Gas Laws and the Mole

Solids, Liquids and Gases

Solids (s): Molecules are held in place by intermolecular interactions.

Liquids (l): Molecules are held next to one another by intermolecular interactions, however, these interactions are not strong enough to prevent the molecules from flowing past one another.

Gases (s): The intermolecular interactions are too weak to hold the molecules next to one another, so the molecules wander off on their own.

Phases of Matter

Particle Theory of Solids

Particles arranged in a regular pattern and cannot move out of position (this gives solids a definite shape and means they cannot flow).

The particles are tightly packed together (this gives solids a definite volume and makes them incompressible). Strong forces hold the particles together

Particle Theory of Liquids

No regular arrangement of particles, particles can slide around each other (this causes liquids to have no definite shape and to flow).Particles are packed together (means liquids are hard to compress and have a definite volume).

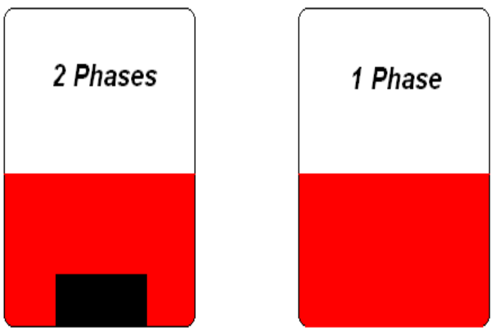
Forces holding particles together are weaker than in solids (allows more movement in liquids).

Particle Theory of Gases

Particles are much farther apart than in solids or liquids (this means gases can be compressed). Particles can move quickly in all directions to fill available space (this means gases have no definite shape or volume and can diffuse).

There are only weak forces between the particles.

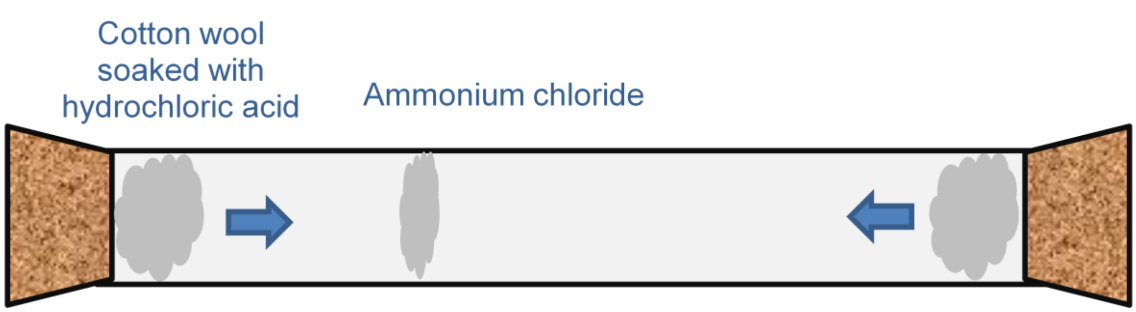
What is a ***phase***?



A mixture containing a solid and a liquid consists of two phases. A mixture of various chemicals in a single solution consists of only one phase, because you can't see any boundary between them.

Diffusion

Diffusion is the spontaneous spreading out of a substance, and is due to the natural movement of its particles.



Gas diffuses from an area of high concentration to an area of low concentration until equilibrium is achieved

Gas Laws

1. Pressure and Volume (Boyle's Law)
2. Temperature and Volume
3. (Charles' Law)
4. Temperature and Pressure
5. (Gay-Lussac's Law)

.......A little on Avogadro

Information that's useful to know

Temperature: 2 scales Celsius and Kelvin

Celsius (centrigrade scale) (^oC)

Anders Celsius (1742)

Freezing point of water is 0^oC

Boiling Point of water is 100^oC

Kelvin Scale

Lord Kelvin (1848)

Zero Kelvin is Temp at which a gas occupies no volume if it could be cooled indefinitely so as not to become a liquid or a solid........called A***bsolute Zero***

Pressure : Newtons

Volume : M^3

Important people in Gas Theory

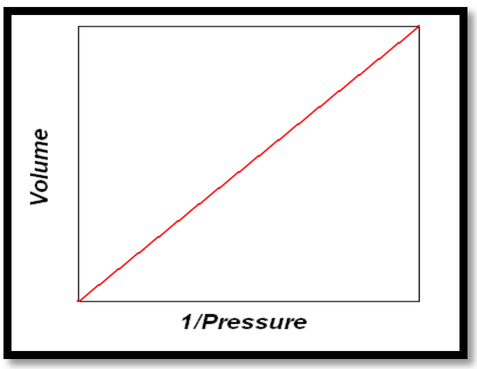
Robert Boyle (Published in 1662)

Worked with an assistant Robert Hooke

Irish

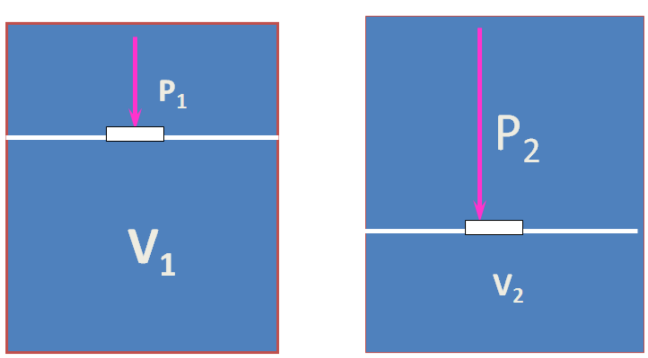
Boyles Law (Irish)

Definition



At a constant temperature, the volume of a fixed mass of Gas is inversely proportional to its pressure

P and V Changes



When we reduce the space in which a gas moves then we increase the rate at which the molecules collide and this in turn increases the pressure

Mathematical expression of Boyles Law

$V \alpha 1/P$

α stands for 'proportional to'

$V = k\ 1/p$

(where k is a constant of proportionality)

i.e.

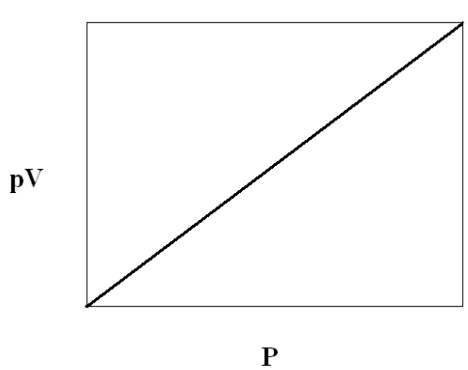
$$pV = k$$

The pressure of a gas when multiplied by its volume is always a constant

Example : Air at 25^{o}C

Pressure (kPa)	***Volume (V) (L)***	***Pressure x Volume (P x V)***
40	***0.1***	***4.0***
100	***.04***	***4.0***

The pressure of a gas when multiplied by its volume is always a constant



Since pV is always a constant

If we plot pV against p we end up with a straight line graph

Jacques Charles (Published 1787) French

Charles Law

Definition

At constant pressure the volume of a fixed mass of gas is directly proportional to it temperature measured on the <u>Kelvin</u> scale

Mathematical expression of Charles Law

- $V \propto T$ provided T is measured in Kelvins
- V = kT where k is a constant of proportionality
  - i.e

$$\frac{V}{T} = k$$

- Therefore the vol of a gas divided by its temp (kelvins) is always a constant

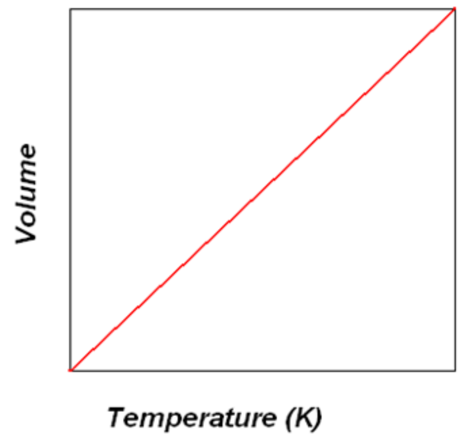
Volume (cm^3)	T (°C)	T (kelvin)	$\frac{V}{T}$
75	-173	100	0.75
225	27	300	0.75
375	227	500	0.75

- Since $\frac{V}{T}$

is always a constant

If we plot $\frac{V}{T}$
against p we end up with

  – a straight line graph



Gay – Lussac's Law of Combining Volumes

When a gases react, the volumes consumed in the reaction bear a simple whole number ratio to each other, and to the volumes of any gaseous product of the reaction, if all volumes are measured under the same conditions of temperature and pressure.

This is an example of what's happening when Hydrogen and Chlorine form Hydrochloric acid

Hydrogen + Chlorine → Hydrogen Chloride

1 Volume : 1 Volume → 2 Volumes

Another example of what is happening when Hydrogen and Oxygen form Gaseous water (steam)

Hydrogen + Oxygen → Steam

2 Volumes : 1 Volume → 2 Volumes

Volume Ratios

Reaction			Gas Volume Ratio for reactants
Ammonia + Hydrogen Chloride	→	Ammonium Chloride	1:1
Hydrogen + Chlorine	→	Hydrogen Chloride	1:1
Carbon Monoxide + Oxygen	→	Carbon Dioxide	2:1
Methane + Oxygen	→	Carbon dioxide + Water	1:2

REMEMBER

Gay Lussac law of combining volumes

When gases react, the volumes consumed in the reaction bear a simple whole number ratio to each other and to the volumes of any gaseous product of the reaction, all volumes being measured under the same conditions of temperature and pressure.

Nitrogen Monoxide	+	Oxygen	→	Nitrogen Dioxide
2 Volumes ($50cm^3$)	+	1 Volume ($25cm^3$)	→	2 Volumes ($50cm^3$)

When these 2 colourless gases mix they form a **brown** gas which occupies a smaller volume than the combined volume of the original gases

Avogadros Law *or theory or hypothesis*

Equal volumes of gases under the same conditions of temperature and pressure , contain equal numbers of molecules

Avogadros Law

Hydrogen + Chlorine $\longrightarrow$ Hydrogen Chloride

1 Vol 1 Vol 2 Vol

Assuming the volume is not constant then V = n

So the correct equation is

n Molecules hydrogen + n Molecules Chlorine $\longrightarrow$ 2n Molecules Hydrogen Chloride

Or

1 Molecule hydrogen + 1 Molecule Chlorine $\longrightarrow$ 2 Molecules Hydrogen Chloride

$$H_2 + Cl_2 \longrightarrow 2HCl$$

Other reactions behaved the same

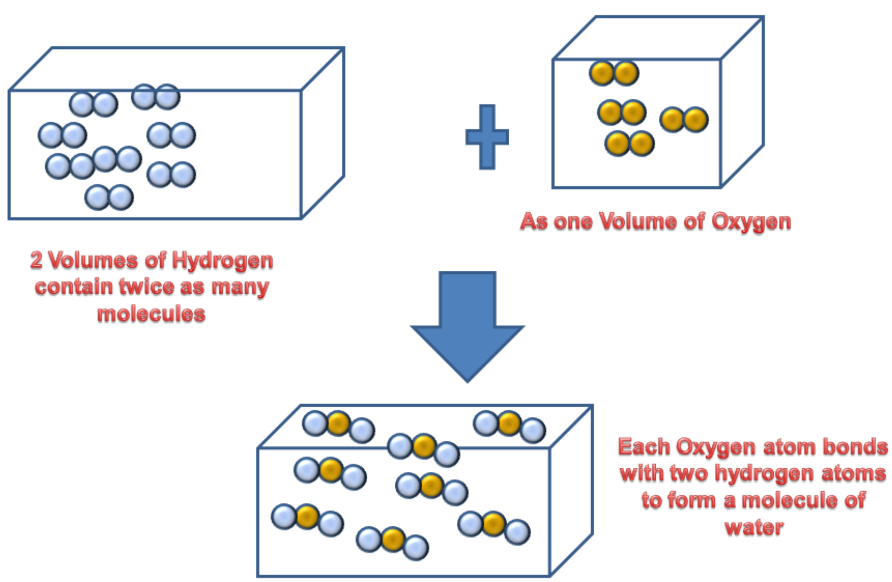
$2H_2$	+	O_2		$2H_2O$
(2 vols)		(1 vol)	$\longrightarrow$	(2 vols)
$2NO$	+	O_2		$2NO_2$
(2 vols)		(1 vol)		(2 vols)

In other words, the ratio in which the volumes of gas combine is the same as the ratio in which the molecules of gases combine.

When dealing with Gaseous reactions and only gaseous reaction the words volume and molecule can be interchanged

Using this theory he proposed that the water molecule contained two hydrogen atoms for every oxygen atom. This permitted him to explain Gay Lussacs results

Avogadros Law



Uses of Avogadros Law

If the ratio of combining gases is known then we can use that info to write the chemical equation

Hydrogen + Chlorine		$\rightarrow$	Hydrogen Chloride
1 Vol	1 Vol		2 Vol

The equation is:

$$H_2 + Cl_2 \longrightarrow 2HCl$$

The Mole

Molecules are small and we cannot measure just one molecule of a substance

But Avogadro's law lets us at s.t.p. measure a set number of molecules

Ok for gases but a problem combining other materials

Hydrogen (gas).... with Sodium (solid) to make Sodium Hydride

$$H_{2(g)} + 2Na_{(s)} \longrightarrow 2NaH_{(s)}$$

The chemical reaction tells us that one molecule of Hydrogen reacts with 2 atoms of sodium to make 2 molecules of sodium hydride

$$H_{2(g)} \quad + \quad 2Na_{(s)} \longrightarrow 2NaH_{(s)}$$

Because sodium is a solid avagadro law and Guy-Lussac's law do not apply and we need a universal unit that is easily measurable

We call it the *Mole*

Definition

A mole of a substance is the amount of that substance that contains as many particles (atoms or molecules or ions) as there are atoms of ^{12}C in 12 grams of ^{12}C

Why

The number of atoms of ^{12}C (isotope) in 12g of ^{12}C can be measured

It is approximately **6×10^{23}**

602,214,199,000,000,000,000,000 atoms!

The is the number of particles per mole for all substances and is called ***Avagadro's constant***

A mole of water molecules.

Weigh out 18.015 grams of water to get $6.02X10^{23}$ water molecules?

That's one mole of water

Add the atomic mass of hydrogen (H) twice to that of oxygen (O).

$$\mathbf{1.008 + 1.008 + 15.999 = 18.015.}$$

What's the point here ?

In one mole of neon there are **6 x 10^{23}** atoms

In one mole of Oxygen there are **6 x 10^{23}** molecules

In one mole of water there are **6 x 10^{23}** molecules

In one mole of sodium chloride which consists of sodium ions and chloride ions there are **6 x 10^{23}** sodium ions and **6 x 10^{23}** chloride ions

Remember the Definition

A mole of a substance is the amount of that substance that contains as many particles (atoms or molecules or ions) as there are atoms of ^{12}C in 12 grams of ^{12}C

Molar Volume of Gases

At s.t.p one mole of gas occupies a volume of 22.4 litres

Deducted by experimentation

A mole of oxygen gas weighs 32 grams and takes up a volume of 22.4 litres @ s.t.p

As a mole of any gas contains 6 x 10^{23} molecules then according to Avogados Law ...a mole of any gas will occupy 22.4 L @ s.t.p

The volume occupied by one mole of a gas is called its Molar Volume

Thus the Molar Volume of all gases @ s.t.p is 22.4L

You will find this value on your exam paper

As we know the Molar Volume we can deduct the density of a gas :

Example

Calculate the density of Carbon Dioxide @ s.t.p (given: C=12, O=16, mol Vol = 22.4L @s.t.p

Solution

Relative Molecular Mass (M_r)= 12+16+16 = 44

i.e. :One mole of CO_2 = 44g

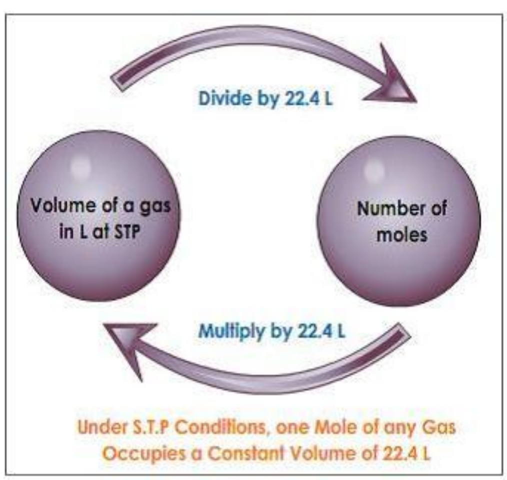
and: 44g of CO_2 occupies 22.4L @ s.t.p

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\text{Density} = \frac{44g}{22.4L}$$

$$\text{Density} = 1.96g/L$$

Converting from volume to moles and back



Questions

- What is the Volume in litres at s.t.p. Of 0.25 moles of chlorine gas

1 mole	=	22.4 L at s.t.p.
0.25 moles	=	0.25 x 22.4L at s.t.p.
	=	5.6L

- How many moles are there in 280cm^3 of nitrogen gas at s.t.p.

22.4L	=	22400cm^3 at s.t.p.
22400cm^3	=	1 mole at s.t.p.
280 cm^3	=	$\frac{280}{22400}$ moles
	=	0.0125 moles

Relative Molecular Mass

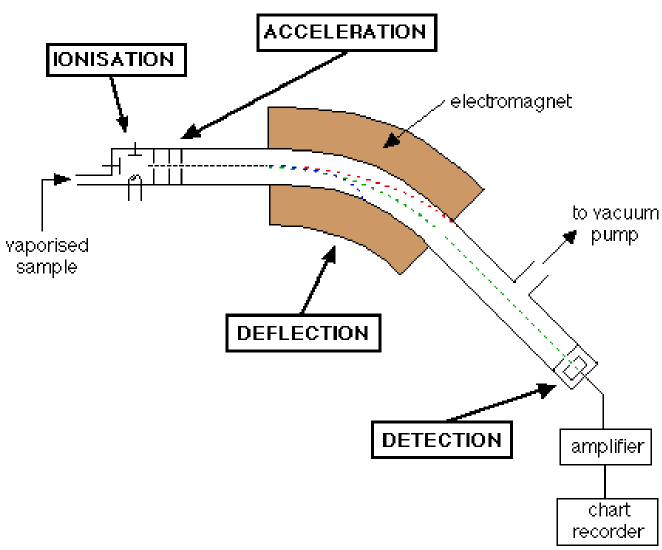
Calculated by adding the relative atomic masses of the constituent atoms. For example, ethanol, CH_3CH_2OH, has a M_r of 46.

$$C = 12 \; ; H = 1 \; ; O = 16$$

There are 2 x C = 24 ; 6 x H = 6 ; 1 x O = 16 total = 46

Measuring Relative Molecular Mass

A mass spectrometer is used to measure the relative molecular mass of an element



We can also use it to determine the relative molecular mass of a substance

The molecules are ionised and broken into positively charged fragments with different masses

These are separated and the relative amounts recorded

Usually these fragments contain the parent ion which has the same **mass** as the relative molecular mass of the element

Molar Mass

Molar mass, symbol M, is the mass of one mole of a substance in grams (chemical element or chemical compound).

Example

carbon is 12g

Aluminium is 27g

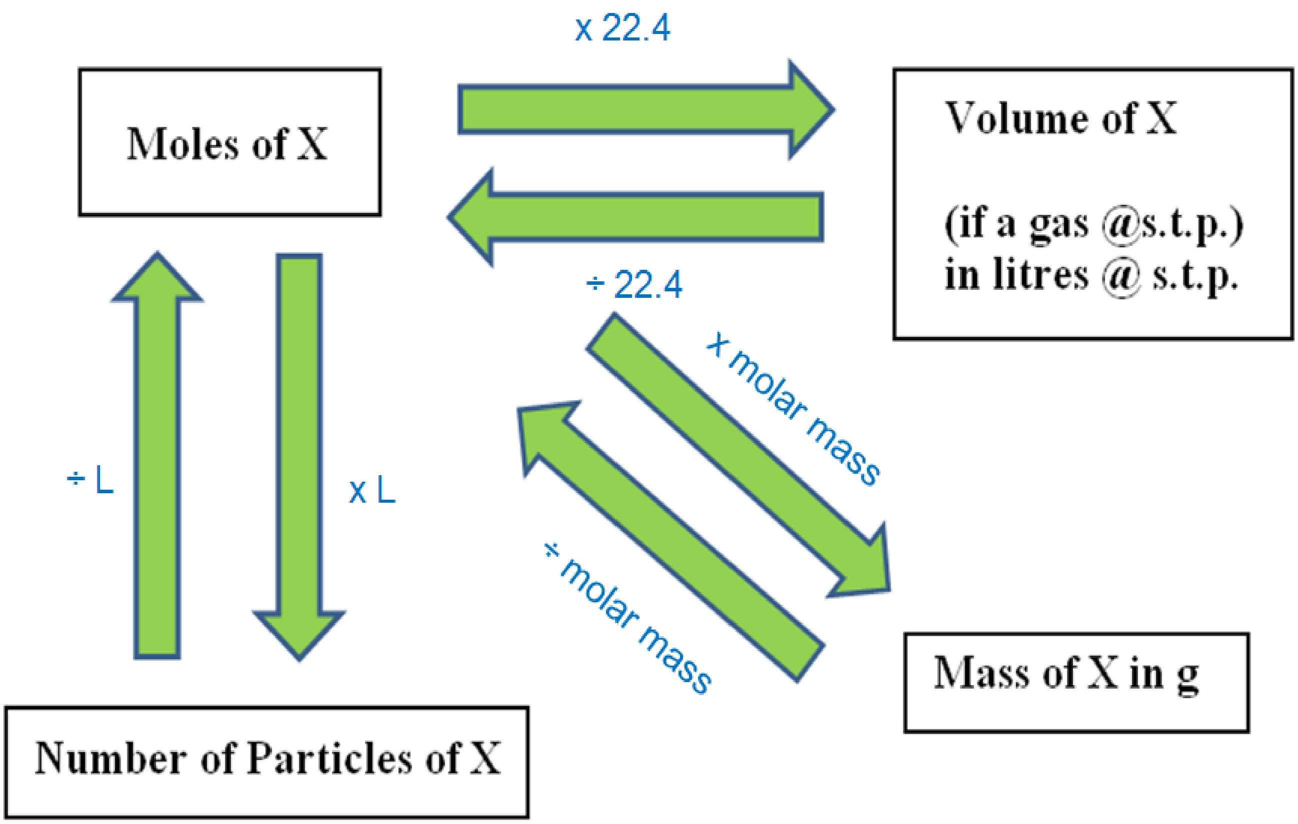
Sulfur is 32g

Molar mass has the same numerical value as its relative molecular mass but the units differ

M_r is measured on the ^{12}C scale and molar mass is measured in g mol^{-1}

Substance	Relative Molecular Mass	Molar Mass
Sulfuric Acid H_2SO_4	98	98 g mol-1
Sucrose $C_6H_{12}O_6$	342	342 g mol-1
Water H_2O	18	18 g mol-1
Carbon Dioxide CO_2	44	44 g mol-1
Oxygen O_2	32	32 g mol-1

A useful diagram



- Question
  - How many <u>molecules</u> are there in 840 cm^3 of carbon dioxide gas at s.t.p.

22 400 cm^3 @s.t.p.	=	1 mole
840 cm^3 @s.t.p.	=	840 ÷ 22 400 moles
	=	0.0375 moles
1 mole	=	6×10^{23} molecules
0.0375 moles	=	$0.0375 \times 6 \times 10^{23}$ molecules
	=	0.225×10^{23} molecules
	=	2.25×10^{23} molecules

- Question
  - How many atoms are there in 560cm^3 of propane gas at s.t.p. Given that the chemical formula for propane is C_3H_8?

560 = 560 ÷ 22400

560 = 0.025 moles

1 mole = 6×10^{23}

0.025 moles = 0.025 moles ÷ 6×10^{23} = 0.15×10^{23}

0.025 = 11* x 0.15×10^{23} atoms

1.65×10^{23} **atoms**

** 11 atoms in propane*

- Question
  - What is (a) the volume at s.t.p. and (b) the number of molecules in 5.5g of CO_2

(a) Mr of CO_2 = 44

44g CO_2 = 1 mole

5.5g = 5.5 / 44 = 0.125 moles

1 mole gas = 22.4 Litres

0.125 moles = 0.125 x 22.4 = 2.81

b) 1 mole = 6×10^{23}

0.125 moles = $0.125 \times 6 \times 10^{23}$

0.125 = 0.75×10^{22} molecules

- Question
  - What is the mass in grams (g) of 280 cm3 of carbon dioxide gas a t s.t.p

22400cm^3 CO_2 at s.t.p = 1 mole

280 = 280 ÷ 22400 = 0.125 moles

Mr of CO_2 = 44

1 mole of CO_2 = 44g

0.125 moles = 0.0125 x 44 = 0.55 grams

- Question
  - Which of the following come closest to an ideal gas

$$H_2 \ ; \ HF \ ; \ F_2$$

- Hydrogen because it has the weakest intermolecular forces

Hydrogen because it has the weakest intermolecular forces

The Combined Gas Laws

Combined Gas Law

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

- P_1, V_1, and T_1 are the initial pressure, volume and Kelvin temperature.
- P_2, V_2 and T_2 are the final pressure, volume and Kelvin temperature.
- Pressure can be in any units as long as it's the same for P_1 and P_2.
- Volume can be in any units as long as it's the same for V_1 and V_2.
- Temperature **<u>must</u>** be in Kelvin's for T_1 and T_2.

  To convert from degrees to Kelvin's add on 273.

  For example $25^o = 25 + 273 = 298$ K

S.T.P. (Standard, Temperature and Pressure)

273 K, and 101,325 Pa.

Question

N_2 gas has a volume of $75cm^3$ and a temp of 27^oC and a pressure of 95 kPa

Find the vol that the gas would have at s.t.p

Given

$V_1 = 75cm^3$

$p_1 = 95$ kPa

$T_1 = 27^oC + 273 = 300K$

s.t.p

$V_2 = ?$

$p_2 = 100$ kPa

$T_2 = 0^oC + 273 = 273K$

Substitute into

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

Since the combined laws are derived
From Charles Law we must convert
Temp into Kelvin

$$\frac{95 \times 75}{300} = \frac{100 \times V_2}{273}$$

$$V_2 = \frac{95 \times 75 \times 273}{300 \times 100}$$

$$= 64.84\ cm^3$$

Rememberto keep the units on either side of the equation consistent

Another example

A sample of gas exerts a pressure of 83,326 Pa in a 300 cm^3 vessel at 25°C. What pressure would this gas sample exert if it were placed in a 500 cm^3 container at 50°C?

$P_1 = 83{,}326 \text{ Pa}$ $\quad\quad$ $P_2 = ?$

$V_1 = 300 cm^3$ $\quad\quad$ $V_2 = 500 cm^3$

$T_1 = 25 + 273 = 298K$ $\quad\quad$ $T_2 = 50 + 273 = 323K$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{83{,}326 \times 300}{298} = \frac{P_2 \times 500}{323}$$

$$\frac{83{,}326 \times 300 \times 323}{500} = P_2$$

$$54{,}189.86 \text{ Pa} = P_2$$

The Kinetic Theory of Gases

Developed by **James Clerk Maxwell** and **Ludwig Boltzmann**.

Theory assumes that:

1. Gases are made up of particles whose diameters are negligible compared to the distances between them.
2. There are no attractive or repulsive forces between these particles.
3. The particles are in constant rapid random motion, colliding with each other and with the walls of the container.
4. The average kinetic energy of the particles is proportional to the Kelvin temperature.
5. All collisions are perfectly elastic .

Ideal Gases versus Real Gases

An **ideal gas** is one which obeys all the gas laws and under all conditions of temperature and pressure.

No such gases exists, but real gases behave most like an ideal gas at high temperatures and at low pressures.

Under these conditions, the particles of a real gas are relatively far away from each other, and the assumptions of the kinetic theory are reasonably valid.

Why do real gases deviate?

1. Intermolecular forces are present.
   a. (Such as dipole – dipole, Van der Waals, etc.,)
2. Molecules have volume.
3. Collisions are not perfectly elastic.

Equation of State for an Ideal Gas

$$pV = nRT$$

Measure	Symbol	Unit
Pressure	p	Pa
Volume	V	m^3
Number of moles	n	mol
Gas constant	R	$JK^{-1}mol^{-1}$
Temperature	T	K

Question

What volume will 24 g of O_2 occupy at 20°C and a pressure of 89000 Pa.

$$p = 89000\,Pa$$

$$V = ?$$

$$n = \frac{\text{acutal mass}}{M_r} = \frac{24}{32} = 0.75 \text{ mols}$$

$$R = 8.3\,J\,K^{-1}\,mol^{-1}$$

$$T = 20 + 273 = 293K$$

$$pV = nRT$$

$$89000 \times V = 0.75 \times 8.3 \times 293$$

$$V = \frac{0.75 \times 8.3 \times 293}{89000}$$

$$V = 0.0204 \ m^3$$

Combined gas law

PV = R x T x n

This relationship is written as

$$\mathbf{PV = nRT}$$

Where R = a universal gas constant (value of R = 8.31 JK^{-1} mol^{-1})

Calculations involving the ideal gas law

Question

8.4g of a gas occupies a volume of 3 litres at 77°C and 100, 000 Pa

a) How many moles are present ?

b) What is the Relative Molecular mass of the gas ?

Answer (a)

PV = nRT

- P = 100, 000 Pa
- V = 3 L or 3 x $10^{-3}m^3$
- R = 8.31 J $K^{-1}Mol^{-1}$
- T = 77°C = 350 K
- N = amount of gas in moles

$$= \frac{100{,}000 \times 3 \times 10^{-3}}{8.31 \times 350}$$

$$= 0.103 \text{ moles}$$

Answer (b)

- 0.103 moles has a mass of 8.4g
- 1 mole has a mass of 8.4 ÷ 0.103 g = 81.55g

∴ **Relative Molecular mass** (Mr) = 81.55

All the Law's Combined