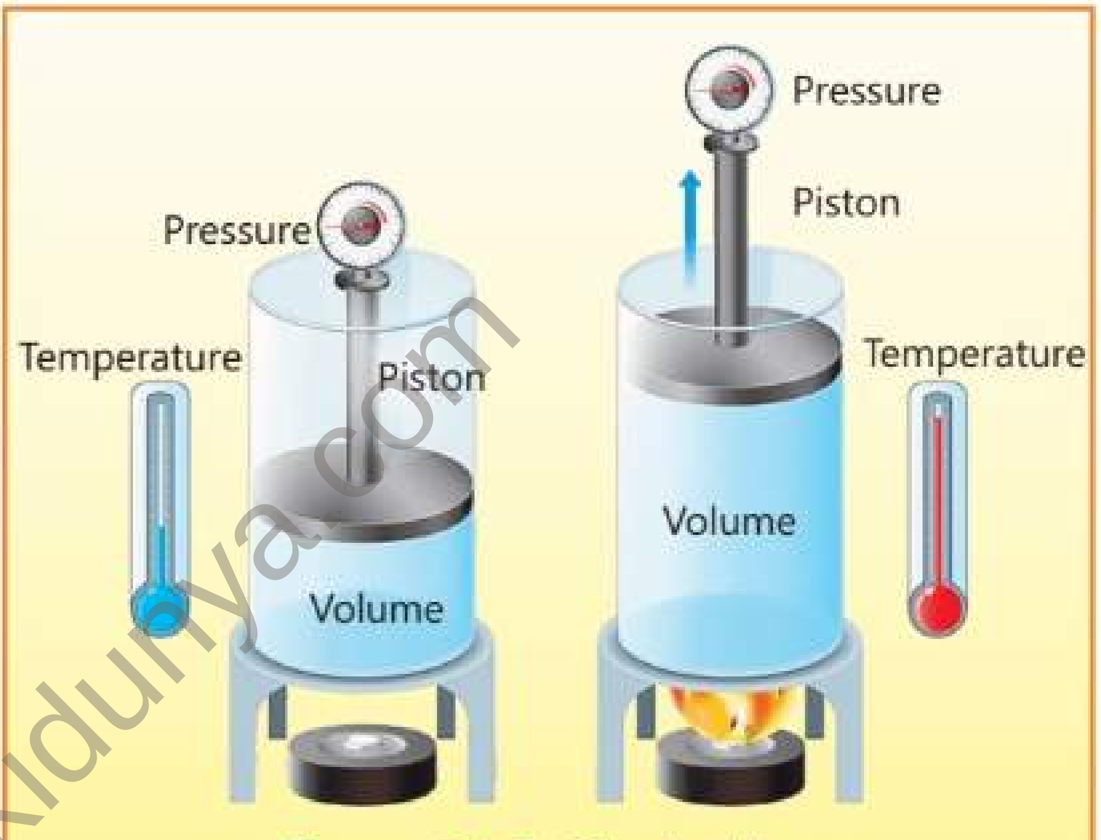

Figure 14.5: Charles' law

French scientist Jacques Alexander Charles summed up these observations in the form of a law which is called Charles' law. The law states that the volume of a given mass of a gas varies directly with temperature when pressure is kept constant. The temperature must, however, be measured on absolute or kelvin scale.

Mathematically, $V \propto T$ (P and mass of gas are kept constant)

Avogadro's Law

According to kinetic theory, the pressure exerted by a gas is due to the number of collisions of its particles per unit area. This, in turn, depends upon the number of particles and their speed.

If you have two containers containing the same amount of a gas at the same temperature and pressure, and you increases the amount of gas in one container. Naturally the pressure of the gas in this container will increase. To keep the pressure constant the volume of the gas must increase. This larger volume compensates for the increased number of particles, ensuring the pressure remains the same. Therefore, at constant temperature and pressure, a greater number of molecules simply requires a larger volume to maintain the same pressure.

These observations led Avogadro to formulate a law which states that equal volumes of different gases must contain an equal number of molecules if the temperature and pressure are kept constant.

Mathematically Avogadro's law is written as:

14.4 Quick Check!

With the help of kinetic particle theory explain:

(I) How does a gas exert pressure?

(ii) How does the volume of a gas change when its temperature is decreased? (Pressure and mass constant)

$$V \propto n \quad \text{(at constant temperature and pressure)}$$

14.7 Diffusion

Molecules present in gases are in a constant state of random motion. Due to this molecular motion the gas particles spread out and intermix from an area of high concentration to an area of low concentration. This property of gases is called diffusion. When a bottle of body perfume is opened in one corner of a room its sweet smell slowly spreads throughout the room after sometime due to the process of diffusion. Figure14.6. shows the diffusion of hydrogen gas from one container to another one. Diffusion is a spontaneous process during which gas particles spread out.

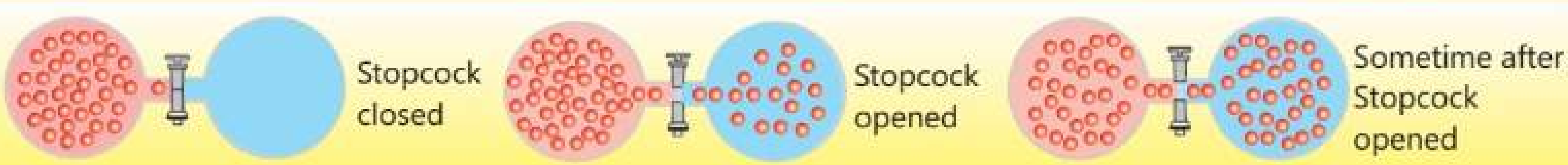

Figure14.6: Diffusion of gases

The difference in the rates of diffusion of gases can be explained with the help of kinetic particle theory of gases. According to the kinetic theory, molecules of all the gases possess same average kinetic energy at constant temperature. Since hydrogen is lighter than oxygen its molecules will move faster than oxygen at a given temperature. The rate at which hydrogen gas will diffuse is thus much faster than that of oxygen.

Rate of diffusion increases with the increase in temperature as the particles have more kinetic energy and hence they move faster. This eventually leads to rapid mixing and spreading.

Activity 14.2 Different gases diffuse at different rates

Two cotton plugs soaked in hydrogen chloride gas and ammonia solutions are introduced in the open ends of a 100 cm long glass tube simultaneously as shown in Figure 14.7. The two gases produce white dense fumes of ammonium chloride at the point at which they meet in the tube. HCl molecules travel a distance of 40.5 cm while ammonia molecules cover 59.5 cm in the same duration.

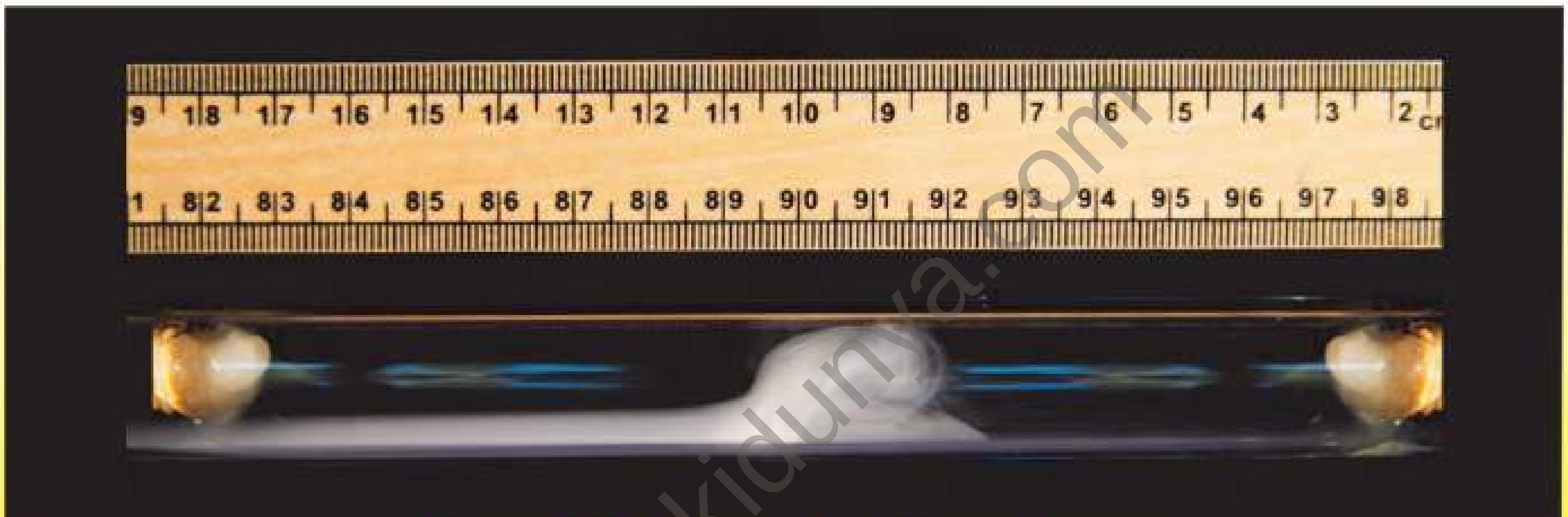

Figure 14.7: Rates of diffusion of gases

Thus ammonia diffuses faster than hydrogen chloride gas because it is lighter than hydrogen chloride gas.

14.5 Quick Check!

1. Which gas among the following will diffuse at the fastest speed and which will diffuse at the slowest speed under similar conditions of temperature and pressure?
   NO_2, SO_2, H_2S
2. Explain with the help of kinetic particle theory why does ammonia gas diffuse faster than hydrogen chloride gas?

14.8 Importance of Rates of diffusion of Medicines in Human Body

The tendency of the molecules contained in a medicine to move from a region of higher concentration to one of lower concentration in called diffusion.

The diffusion rates of medicines control how rapidly and effectively they can be absorbed, distributed and eliminated from the body.

When the medicines are taken orally, the rates of their diffusion between the stomach and intestine control how quickly they are absorbed in the blood. A faster diffusion rate means early absorption and hence a faster onset of action.

Once the drug molecules are absorbed by the blood, they start diffusing into various tissues and organs. The rate of diffusion here determines how quickly the drug becomes effective. For example, lipid-soluble drugs diffuse more easily through cell membranes, making them more effective in shorter time. Generally, a faster rate of diffusion leads to higher drug concentration at its target organ which means a more effective response.

In short, rates of diffusion play a crucial role in the delivery and movement of drugs throughout the body. This process of diffusion ensures that essential substances reach their target locations quickly which eventually helps in the treatment of diseases.

EXERCISE

A Multiple Choice Questions

Choose and tick the correct answer from the given choices.

1. According to kinetic theory, the basic difference between solid, liquid and gas is due to:
   (a) the difference in the movements of the particles.
   (b) the chemical properties of the particles.
   (c) the size of the particles.
   (d) the shape of the particles.
2. Upon heating the rate of evaporation:
   (a) decreases
   (b) increases
   (c) remains the same
   (d) initially decreases and then increases upon further heating
3. The inter-particle attractions are the strongest in:
   (a) Solids (b) Liquids
   (c) Plasma (d) Gas

4. Cooling the vapours of some gases change them directly into solid state. This phenomenon is called:
   (a) evaporation (b) condensation
   (c) sublimation (d) deposition
5. Physical state in which the particles possess the maximum energy:
   (a) Solid (b) Liquid
   (c) Gaseous (d) Vapour
6. How does the process of evaporation depend on the force of attraction present among the molecules of a liquid?
   (a) It decreases with the increasing strength of attraction.
   (b) It increases with the increasing strength of attraction.
   (c) It is independent of the strength of the force of attraction.
   (d) It first increases and then decreases with the increasing strength of the force of attraction.
7. Which gas will diffuse at the fastest rate?
   (a) HCl (b) SO_2
   (c) H_2S (d) CO_2
8. The phase changes A and B in gas $\xrightarrow{A}$ liquid $\xrightarrow{B}$ solid are:
   (a) Melting, evaporating (b) Condensation, melting
   (c) Condensation, freezing (d) Boiling, freezing
9. A student noticed frost falling on the ground at 6.30 am and disappearing by 8.30 am. Which phase change was responsible for changing the frost into water vapours?
   (a) Melting (b) Evaporation
   (c) Sublimation (d) Deposition

B Short Answer Questions

14.1 From where does the energy come when a liquid evaporates?
14.2 Is condensation an endothermic process?
14.3 Why naphthalene balls (used to repel insects) disappear after sometime?
14.4 Why does the temperature remain constant during a phase change?
14.5 Is it possible to compress a liquid like a gas?
14.6 Can you change the temperature at which water boils in an experiment in your lab?

14.7 In which season the wet clothes get dry after a relatively longer time?

14.8 When a solid is heated, what happens to its particles which are vibrating?

14.9 Do solids and liquids also diffuse just like gases?

14.10 Why dew is formed in the early hours of the morning?

C Constructed Response Questions

14.1 Differentiate between evaporation and boiling.

14.2 Describe how boiling is related to the external pressure?

14.3 Why the process of evaporation does not need the input of energy?

14.4 Why the heating and cooling curves for the phase changes adopt the same path?

14.5 Why ice melts when the pressure is exerted on it?

14.6 Why do phase changes occur?

D Descriptive Questions

14.1 Explain the difference in the rates of diffusion of two gases based on kinetic theory.

14.2 How does the process of sublimation helpful in printing and in the usage of air freshner?

14.3 Draw heating curve for the physical changes water undergoes with change in temperature.