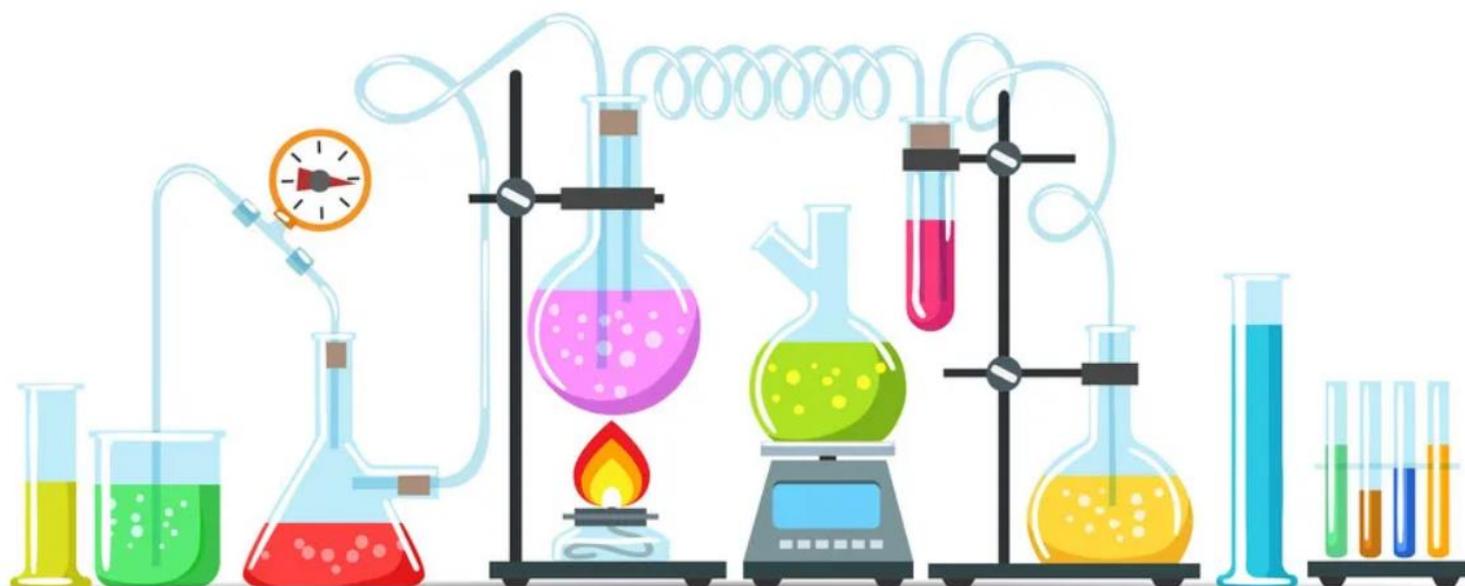


# CHEMISTRY

## CHAPTER 5: STATES OF MATTER



# STATES OF MATTER

## Introduction

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Gas is the state of matter in which molecules are always in random motion. Intermolecular interactions are extremely small (almost negligible) as compared to other states like solid and liquid. Gases are highly compressible state of matter and its state of diffusion is maximum. Gases have their own importance in living world. Air is a gaseous mixture of oxygen, nitrogen, CO<sub>2</sub>, Ar, etc.

## Intermolecular Forces

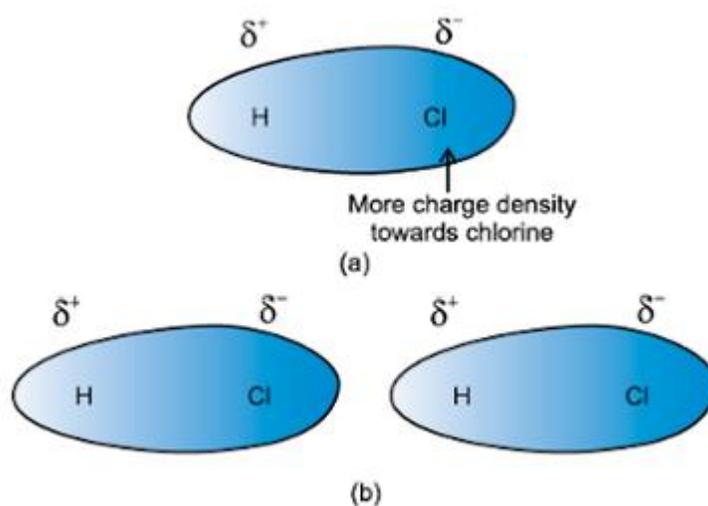
Intermolecular forces are the forces of attraction and repulsion between interacting particles. This term does not include the electrostatic forces that exist between the two oppositely charged ions.

## Van der Waal's Forces

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These are the weak forces of attraction between two molecules with or without any strong bond. These are electrostatic in nature. Types of van der Waal's forces are as follow:

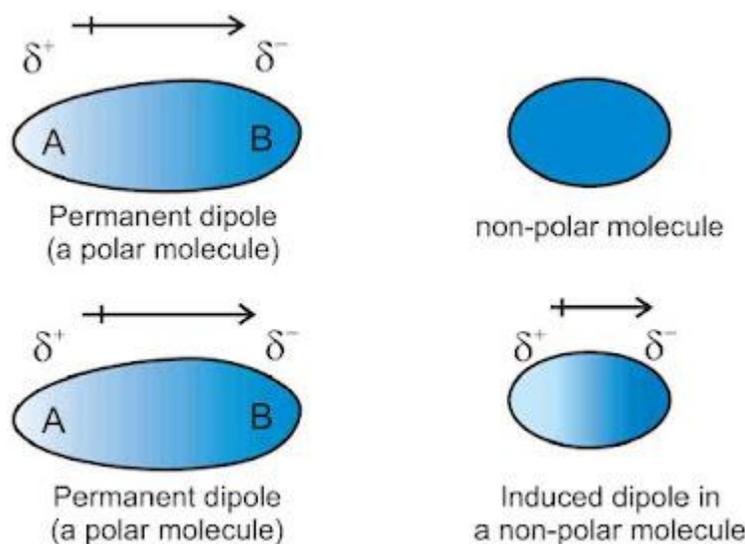
1. **Dipole-dipole interaction:** These forces exist between two molecules which are polar in nature. Opposite charges of two dipoles attract each other and produce interactions called keesom forces. In HCl, dipole-dipole interactions exist.



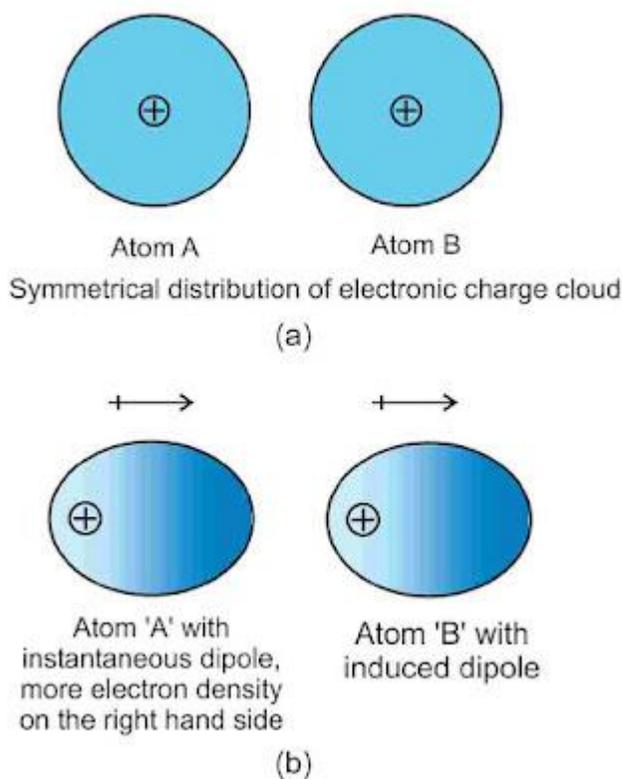
Dipole-dipole interaction energy is inversely proportional to the sixth power of the distance between the rotating polar molecules.

$$\text{interaction energy} \propto \frac{\pi}{r^6}$$

2. **Dipole-induced dipole interaction:** When a polar molecule comes closer to a non-polar molecule it induces weak polarity (dipole) in that molecule. Now, weak interactions develop between polar molecule and molecule in which polarity is induced. These interactions are known as Debye interactions.



3. **London dispersion forces:** This polar molecule produces polarity in other molecule. Weak interaction arises between instantaneous dipoles. These interactions are known as Dispersion forces or London forces.



## Measurable Properties of Gases

1. **Temperature:** Temperature is a relative measure, or indication of hotness or coldness. At absolute zero on Kelvin scale is equivalent to  $-273.15^{\circ}\text{C}$  on the Celsius scale. Both the Celsius and the Kelvin scales have units of equal magnitude that is one degree celsius equivalent to one kelvin.

$$\text{Thus } T(\text{K}) = T(^{\circ}\text{C}) + 273.15$$

2. **Pressure of a gas:** According to laws of motion, pressure is defined as force applied per unit area of surface. It is denoted by  $P$  and SI unit of it is pascal (Pa). It is a scalar quantity.

$$P = \frac{F}{A}$$

3. **Atmospheric Pressure:** The atmospheric pressure at a point is equal to the weight of a column of air of unit cross-sectional area extending from that point to the top of the atmosphere. Its value is  $1.013 \times 10^5$  Pa at sea level. Atmospheric pressure is measured using an instrument called barometer.

## Gaseous Laws

### Boyle's Law (Volume-Pressure Relation)

According to this, "The volume of a given mass of gas is inversely proportional to pressure at constant temperature." This law is given by Robert Boyle.

$$P \propto \frac{1}{V} \dots \dots \text{(at Constant } T \text{ and } n)$$

$$P = k \frac{1}{V}$$

where  $k$  is the proportionality constant.

If a fixed amount of gas at constant temperature  $T$  occupying volume  $V_1$  at pressure  $P_1$  undergoes expansion, so that volume becomes  $V_2$  and pressure becomes  $P_2$ , then according to Boyle's law:

$$P_1V_1 = P_2V_2 = \text{constant}$$

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

### Charle's Law (Volume-Temperature Relation)

According to this, "The volume of a given mass of gas is directly proportional to its absolute temperature at constant pressure." This law is given by Jacques Charles.

$$V \propto T \text{ ..... (at constant P)}$$

$$V = kT$$

where k is the proportionality constant.

If a fixed amount of gas at constant pressure P occupying volume  $V_1$  at temperature  $T_1$  undergoes expansion, so that volume becomes  $V_2$  and temperature becomes  $T_2$ , then according to Charle's Law:

$$\frac{V}{T} = \dots \dots \dots \text{constant}$$

$$\frac{V_2}{V_1} = \frac{T_2}{T_1}$$

### Gay Lussac's Law (Pressure-Temperature Relation)

It states that at constant volume, the pressure of a fixed mass of a gas is directly proportional to the Kelvin temperature. The law may be expressed mathematically as

$$P \propto T \text{ ..... (at constant V)}$$

$$P = kT$$

where k is the proportionality constant.

If a fixed amount of gas at constant volume V occupying pressure  $P_1$  at temperature  $T_1$  undergoes expansion, so that pressure becomes  $P_2$  and temperature becomes  $T_2$ , then according to Gay Lussac's Law:

$$\frac{P}{T} = \text{constant}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

### Avogadro's Law ((Volume - Amount Relationship)

According to this, "Equal volumes of all gases at same temperature and pressure contain equal numbers of molecules".

$$V \propto n$$

$$V = kn$$

where  $k$  is the proportionality constant.

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

## Ideal Gas Equation

On combining the Boyle's law, Charles law and Avogadro's law we get an equation known as ideal gas equation which correlate  $P$ ,  $V$ ,  $T$  of a gas.

$$V \propto \frac{1}{P} \text{ (according to Boyle's law at constant } T)$$

$$V \propto T \text{ (according to Charles's law at constant } P)$$

$$V \propto n \text{ (according to Avogadro's law at constant } P \text{ and } T)$$

$$V \propto \frac{nT}{P}$$

$$PV \propto nT$$

$$PV = nRT$$

Where  $R$  is proportionality constant known as universal gas constant.

### Numerical value of $R$ :

- $R = 0.0821 \text{ litre atm K}^{-1} \text{ mol}^{-1}$
- $R = 0.0831 \text{ litre bar K}^{-1} \text{ mol}^{-1}$
- $R = 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$
- $R = 1.987 \approx 2 \text{ cal K}^{-1} \text{ mol}^{-1}$
- $R = 8.314 \times 10^7 \text{ erg K}^{-1} \text{ mol}^{-1}$

If temperature, volume and pressure of a fixed amount of gas vary from  $T_1$ ,  $V_1$  and  $p_1$  to  $T_2$ ,  $V_2$  and  $p_2$  then we can write

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

This equation is also known as Combined gas law.

## Dalton's Law of Partial Pressure

Dalton's law of partial pressure states that "the total pressure exerted by a mixture of non reacting gases is equal to the sum of partial pressure of each gas present in the mixture".

$$\text{Total} = p_1 + p_2 + p_3 + \dots (\text{at constant } T, V)$$

## Kinetic Theory of Gases

The postulates of kinetic theory of gases are as follows:

1. The gaseous molecules are considered to be point masses.
2. The volume of a molecule is negligible as compared to total volume of the gas.
3. The molecules neither attract nor repel each other.
4. The collisions are perfectly elastic i.e. there is no loss of energy during the molecular collisions.
5. The average kinetic energy of molecules is directly proportional to the absolute temperature of the gas.
6. The effect of gravity on molecular motion is negligible.

## The Kinetic Gas Equation

where P = Pressure of the gas

$$PV = \frac{1}{3}mv^2$$

V = Volume of the gas

m = Mass of one molecule of a gas

n = number of molecules of gas

u = root mean square speed of the molecule

$m \times n = M$  = molecular weight of the gas.

$$PV = \frac{1}{3}Mu^2$$

## Graham's Law of Diffusion

According to Graham's Law "at constant pressure and temperature, the rate of diffusion or effusion of a gas is inversely proportional to the square root of its vapour density or molecular

mass".

$$r \propto \sqrt{\frac{1}{d}}$$

## Behaviour of Real gases

**Ideal gas:** A gas which obeys the gas laws and the gas equation  $PV = nRT$  strictly at all temperatures and pressures is said to be an ideal gas. But actually the concept of ideal gas is hypothetical as there is no gas which practically is ideal. So, the non-ideal gases are the real gases which are the actually existing gases which obey gas equation approximately only under two conditions.

- (i) Low pressure.
- (ii) High temperature.

## Causes of Deviation

There are two hypothetical postulates in the kinetic theory of gases. These are as follows:

1. The volume of a molecule is negligible as compared to total volume of the gas. Actually, gas molecules do possess some volume which account for the deviation.
2. There is no intermolecular forces of attraction between gaseous molecules.

By correcting these two postulates, we get an equation which can be applied to the gases which deviate from ideal behaviour. This deviation of a gas from ideal behaviour can also be expressed in terms of compressibility factor ( $Z$ ).

$$Z = \frac{PV}{RT}$$

## Van der Waal's Equation

$$\left(P + \frac{an^2}{V^2}\right)(V - nb) = nRT \quad A = \pi r^2$$

Where  $a$  and  $b$  are van der waal's constant.

## Liquifaction of Gases

Gases can be liquefied by applying high pressure or by cooling.

**Critical Temperature:** It is the temperature above which gas cannot be liquefied, no matter how

high be pressure.

$$T_c = \frac{8a}{27Rb}$$

**Critical Pressure:** It is the minimum pressure that is required to liquefy a gas at critical temperature.

$$P_c = \frac{a}{27b^2}$$

**Critical Volume:** It is the volume occupied by gas at critical temperature and critical pressure.

$$V_c = 3b$$

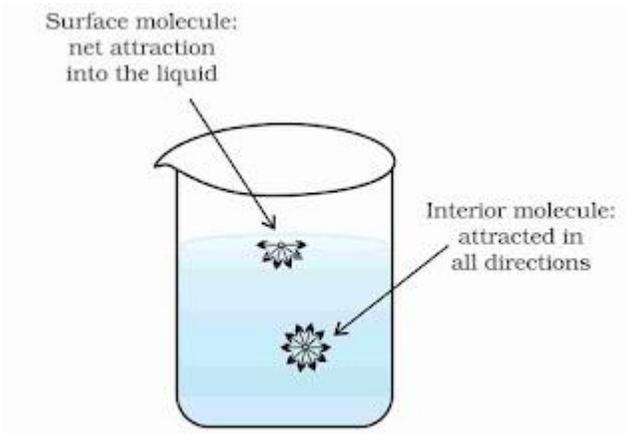
### 1. Liquid State:

It is the intermediate state between gaseous and solid states. Liquids possess fluidity like gases but incompressibility like solids.

**Properties of liquid are:**

- a. A liquid is made up of molecules. Only Hg(l) is in atomic state.
  - b. The intermolecular forces of attraction in a liquid are quite large.
  - c. Liquids have no definite shape but have definite volume as the cohesive forces are strong.
  - d. Liquids diffuses slowly in comparison to gas.
  - e. They have definite volume but irregular shapes or we can say that they can take the shape of the container.
2. **Evaporation:** The process of change of liquid into vapour state at any given temperature is evaporation. Evaporation is accompanied by cooling as average kinetic energy of remaining molecules decreases. Example: Ether evaporates faster than alcohol.
  3. **Vapour Pressure:** In a closed vessel when the rate of evaporation become equal to rate of condensation, i.e. equilibrium is established, the pressure exerted by the vapours of liquid on its on surface is known as vapour pressure.
  4. **Boiling Point:** Boiling point of the liquid is the temperature at which the vapour pressure of the liquid is equal to the atmospheric pressure. Ex- Boiling point of pure water is 100 °C.
  5. **Surface tension:** "It is the force acting on the surface at right angles to any line of unit length". The property of surface tension may also be described in terms of the tendency of a liquid to decrease its surface area. It's SI unit is N/m.

$$\text{Surface tension, } S = \frac{F}{l}$$



6. **Viscosity:** The property of the liquids which determines their resistance to flow, is called viscosity. The forces between the layers which oppose the relative motion between them are known as the forces of viscosity. Thus viscosity may be thought of as the internal function of a fluid in motion.

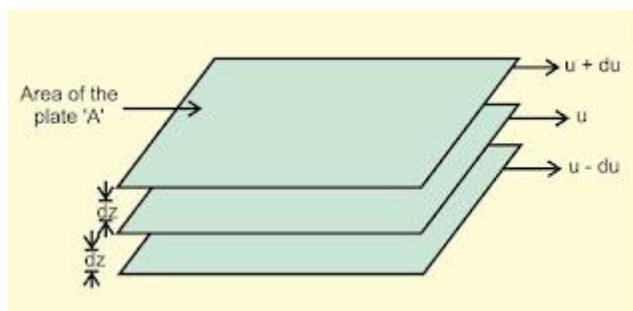
$$F \propto \frac{dv}{dz} \text{ [is called velocity gradient]}$$

$$F \propto A$$

$$F = nA \frac{dv}{dz}$$

$\eta$  is the coefficient of viscosity. It is expressed in  $\text{Nm}^{-2}\text{s}$  or poise

$$1 \text{ poise} = 0.1 \text{ Nm}^{-2}\text{s}$$



7. **Fluidity( $\Phi$ ):** The reciprocal of the coefficient of viscosity is called Fluidity.

$$\Phi = \frac{1}{\eta}$$

1. **Three different states of matter (solid, liquid and gas):** Solid is that state of matter which has a definite shape and a definite volume, liquid has a definite volume but no definite shape whereas gas has neither definite shape nor definite volume.

2. **Two more states of matter:**
  - i. Plasma state which consists of a mixture of electrons and positively charged ions formed due to super heating of gases, e.g., in sun or stars.
  - ii. Super cooled solid state in which atoms lose their identity to form a single super atom.
3. **Triple point:** It is the temperature at which all the three states of matter or phases of the same substance exist together, e.g., ice, water and water vapour exist together at  $0.01^{\circ}\text{C}$  ( $273.16\text{ K}$ ) and  $4.58\text{ mm}$  pressure.
4. **Ideal and Real gases:** A gas which obeys ideal gas equation under all conditions of temperature and pressure is called an ideal gas. However, the concept of ideal gas is only hypothetical. The gases obey gas laws only if pressure is low or temperature is high. Such gases are called real gases.
5. **Significance of van der Waal's constants:** 'a' is a measure of the magnitude of attractive forces whereas 'b' is a measure of the effective size of the gas molecules.  $b = 4v$  where  $v$  is actual volume of gas molecules. 'b' is called excluded volume or co-volume.
6. **Boiling point:** It is the temperature at which vapour pressure of the liquid becomes equal to external pressure. When external pressure =  $1\text{ atm} = 760\text{ mm}$ , it is called normal boiling point.
7. **Surface tension of liquids:** It is the force acting at right angles to the surface along one centimeter length of the surface. Its units are  $\text{dynes cm}^{-1}$  or  $\text{Nm}^{-1}$ .
8. **Vapour pressure of a liquid:** It is the pressure exerted by the vapour present in equilibrium with a liquid in a closed vessel at a particular temperature. Cooling is caused by evaporation because more energetic molecules leave the liquid.
9. **Viscosity of liquids:** It is the internal resistance of a liquid to flow or it is the force of friction which one part of the liquid offers to another part of the liquid.
10. **Factors affecting viscosity:**
  - i. **Nature of the liquid :** Greater the inter-molecular forces, higher is the viscosity.
  - ii. **Temperature:** Viscosity of a liquid decreases with increase of temperature because kinetic energy increases and hence inter-molecular forces of attraction decrease.
11. **Boyle's law:** Temperature remaining constant, volume of a given mass of a gas is inversely proportional to its pressure, i.e.,  $V \propto \frac{1}{P}$  at constant  $T$  or  $PV = \text{constant}$ .
12. **Dalton's law of partial pressures:** If two or more gases which do not react chemically with

each other are enclosed in a vessel, then total pressure exerted by the gaseous mixture is the sum of their partial pressure.

13. **Graham's law of diffusion/effusion:** Under similar conditions of temperature and pressure, rates of diffusion/effusion of different gases are inversely proportional to the square root of their densities.
14. **Compressibility factor (Z):** The extent of deviation of a real gas from ideal behaviour is expressed in terms of compressibility factor (Z) viz.  $Z = P \frac{V}{n} RT$ .

## Characteristics of Gases

### Characteristics of Gases

- 1) Gases have neither definite shape nor definite volume. They take up the shape and volume of the container.
- 2) They have lower density than liquids and solids.
- 3) They are highly compressible
- 4) Gases intermix completely in all proportion without any mechanical aid.
- 5) They exert pressure equally in all direction.

### Measurement of mass

The mass of a gas can be easily determined by weighing the container containing the gas, and then emptying the container by taking out the gas and weighing the empty container again. The difference between the two masses gives the mass of the gas.

$$\text{number of moles } (n) = \frac{\text{mass of substance of substance (g)}}{\text{molar mass of substance}}$$

$$n = \frac{m}{M}$$

$$1 \text{ mole} = 6.022 \times 10^{23}$$

### Measurement of volume

As a gas fills the whole of the vessel in which it is put, hence the volume of the gas is equal to the volume of its container which in turn can be calculated from the dimensions of the container.

The S.I. unit of volume is  $\text{m}^3$ .

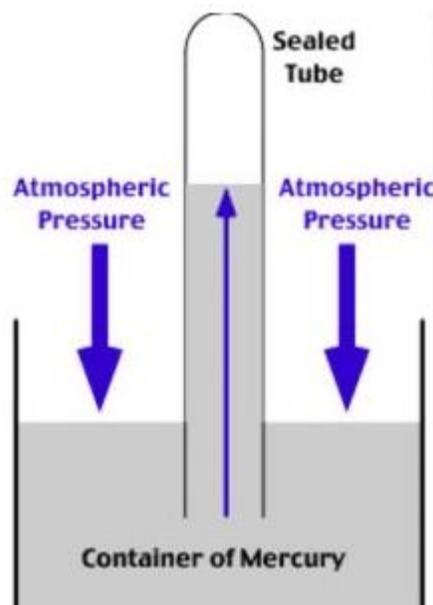
$$1 \text{ m}^3 = 10^3 \text{ dm}^3 = 10^6 \text{ cm}^3$$

$$1 \text{ ml} = 1 \text{ cm}^3$$

$$1 \text{ L} = 10^3 \text{ cm}^3 = 1 \text{ dm}^3 = 10^{-3} \text{ m}^3$$

### Measurement of pressure

The instrument used for the measurement of atmospheric pressure is called a barometer.



It consists of inverting a tube filled with mercury in a dish of mercury. The height of the mercury column above the level of mercury in the dish is a measure atmospheric pressure at that place.

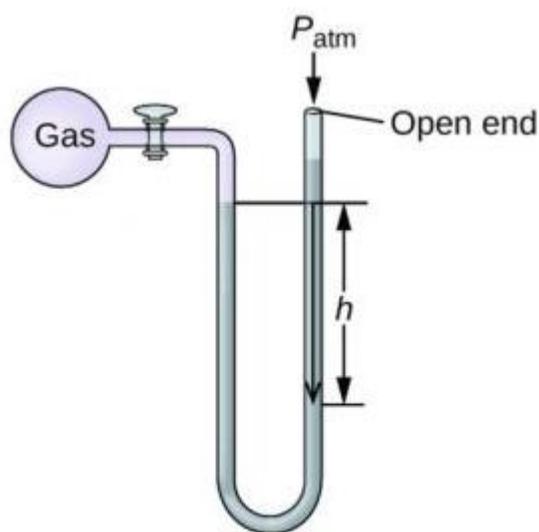
### Mercury is used as a barometric liquid because

- 1) The height of the column in a barometer is inversely proportional to the density of the liquid. As Mercury has very high density, the height of the column setup is very convenient for study.
- 2) Mercury is non-volatile at room temperature. Hence, the vapour pressure due to Mercury vapour is negligible.

The instrument used for the measurement of the pressure of a gas is called manometer. It simply consists of a U- shaped tube containing mercury usually.

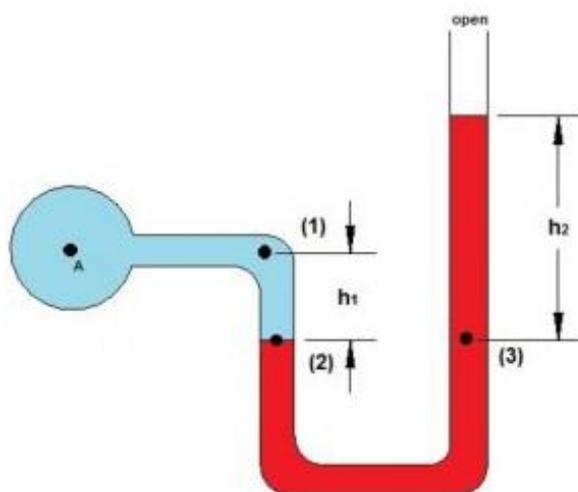
### Two types of manometers are:

- 1) Those in which the longer limb is closed. Closed limb manometer is used only for gases at pressure less than the atmospheric pressure.



$$P_{\text{gas}} = P_{\text{atm}} + h\rho g$$

2) Those in which the longer limb is open. Open limb manometer is used for all.



Suppose height of the mercury column =  $h$  cm

Area of cross section of the tube =  $A$  cm<sup>2</sup>

Volume of the mercury column =  $A \times h$  cm<sup>3</sup>

Density of mercury at room temperature =  $\rho$  g cm<sup>-3</sup>

mass of mercury column =  $A \times h \times \rho$  grams

weight of mercury column =  $(A \times h \times \rho) \times g$  gram

Weight of mercury column is the force acting on  $A$  cm<sup>2</sup>. Hence

Pressure =  $h \times \rho \times g$

A standard or normal atmospheric pressure is defined as the pressure exerted by a mercury column of exactly 76 cm at 0°C. This is the pressure exerted by the atmosphere at the sea level.

$$1 \text{ atm} = 76 \text{ cm} = 760 \text{ mm} = 760 \text{ torr}$$

$$1 \text{ atm} = 1.01325 \text{ bar}$$

$$1 \text{ atm} = 0.987 \text{ atm}$$

The S.I. unit of pressure is pascal (Pa)

$$1 \text{ Pa} = 1 \text{ Nm}^{-2} = 1 \text{ kg m}^{-1} \text{ s}^{-2}$$

$$1 \text{ atm} = 1.01325 \times 10^5 \text{ Nm}^{-2}$$

$$1 \text{ bar} = 10^2 \text{ kPa}$$

### Measurement of temperature

Temperature is a measure of the extent of hotness or coldness of a body.

It is based on the principle that substances expand on heating.

Substance used in the measurement of temperature is mercury.

There are three different scales on which the temperature are measured

1) Fahrenheit scale

2) Kelvin scale

3) Celsius scale

$$T_K = T_C + 273.15 \quad T_C = \frac{5}{9} (T_F - 32) \quad T_F = \frac{9}{5} T_C + 32$$

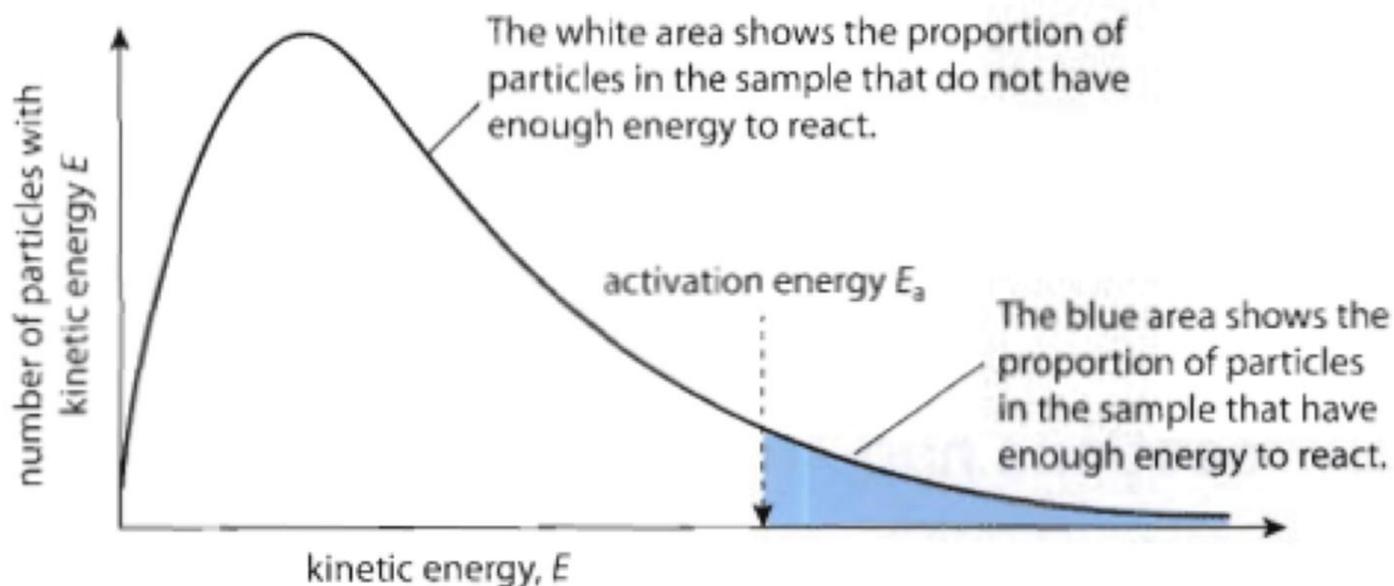
### Maxwell-Boltzmann Distribution

Maxwell-Boltzmann distribution of Molecular speed

At a particular temperature, different molecules of a gas possess different speeds. Due to continuous collision among the molecules themselves and against the walls of the container, their speed keeps on changing.

As a result of collision, some are speeded up, some are slowed down and hence the number of molecules possessing particular speed remains constant at constant temperature.

If fractions of molecules possessing particular speed are plotted against their corresponding speeds at a particular temperature, a curve is obtained. This distribution of speed is called **maxwell-Boltzmann distribution**.



From this curve, it may be observed that,

- (1) Fraction of molecules having too low or too high-speed are very small.
- (2) The peak of the curve corresponds to a speed possessed by the maximum fraction or maximum number of molecules. This speed is called most probable speed and is represented by  $c^*$

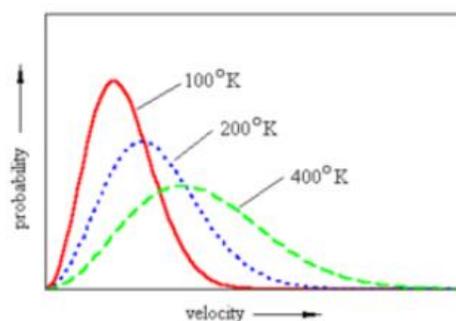
### Effect of nature of the gas

At the same temperature, lighter gas will have higher value of most probable speed i.e. move faster than heavier gases.

For example : Distribution curve for chlorine and nitrogen gases are:

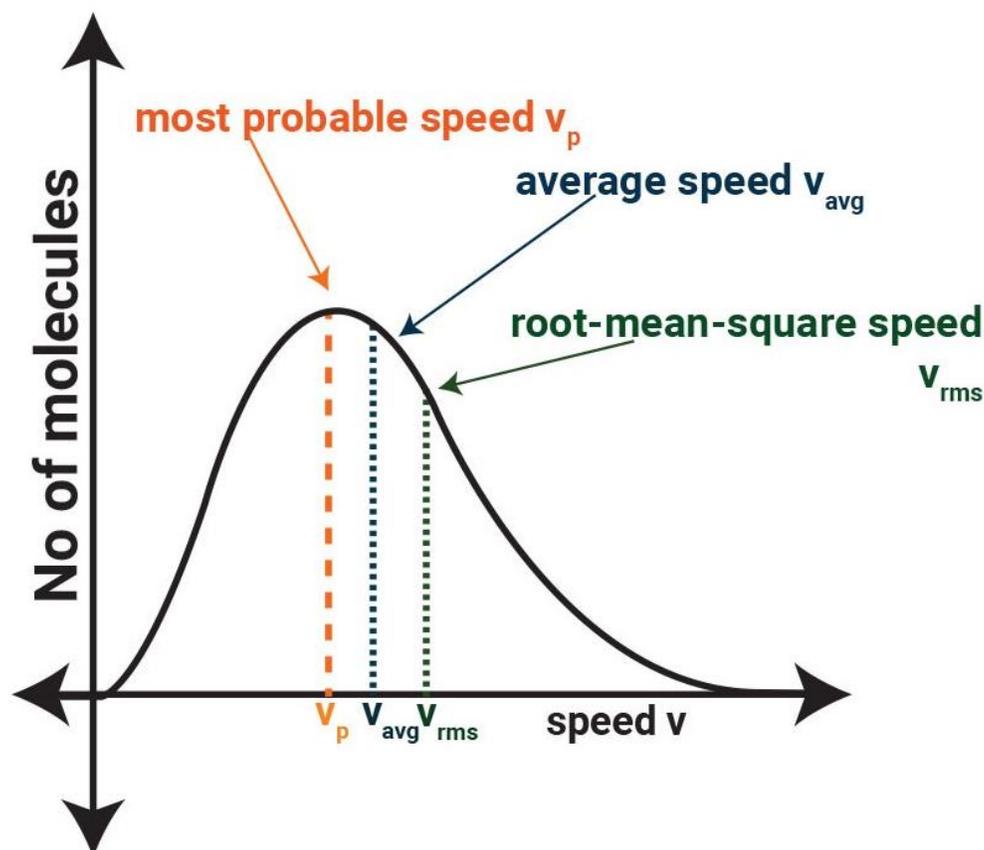
### Effect of temperature

Maxwell – Boltzmann distribution curve for a gas at three different temperatures is



- (1) The peak shift forward showing that the most probable velocity increases.
- (2) The peak shift downwards showing that fraction of molecules or number of molecules possessing most probable velocity decreases.
- (3) The curve is flattened in the middle showing that more molecules have speeds near to the most probable speed.
- (4) The fraction of molecules having higher speed increases.
- (5) The fraction of molecules having lower speed decreases.

#### Relationship between different types of speed



## Liquefaction of Gases And Critical Temperature

The liquefaction of a gas takes place when the intermolecular forces of attraction become so high that they bind the gas molecules together to form the liquid state.

The intermolecular forces of attraction can be increased either by increasing the pressure so that the molecules come close together or by cooling the gas so that the kinetic energy of the molecules decreases and they become slower.

The effect of temperature on the liquefaction of gases is found to be very important as higher the temperature of the gas, more difficult it is to liquefy it and higher is the pressure required.

Gas like hydrogen, helium, oxygen, nitrogen could not be liquefied at room temperature by application of pressure alone. Each of these gases could also be liquefied provided first it is cooled down to or below a particular temperature. For each gas, there is a particular temperature above which it cannot be liquefied, however, high pressure may be applied on the gas. This temperature is called critical temperature.

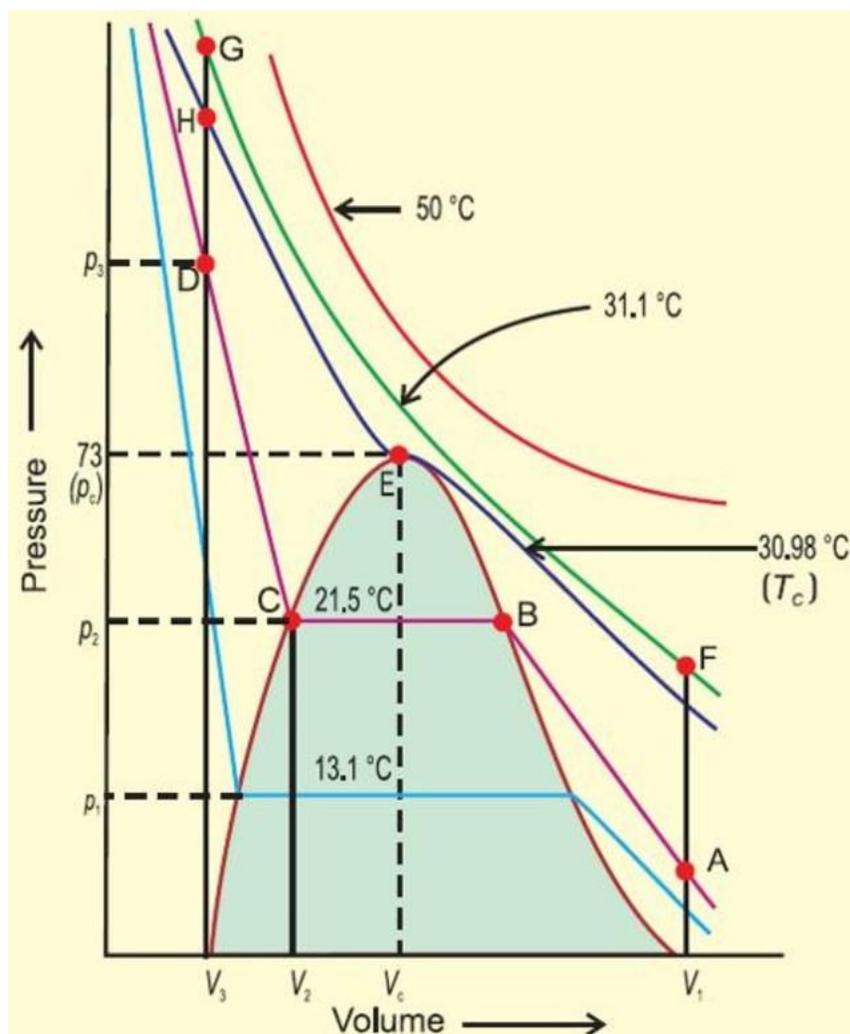
Critical temperature of a gas may be defined as that temperature above which it cannot be liquefied however high pressure may be applied on the gas.

The pressure required to liquefy the gas at the critical temperature is called critical pressure.

The volume occupied by 1 mole of the gas at critical temperature and critical pressure is called critical volume.

All the three are called critical constants of the gas and are represented by  $T_c$ ,  $T_p$ ,  $T_v$ .

### Andrews experiment on critical phenomena



Andrews in 1861 was the first to study the critical phenomena experimentally using carbon dioxide gas.

He studied the effect of pressure on the volume of carbon dioxide at different constant temperature. The plots obtained are called isotherms.

At the lowest temperature employed i.e.  $13.1^{\circ}\text{C}$ , at low pressure, carbon dioxide exist as a gas, as shown at the point A.

As the pressure is increased, the volume of the gas decreases along the curve.

The point at which liquefaction of the gas starts, volume decreases rapidly because liquid has much less volume than the gas.

Once the liquification is complete, the increase in pressure has very little effect upon volume because liquids are very little compressible. Hence a steep curve is obtained.

As the temperature is increased, horizontal portion becomes smaller and smaller and at  $30.98^{\circ}\text{C}$ , it is reduced to a point E.

Above  $30.98^{\circ}\text{C}$ , the gas cannot be liquefied at all, however high pressure may be applied. Thus  $30.98^{\circ}\text{C}$  is the critical temperature.

We get a dome shaped curve.

A point like A represent gaseous state.

A point Like D represents a liquid state.

A point within the dome shaped area represents existence of liquid and gaseous carbon dioxide in equilibrium.

### Importance of critical temperature

The critical temperature of a gas is a measure of the strength of the intermolecular forces of attraction.

Weaker are the intermolecular forces, more difficult it is to liquefy that gas and hence lower would be the critical temperature of that gas.

Helium and hydrogen have weak intermolecular forces, thus they are difficult to liquefy and hence have low critical temperature.

Carbon dioxide and ammonia have strong intramolecular forces of attraction, they can be easily liquefied and their critical temperature are high which are above room temperature.

Van der waals constant  $a$  is also a measure of intermolecular forces of attraction. Hence it is found that the values of constant  $a$  increase in the same order as the critical temperature.

As a gas can be liquefied below the critical temperature by applying pressure. Therefore above the critical temperature, it is a gas but below the critical temperature it is a vapour.

For ex: Carbon dioxide below its critical temperature is called carbon dioxide vapour.

Filed Under: States of Matter, Chemistry, Class 11

Tagged With: Andrews experiment on critical phenomenon, carbon dioxide vapour, critical constants, critical pressure, Critical temperature, critical volume, Importance of critical temperature, isotherms, liquefaction of a gas

You are here: Home / Class 11 / Chemistry / States of Matter / Vapour Pressure

### Vapour Pressure

In a liquid, the molecules are quite close together so that there are considerable forces of attraction between them and hence they are held together in a definite volume.

The liquids possess fluidity like gases but incompressibility like solid.

### Properties of Liquid

(1) Liquids have no definite shape: They take up the shape of the vessel in which they are put. This is because the molecules in a liquid are in a state of constant rapid motion.

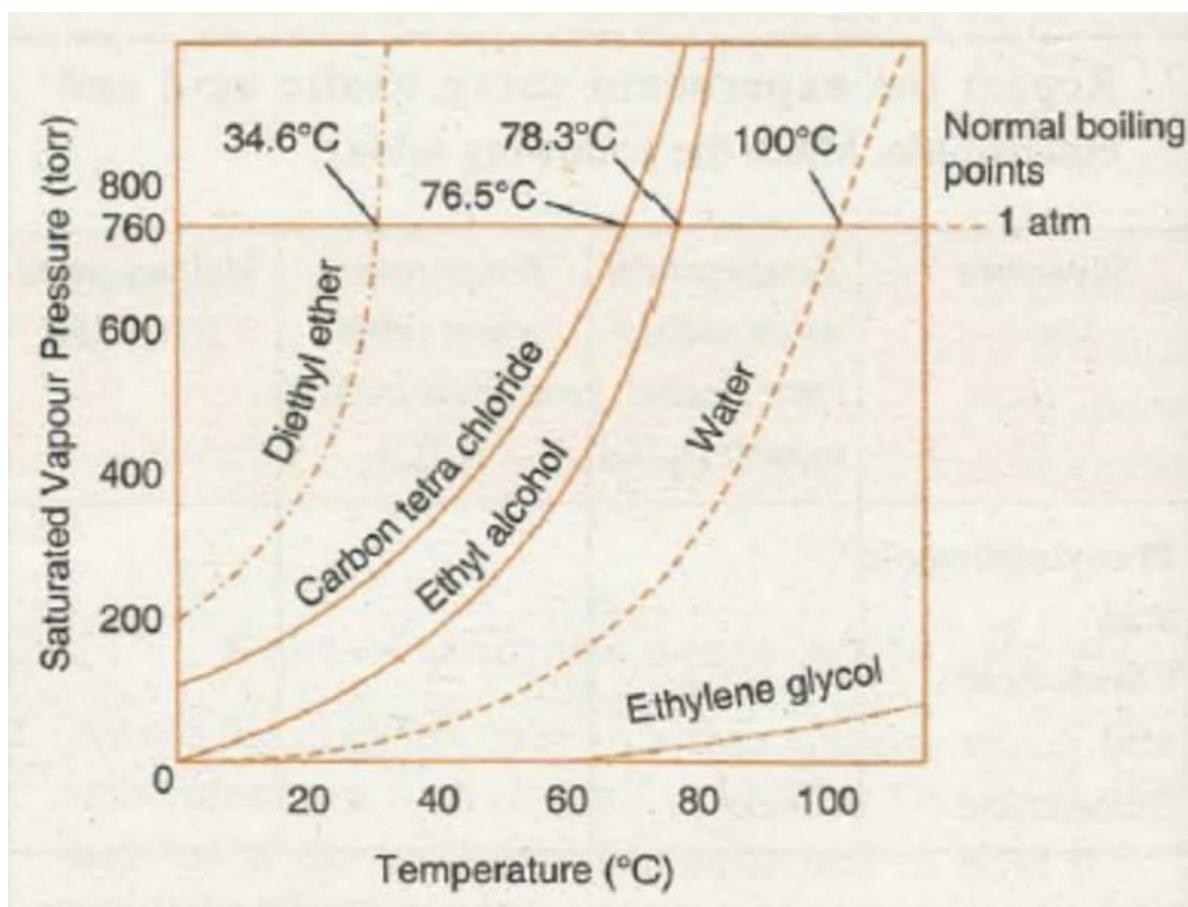
(2) Liquids have a definite volume: This is because the intermolecular forces of attraction in a liquid are quite strong and unlike gas molecules, the liquid molecules are not completely free to move.

(3) Liquids have much higher density than gases: This is because the molecules in a liquid are quite close together. Thus the molecules are much more closely packed than those of the gases.

(4) Compressibility :liquids are much less compressible than gases. This is because the intermolecular distances of separation are much smaller in liquid than that in gases.

(5) Diffusion: liquids diffuse like gases but the diffusion is much slower because the liquid molecules are quite close, they undergo a much larger number of collisions with each other.

### Vapour Pressure



Suppose some liquid is placed in an evacuated vessel connected to a manometer. According to

kinetic theory of liquids, the molecules of the liquid are constantly moving in different directions with different speeds. As these molecules are moving with different speeds, they possess different kinetic energy.

At any particular temperature, the energy of some of the molecules may be so high that they may overcome the forces of attraction by the neighbouring molecules and may leave the liquid and come in the space above the liquid. This process is called evaporation.

As the time passes, more and more molecules of the liquid leave the liquid and come in space above the liquid. The molecules thus present above the liquid are called vapour. The molecules in the vapour phase are also constantly moving and some of them strike the surface of the liquid and maybe recaptured by the liquid. The process is called condensation.

If the liquid is added into the evacuated vessel, then initially, as there are no molecules of vapour, the rate of condensation is zero.

If the temperature is kept constant, the evaporation continues at constant rate as shown by the straight line plot. With the passage of time, as a number of molecules in the vapour phase becomes more and more, the rate of condensation also increases.

A stage is reached when rate of condensation becomes equal to rate of evaporation i.e. as many molecules re-enter into a liquid as leave the liquid in the same time. This state is called state of equilibrium.

The pressure exerted by the vapours at this stage is called vapour pressure or saturated vapour pressure as the vapour phase is saturated with vapours at this stage.

Vapour pressure of a liquid at any temperature may be defined as the pressure exerted by the vapour present above the liquid in equilibrium with the liquid at that temperature.

### **Important results related with process of evaporation**

#### **(1) Cooling caused by Evaporation**

When a liquid evaporates, the more energetic molecules leave the liquid. As a result the average kinetic energy of the remaining liquid decreases and hence the temperature falls.

#### **(2) Factors affecting Vapour Pressure**

(i) Nature of the liquid : If the intermolecular forces of attraction in the liquid are weak, the molecules can easily leave the liquid and come into vapour phase and hence the vapour pressure is higher.

For example: The vapour pressure of acetone, benzene is higher than that of water at same temperature.

(ii) Effect of temperature: As the temperature of a liquid is increased, the vapour pressure of liquid increases.

### **(3) Boiling point**

The vapour pressure of a liquid increases as the temperature is increased. The vapour escaping are only from the surface of the liquid. If the temperature is further increased till the vapour pressure becomes equal to atmospheric pressure, the vapour in the form of bubbles from below the surface start rising to the surface and escape into the air. The temperature at which this happens is called boiling point.

#### **Boiling**

Boiling point of a liquid is defined as the temperature at which the vapour pressure of the liquid becomes equals to external pressure.

When the external pressure is normal atmospheric pressure, the boiling point is called normal boiling point.

When the external pressure is equal to 1 bar, the boiling point is called standard boiling point of the liquid.

Standard boiling point of a liquid is slightly less than the normal boiling point because one bar is slightly less than 1 atmosphere pressure.

#### **Application of effect of external pressure on boiling point**

(1) If the external pressure is higher, more heat will be required to make the vapour pressure equal to external pressure and hence higher will be the boiling point. That is why in hospitals, the surgical instruments are sterilised in autoclaves in which boiling point of water is raised by using a weigh to cover the vent.

(2) If the external pressure is decreased, the boiling point is lowered. This is the reason that a liquid boils at a lower temperature on the top of the mountain than on the sea shore. That is why at hills, use of pressure cooker is essential for cooking food.

(3) It is used for purifying the unstable liquids by distillation under reduced pressure.

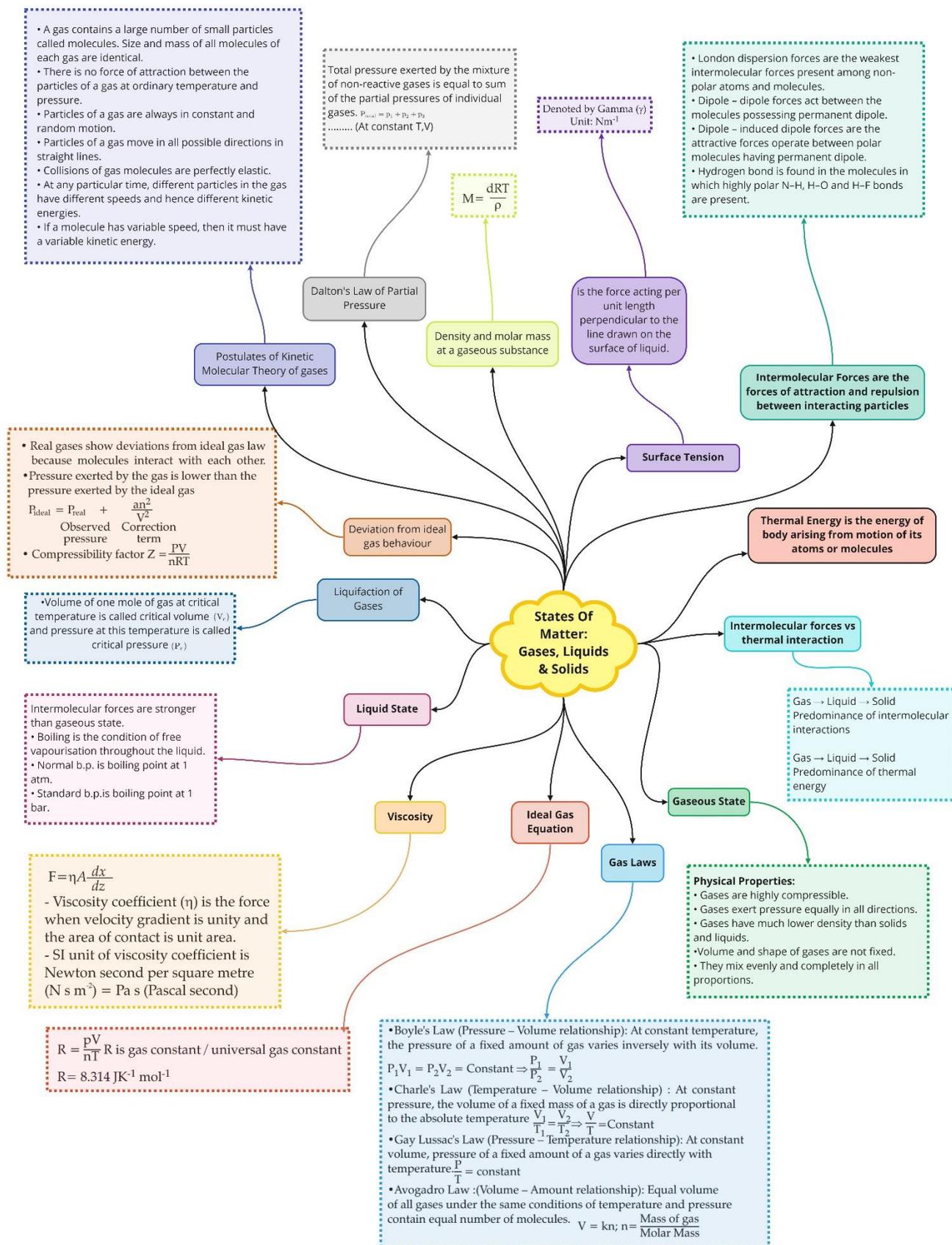
### **(4) Heat of Vaporisation**

When the liquid starts boiling, if extra heat is supplied to the liquid, it is used up not in increasing the temperature of the liquid but to overcome the intermolecular forces of attraction, existing in the liquid and thus changing the liquid into vapour. Hence the temperature remain constant till whole of the liquid changes into vapour.

The amount of heat required to change 1 mole of the liquid into its vapour at the boiling point is called the heat of vaporisation of the liquid.

Greater the intermolecular forces of attraction present in a liquid, greater is the heat of vaporisation and higher is the boiling point.

Class : 11th Chemistry  
Chapter- 5: States Of Matter: Gases, Liquids & Solids



## Important Questions

### Multiple Choice questions-

Question 1. Three containers A, B, C of equal volume contain oxygen, neon and methane respectively at same temperature and pressure. The increasing order of their masses is

- (a)  $A < B < C$
- (b)  $B < C < A$
- (c)  $C < A < B$
- (d)  $C < B < A$

Question 2. A gas will approach ideal behaviour at

- (a) Low temperature, low pressure
- (b) Low temperature, high pressure
- (c) High temperature, low pressure
- (d) High temperature, high pressure

Question 3. Containers A and B have same gas. Pressure, volume and temperature of A are all twice those of B. The ratio of number of molecules of A and B is

- (a) 1 : 2
- (b) 2 : 1
- (c) 1 : 4
- (d) 4 : 1

Question 4. According to kinetic theory of gases, in an ideal gas, between two successive collisions a gas molecule travels

- (a) In a circular path
- (b) In a wavy path
- (c) In a straight line path
- (d) With an accelerated velocity

Question 5. When substances exist in different crystalline forms the phenomenon is called:

- (a) Allotropy
- (b) Polymorphism
- (c) Polymerization
- (d) Isomorphism

Question 6. SI unit of pressure is :

- (a) Pascal
- (b) torr
- (c) mm of Hg
- (d) none of the above

Question 7. If the pressure of a gas is increased then its mean free path becomes:

- (a) 0
- (b) Less
- (c) More
- (d) Infinity

Question 8. 1 atmosphere is equal to:

- (a) 1 torr
- (b) 760 cm
- (c) 760 mm
- (d) 76 torr

Question 9. Grahams law refers to :

- (a) Boiling point of water
- (b) Gaseous Diffusion
- (c) Gas Compression
- (d) Volume changes of gases

Question 10. The rise or fall of a liquid within a tube of small bore is called :

- (a) Surface Tension
- (b) Capillary Action
- (c) Viscosity
- (d) Formation of Curvature

Question 11. The rates of diffusion of gases are inversely proportional to square root of their densities . This statement refers to :

- (a) Daltons Law
- (b) Grahams Law
- (c) Avogadros Law
- (d) None of the Above

Question 12. Cooling is caused by :

- (a) Evaporation
- (b) Convection
- (c) Conduction
- (d) none of the above

Question 13. If helium and methane are allowed to diffuse out of the container under the similar conditions of temperature and pressure, then the ratio of rate of diffusion of helium to methane is:

- (a) 2 : 1
- (b) 1 : 2
- (c) 3 : 5
- (d) 4 : 1

Question 14. Equal masses of ethane and hydrogen are mixed in an empty container at 25°C . The fraction of total pressure exerted by hydrogen is

- (a) 1 : 2
- (b) 1 : 1
- (c) 01 : 16
- (d) 15 : 16

Question 15. The volume of 2.8 g of carbon monoxide at 27°C and 0.0821 atm is

- (a) 30 L
- (b) 3 L
- (c) 0.3 L
- (d) 1.5 L

### Very Short:

1. What change in energy takes place when a molecule is formed from its atoms?
2. Arrange the following in order of increasing bond strengths.
3. Name the shapes of the following molecules: CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, CO<sub>2</sub>.
4. Arrange the following in order of increasing strengths of hydrogen bonding O, F, S, Cl, N
5. Identify the compound/compounds in the following in which S does not obey the Octet rule: SO<sub>2</sub>, SF<sub>2</sub>, SF<sub>4</sub>, SF<sub>6</sub>.
6. Name one compound each involving sp<sup>3</sup>, sp<sup>2</sup>, sp hybridization.
7. s-s, s-p, p-p form a bond, and only p-p form π bond.

## Short Questions:

1. Which out of  $\text{CH}_3\text{F}$  and  $\text{CH}_3\text{Cl}$  has a higher dipole moment and why?
2. Define the term chemical bond. What are its different types?
3. Why covalent bonds are called directional bonds whereas ionic bonds are called non-directional?
4.  $\text{AlF}_3$  is a high melting solid whereas  $\text{SiF}_4$  is a gas. Explain why?
5. Using the VSEPR theory identifies the type of hybridization and draw the structure of  $\text{OF}_2$  What are oxidation states of O and F?
6. Account for the following: The experimentally determined N-F bond length in  $\text{NF}_3$  is greater than the sum of the single covalent radii of N and F.

## Long Questions:

1. State with reasons, which is more polar  $\text{CO}_2$  or  $\text{N}_2\text{O}$ ?
2. Out of peroxide ion ( $\text{O}_2$ ) and superoxide ion ( $\text{O}_2^-$ ) which has larger bond length and why?
3. Explain the formation of the following molecules according to the orbital concept,  $\text{F}_2$ ,  $\text{HF}$ ,  $\text{O}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$ ,  $\text{NH}_3$  molecules.
4. What is a hydrogen bond, what are its causes, and give the conditions for hydrogen bonding? What is the strength of hydrogen bonding? Describe the two types of hydrogen bonding.

## Assertion Reason Questions:

1. In the following questions, a statement of Assertion (A) followed by a statement of Reason (R) is given. Choose the correct option out of the choices given below each question.

**Assertion (A):** Three states of matter are the result of balance between intermolecular forces and thermal energy of the molecules.

**Reason (R):** Intermolecular forces tend to keep the molecules together but thermal energy of molecules tends to keep them apart.

(i) Both A and R are true and R is the correct explanation of A.

(ii) Both A and R are true but R is not the correct explanation of A.

(iii) A is true but R is false.

(iv) A is false but R is true.

2. In the following questions, a statement of Assertion (A) followed by a statement of Reason

(R) is given. Choose the correct option out of the choices given below each question.

**Assertion (A):** At constant temperature,  $pV$  vs  $V$  plot for real gases is not a straight line.

**Reason (R) :** At high pressure all gases have  $Z > 1$  but at intermediate pressure most gases have  $Z < 1$ .

(i) Both A and R are true and R is the correct explanation of A.

(ii) Both A and R are true but R is not the correct explanation of A.

(iii) A is true but R is false.

(iv) A is false but R is true.

### Case Study Based Question:

1. Intermolecular forces are the forces of attraction and repulsion that exist between molecules of a compound. These cause the compound to exist in a certain state of matter – solid, liquid or gas and affect the melting and boiling points of compounds as well as the solubilities of one substance in another. Attractive intermolecular forces are also called van der Waals' forces. These are weak forces.

(1) Dipole-dipole forces act between the molecules possessing permanent dipole. Ends of dipoles possess 'partial charges'. The partial charge is:

(a) More than unit electronic charge

(b) Equal to unit electronic charge

(c) Less than unit electronic charge

(d) Double the unit electronic charge

(2) The nature of inter-particle forces in benzene is:

(a) Dipole-dipole interaction

(b) Dispersion force

(c) Ion-dipole interaction

(d) H-bonding.

(3) The interaction energy between two temporary dipoles is proportional to (where  $r$  is the distance between the two particles)

(a)  $1/r^4$

(b)  $1/r^2$

(c)  $1/r^5$

(d)  $1/r^6$

(4) Attractive intermolecular forces known as van der Waals forces do not include which of

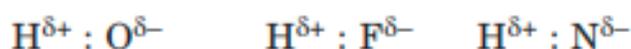
the following types of interactions?

- (a) London forces
- (b) Dipole-dipole forces
- (c) Ion-dipole forces
- (d) Dipole-induced dipole forces

(5) In which of the following molecules, the van der Waals forces are likely to be the most important in determining the m.pt. and b.pt?

- (a) CO
- (b) H<sub>2</sub>S
- (c) Br<sub>2</sub>
- (d) HCl

2. If a hydrogen atom is bonded to a highly electronegative element such as fluorine, oxygen, nitrogen, then the shared pair of electrons lies more towards the electronegative element. This leads to a polarity in the bond in such a way that a slight positive charge gets developed on H-atom, viz



Such a bond between the hydrogen atom of one molecule and the more electronegative atom of the same or another molecule is called a hydrogen bond.

(1) Which of the following compounds can form hydrogen bond?

- (a) CH<sub>4</sub>
- (b) H<sub>2</sub>O
- (c) NaCl
- (d) CHCl<sub>3</sub>

(2) The boiling point is not affected due to hydrogen bonding in:

- (a) Water
- (b) Ammonia
- (c) Methyl alcohol
- (d) Hydrogen chloride

(3) Unusual high b.p. of water is result of:

- (a) Intermolecular hydrogen bonding
- (b) Intramolecular hydrogen bonding

- (c) Both intra and intermolecular hydrogen bonding  
(d) High specific heat
- (4) Which of the following statements is not true?
- (a) Intermolecular hydrogen bonds are formed between two different molecules of compounds.  
(b) Intramolecular hydrogen bonds are formed between two different molecules of the same compound.  
(c) Intramolecular hydrogen bonds are formed within the same molecule.  
(d) Hydrogen bonds have a strong influence on the physical properties of a compound.

### Answer Key:

#### MCQ

1. (a) 0
2. (a)  $sp^2$
3. (b)  $sp$  and  $sp^2$
4. (c)  $sp^3$ , 0
5. (d)  $K^+ < Ca^{2+} < Mg^{2+} < Be^{2+}$
6. (c) Acetonitrile
7. (c)  $O_2^-$
8. (c) Triangular
9. (b)  $A_2 B_3$
10. (b)  $SF_4$
11. (c) NaCl
12. (d) Ice
13. (d)  $NO^+$  and  $CN^+$
14. (c) HCl and He atoms
15. (b)  $sp$  and  $sp^2$

### Very Short Answer:

1. There is a fall in energy.
2.  $F_2 < Cl_2 < O_2 < N_2$
3.  $CH_4$ : Tetrahedral;  $C_2H_2$ : Cylindrical;  $CO_2$ : linear
4.  $Cl < S < N < O < F$ .
5.  $SF_4, SF_6$ .
6.  $sp^3$ :  $CH_4$ ;  $sp^2$ :  $C_2H_4$ ;  $sp$ :  $C_2H_2$
7. s-s, s-p, p-p form a bond, and only p-p form  $\pi$  bond.

### Short Answer:

**Ans: 1.** The dipole moment of  $CH_3Cl$  is greater than that of  $CH_3F$ . The C-F bond length in  $CH_3F$  is smaller than the C-Cl bond length in  $CH_3Cl$ . The charge separation in the C-F bond is more than in the Cl-C bond- fluoride being more electronegative than chlorine. The bond length has a greater effect than the charge separation. Hence the dipole moment of  $CH_3Cl$  is greater than that of  $CH_3F$ .

**Ans: 2.** The attractive forces which hold the constituent atoms in molecules or species in lattices etc. are called a chemical bond.

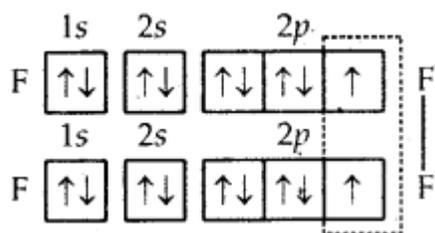
They are of the following types:

1. Electrovalent or ionic bond
2. Covalent bond
3. Coordinate or dative bond
4. metallic bond
5. hydrogen bond
6. van der Waals forces.

**Ans: 3.** A covalent bond is formed by the overlap of half-filled atomic orbitals which have definite directions. Hence covalent bond is directional. In ionic compounds, each ion is surrounded by a number of oppositely charged ions and hence there is no definite direction.

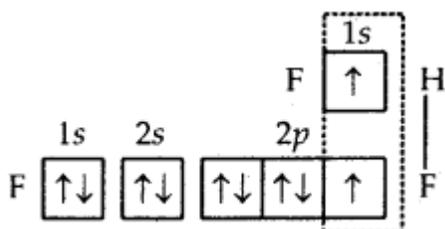
**Ans: 4.**  $AlF_3$  is an ionic solid due to the large difference in electronegativities of Al and F whereas  $SiF_4$  is a covalent compound and hence there are only weak van der Waal's forces among its molecules.



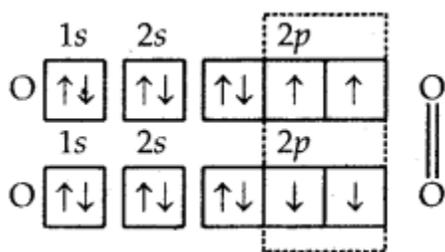


### Formation of $F_2$ molecule

2. Formation of HF molecule. Fluorine atom, as stated above, has one half-filled atomic orbital. Hydrogen atom ( $Z = 1$ ) has only one electron in  $1s$  orbital. Thus, the hydrogen fluoride (HF) molecule, is formed as a result of the combination (or overlap) of the half-filled orbitals belonging to the participating atoms.



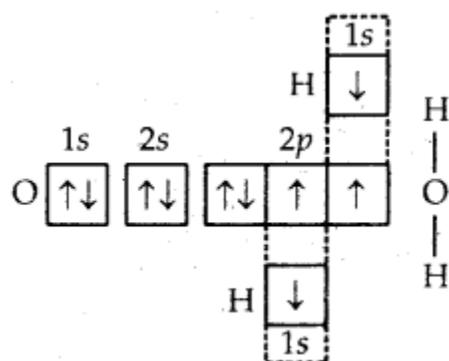
3. Formation of  $O_2$  molecules. The atomic number ( $Z$ ) of oxygen is 8 and its orbital electronic configuration is  $1s^2 2s^2 2p^2_x 2p^1_y 2p^1_z$ . This means that an oxygen atom has two half-filled orbitals with one electron each. Two such atoms will combine to form a molecule of oxygen as a result of the overlap of the half-filled orbitals with opposite spins of electrons.



### Formation of $O_2$ molecule

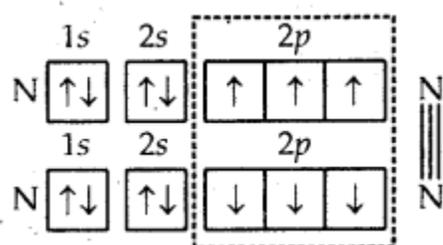
Thus, the two atoms of oxygen are bonded to each other by two covalent bonds or double bonds ( $O = O$ ).

4. Formation of  $H_2O$  molecule. In the formation of the  $H_2O$  molecule, the two half-filled orbitals of the oxygen atom combine with the half-filled orbitals ( $1s$ ) of the hydrogen atoms. Thus, the oxygen atom gets linked to the two hydrogen atoms by single covalent bonds as shown in



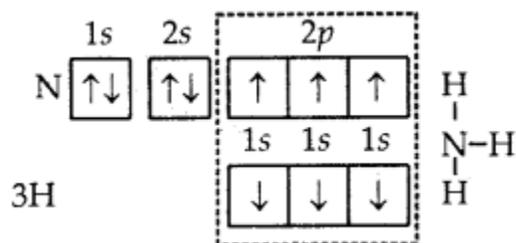
### Formation of $\text{H}_2\text{O}$ molecule

5. Formation of  $\text{N}_2$  molecule. The atomic number of nitrogen is 7 and its orbital electronic configuration is  $1s^2 2s^2 2p^1_x 2p^1_y 2p^1_z$ . This shows that the nitrogen atom has three half-filled atomic orbitals. Two such atoms combine as a result of the overlap of the three half-filled orbitals and a triple bond gets formed ( $\text{N} = \text{N}$ )



### Formation of $\text{N}_2$ molecule

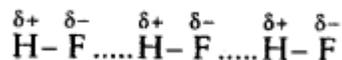
6. Formation of  $\text{NH}_3$  molecule. In the formation of ammonia ( $\text{NH}_3$ ) molecule, three half-filled orbitals present in the valence shell of nitrogen atom combine with 1s orbital of three hydrogen atoms with one electron each. As a result, the nitrogen atom completes its octet and a molecule of  $\text{NH}_3$  is formed in which the nitrogen atom is linked to three hydrogen atoms by covalent bonds.



### Formation of $\text{NH}_3$ molecule

**Ans: 4.** When hydrogen is connected to small highly electronegative atoms such as F, O, and N in such cases hydrogen forms an electrostatic weak bond with an electronegative atom of

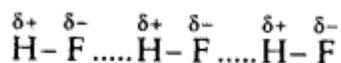
the second molecule, this type of bond binds the hydrogen atom of one molecule and the electronegative atom of the 2nd molecule is called as hydrogen bond. It is a weak bond and it is denoted by dotted lines e.g., in HF, hydrogen forms a weak bond with the electronegative F atom of the 2nd molecule neighboring HF.



So it means hydrogen is acting as a bridge between two molecules by one covalent bond and the other by a hydrogen bond. Due to this hydrogen bonding, HF will not exist as a single molecule but it will exist as an associated molecule (HF)<sub>n</sub>. So hydrogen bond may be defined as a weak electrostatic bond that binds the hydrogen atom of one molecule and electronegative bond atoms (F, O, N) of the second neighboring molecule.

Cause of hydrogen bonding: When a hydrogen atom is bonded to an electronegative atom (say F, O, N) through a covalent bond, due to electronegativity difference, the electronegative atom attracts the shared pair of electrons towards its side with a great force as a result of which the shared pair of electrons will be displaced toward electronegative atom and away from a hydrogen atom.

Due to which hydrogen atom will acquire a slightly negative charge and if another molecule is brought nearer to it in such a way that electronegative atom of the second molecule faces hydrogen atom of the 1st molecule, due to opposite charges present on the atoms, an electrostatic bond will be formed between the hydrogen atom of one molecule and electronegative atom of 2nd molecule and this is called as hydrogen bond.



Conditions for hydrogen bonding. The following two necessary conditions for hydrogen bonding are:

1. Hydrogen atom should be connected to highly electronegative atom say F, O, or N.
2. The electronegative atom of which the hydrogen atom is connected should be the same in size.

The smaller the size of the electronegative atom greater will be the attraction of that atom for shared pair of electrons and hence that pair will be displaced more nearer to that atom and hence that atom will develop greater negative charge and the hydrogen atom will develop a greater positive charge and hence hydrogen atom of this molecule will easily attract negative atom of the 1st molecule and hence a hydrogen bond will be

easily formed.

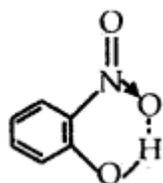
As both these conditions are satisfied only by F, O, N atoms so only three atoms show hydrogen bond.

**Strength of Hydrogen Bond:** A hydrogen bond is a very weak bond. It is weaker than an ionic or a covalent bond. Its strength ranges from  $13 \text{ kJ mol}^{-1}$  to  $42 \text{ kJ mol}^{-1}$ . The strength of the hydrogen bond for some of the molecules is the order  $\text{H-F} > \text{H-O} > \text{H-N}$  whereas the strength of a covalent bond is quite high. For example, the bond strength of the H-H bond in  $\text{H}_2$  is  $433 \text{ kJ mol}^{-1}$ .

Types of H-bonding

There are two types of hydrogen-bonds

1. Intermolecular hydrogen bond. It is formed between two different molecules of the same or different compounds. For example H-bond in case of HF, alcohol, or water.
2. Intramolecular Hydrogen bond. It is formed when a hydrogen atom is in between the two highly electronegative (F, O, N) atoms present within the same molecule. For example, in o-nitrophenol, hydrogen is in between the two oxygen atoms.



### Assertion Reason Answer:

1. (i) Both A and R are true and R is the correct explanation of A.
2. (ii) Both A and R are true but R is not the correct explanation of A.

### Case Study Answer:

#### 1. Answer:

- (1) (c) Less than unit electronic charge
- (2) (b) Dispersion force
- (3) (d)  $1/r^6$

(4) (c) Ion-dipole forces

(5) (c) Br<sub>2</sub>

**2. Answer:**

(1) (b) H<sub>2</sub>O

(2) (d) Hydrogen chloride

(3) (a) Intermolecular hydrogen bonding

(4) (b) Intramolecular hydrogen bonds are formed between two different molecules of the same compound.