CHAPTER 5

5.0 STOICHIOMETRY AND MOLE CONCEPT

This is the aspect of chemistry that deals with quantities of substances. These quantities can be expressed in terms of number of moles, mass, volume and Avogadro‟s number. And these are based on;

i. Conservation of mass
ii. Relative masses of atoms
iii. The mole concept

This concept is used in all areas of chemistry which include;

i. predicting the quantities of reactants and products
ii. interpreting analytical results in chemistry
iii. preparation of standard solutions
iv. ascertaining the cost effectiveness of large scale chemical reactions

5.1 THE MOLE CONCEPT

The mole concept is the expression of quantities (i.e. amount of solute in solution or solvent) in terms of number of moles, mass, volume and Avogadro‟s number.

5.1.1 THE MOLE AND THE ADVOGADRO'S NUMBER

The ***mole*** is the chemist way of measuring the amount of a substance. One mole of a chemical species contains exactly one gram atomic mass, molecular mass or formula mass of the species. For example:

1 mole = One atomic mass

Fluorine = 19g

Calcium = 40g

A mole of specie also contains a constant number of the elemental particles, atoms, ions molecules etc. The number is 6.02×10^{23} and it is called the Avogadro‟s number. One mole ofspecie will contain one atomic mass of that specie and will also contain the Avogadro‟s numberof particles.

Table 5.1 Relationship between atomic mass and the Avogadro's number

ONE MOLE	ONE ATOMIC MASS	ONE AVOGADROS NUMBER
Hydrogen	1g	6.02×10^{23} atoms
Boron	11g	6.02×10^{23} atoms
Fluorine	19g	6.02×10^{23} atoms

There is a relationship between one mole, one gram atomic mass (gram atomic weight) and the number of particles (Avogadro‟s number) of a chemical species. Their values are inter - changeable. It is also important to note that when one is converting from any of these three quantities to another, one mole, one atomic mass and one Avogadro number is used as the conversion factor.

Example 5.1
Express as mole (a) 24g of carbon (b) 10g of Neon (c) 120g of calcium

Solution

Since we are expected to convert from mass to mole, then our conversion factor will be 1 mole = 1 gram atomic mass

(a)
1 mole = 12g
$\underline{x}$ mole = 24
Note that like terms are always on the same side of the equation. Cross multiply and make x subject

24g x 1 mole = 12g X $\underline{x}$mole

$$\frac{24g \ x\ 1\ mole}{12g} = x\,mole = 2\,moles$$

: - 24g of carbon is 2 moles

(b) 1 mole of Neon = 20g

$\underline{x}$ mole of Neon = 10g

$$x\,mol = \frac{10g\ x 1 mol}{20} = 0.5$$

:- 10g of Neon is 0.5 mol

(c) 1 mole of calcium = 40g

X mole of calcium = 12g

$$x\,mol = \frac{120g\ x1mol}{40} = 3$$

12g of calcium is 3 moles

Example 5.2

What is the mass of 0.3mol of phosphorus and how many atoms does it have?

Solution

For the first part of the question, we are expected to covert from mole to mass. Therefore, our conversion factor is:

1 mole = 1 gram atomic mass

1 mole phosphorus = 31g

0.3 mole phosphorus = x g

Note that like terms are always on the same side of the equation. Cross multiply and make *x* subject

1 mole x xg = 31g x 0.3mol

$$xg = \frac{31g\ x0.3mol}{1mol} = 9.3g$$

: - 0.3mol of phosphorus has mass of 9.3g.

In the second part of the question, you are expected to calculate the number of atoms (Avogadro's number) in 0.3moles or 9.3 gram phosphorus. Depending on how we want to solve this problem, ourconversion factor can either be

i) 1 mole = 1 Avogadro number (6.02 x 10^{23}) OR

ii) 1 gram atomic mass = 1 Avogadro number (6.02 x 10^{23})

But whichever path we take, we will still arrive at the same answer.
Solving from the first path, we have,
1 mol = 6.02 x 10^{23}
0.3mol = x
xx 1mol = 0.3mol x 6.02 x 10^{23}

$$x = \frac{0.3mol\,x6.02x10^{23}}{1mol}$$

x= 1.806 X 10^{23} atoms in 0.3mole phosphorus

Try and solve the question, using the second path way.

5.1.2 THE MOLE AND THE GRAM FORMULA MASS

The ***gram formula mass*** is the quantity of a chemical specie whose mass in gram is numerically equal to the sum of all the atomic masses of its constituent elements. When the formula is for an element, e.g. B, F, O, Zn, N, etc we use the atomic mass. Also when the formula is that of a molecule (e.g. H_2O, CH_4, $CaCO_3$etc.) the term gram molecular mass is used in place of gram formula mass. The term gram formula mass is still retained for ionic compounds since it also represent a mole and one Avogadro number.

Example 5.3

Determine the gram formula mass of $CaCO_3$

Solution

The atomic masses of the constituent elements are

Element		Gram Atomic mass
Ca		40
C		12
O	(16 x 3) =	48

Gram molecular mass = 40+12+48=100g

The gram atomic mass of oxygen is multiplied by three because there are three atoms of oxygen in the compound's formula. Therefore, the sum in gram of the masses of all the atoms in the formula $CaCO_3$ is 100g.

This, implies that one mole of $CaCO_3$ is equivalent to 100g and has 6.02×10^{23} number of $CaCO_3$ molecules.

5.1.3 MOLE, MASS AND VOLUME RELATIONSHIP

At standard temperature, (0^OC or 273k) and standard pressure (760mmHg or 101.3×10^3 pa), the volume occupied by one mole of any gas is a constant value. That value is called the molar volume and it is numerically equal to $22.4dm^3$• For example, the gram molecule mass of one mole of carbondioxide (CO_2) is

Element	Gram Atomic Mass
C	12
O	16 x 2 = <u>32</u>
	<u>449</u>

This one mole, contains 6.02×10^{23} molecules and occupies a volume of $22.4dm^3$ at stp

In summary,

1 mole = one gram formula mass

1 mole = 6.02×10^{23} atoms, molecules, formulas, species etc.

1 mole = $22.4dm^3$ for any gas at s.t.p

Examples 5.4

Calculate the (a) volume at s.t.p of ammonia in 8.50g of ammonia gas.

(b) How many molecules of ammonia will there be in the sample

(c) Express the volume at s.t.p in moles (one gram atomic mass of NH_3 = 17g, one Avogadro number = 6.02×10^{23})

Solution

(a) 17g = 22.4 dm^3 (conversion factor) 8.59 = x

$$\underline{x} = \frac{8.5g x 22.4 dm^3}{17g} = 11.2 dm^3$$

(b) 179 = 6.02×10^{23} molecules (conversion factor)

8.5g = x

$$\underline{X} = \frac{8.5g x 6.02 x 10^{23}}{17g} =$$

(c) 1 mole = 22.4dm^3 (conversion factor)

x = 11.2dm^3

$$\underline{x} = \frac{11.2\text{dm}^3 \text{ x } 1 \text{ mole}}{22.4\text{dm}^3} = 0.5 mile$$

5.1.4. MOLE RATIO, MASS AND VOLUME RELATIONSHIP IN CHEMICAL EQUATION

The whole number in front of the reactant and product formula in a chemical reaction represents the number of moles of reactants, reacting to give the number of moles of product. These whole numbers are the mole ratio of the reactants and products in a chemical reaction. When no whole number is written in front of a formula in a chemical equation, it implies that the mole ratio is one. Example

Equation	$2H_2+$	O_2 $\longrightarrow$	$2H_2O$
Mole ratio	2	1	2
Reacting mass	(2x2)	(16x2)	(18x2)
Reacting mass	4g	32g	36g

From the above example, it is clear that the mass that reacted is simply the product of the number of moles and the gram formula mass.

: - Reacting mass = Number of moles x gram formula mass Rearranging, we get

$$\text{Number of moles} = \frac{\text{Re acting mass gram}}{\text{Gram formula mass}}$$

Example 5.5

A sample of CO_2 has a mass of 11.0 grams

(a) Calculate the number of moles of CO_2 in the sample

(b) What volume will the sample occupy at s.t.p. (C = 12 0 =16)

Solution

(a) Reacting mass= 11.0g
Formula mass= 44g
No. of mole = x

Reacting mass = formula mass x number of moles

$$numberof\ \ moles = \frac{\mathrm{Re}\ actingmass}{formulamass}$$

$$\frac{11.0g}{44g} = 0.25mol$$

(b) At Stp 1 mole = 22.4dm^3
0.25mole = x dm^3

$$X = \frac{0.25mol\ x\, 22.4dm^3}{1} = 5.6dm^3$$

Example 5.6

Calculate the mass of carbon (iv) oxide CO_2 produced on burning a mass of 104g ethyne C_2H_2 (C=12, O=16, H=l)

Solution

	$2C_2H_2$ +	$5O_2$ $\longrightarrow$	$4CO_2$ +	$2H_2O$
Mole ratio	2	5	4	2
Gram formula	2 x 26,	32 x 5,	44 x 4	18 x 2
Mass	52g	160g	176g	36g

From the equation, 176g of CO_2 is produced on burning 52g of C_2H_2. What mass of CO_2 will be produced on burning 104g of C_2H_2?

As usual, arrange like terms on the same side of the two equations, cross multiply and make the unknown the subject

52g C_2H_2 produced 176g of CO_2

104g C_2H_2 producedxg of CO_2

$$x = \frac{104 x 176}{52} = 352$$

Example 5.7

What mass of zinc tetraoxosulphate (VI) is obtained from reacting 10g of zinc with excess dilute tetraoxosulphate (VI) acid. (Zn = 65, S =32, O=16)

$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_2$

Solution

Question summary

What mass of $ZnSO_4$ is obtained from 10g of Zn?

From the equation, the conversion factor is 161g $ZnSO_4$ is obtained from 65g Zn

i.e. 161g$ZnSO_4$ = 65g Zn

X g$ZnSO_4$ = 10g Zn

$$X = \frac{161 \text{ K } 10}{65} = 24.8\text{g ZnSO4}$$

5.2. STOICHIOMETRIC CALCULATIONS INVOLVING A LIMITING REAGENT

So far, we have been dealing with reaction were reactants are mixed in stoichiometric quantities. That is reactants reacts at exactly the correct amount and are completely used up in the reaction.

There are some other instances where some reactants are not enough to completely react with the others, or when one reactant is in excess of what would exactly and completely react with the other reactant. In this case, the insufficient reactant will be consumed before the reactants in excess are used up. And as such the quantity of the product is determined by the insufficient reagent, which when used up no more products can be formed. The insufficient reagents limit the amount of the product that can be formed and therefore called the **limiting reactant or reagent.**

Example 5.8
What mass of zinc is required to completely react with 73.9g of hydrogen tetraoxosulphate (VI) acid?(Zn = 65, S =32, O=16)
$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_2$

Solution
Question summary
The question is asking what quantity of zinc will completely use up 73.9g of hydrogen tetraoxosulphate (VI) acid.

From the equation, one mole of zinc reacts completely with one mole of hydrogen tetraoxosulphate (VI) acid and we were giving the reacting mass of H_2SO_4. We can thenuse this value to calculate the number of mole of H_2SO_4 that reacted.

Reacting mass (H_2SO_4) = molecular mass x number of moles

Therefore, $\frac{Reacting\ mass}{molecular\ mass} = number\ of\ moles\ of\ \mathrm{H2}SO4$

Number of moles of H_2SO_4 = $\frac{73.9\mathrm{g}}{98\mathrm{g}/mol} = 0.754 mol\ of\ H2SO4$

Recall from the equation that one mole of zinc will completely react with one mole of H_2SO_4. Therefore, since the number of moles of H_2SO_4 that reacted is 0.754mol, then it will react with 0.754mol of Zn.

Now to get the mass of zinc that reacted we use the same formula

Reacting mass (Zn) = molecular mass x number of moles

Reacting mass (Zn) = 65g/mol x 0.754 moles

Reacting mass (Zn) = 49.01g

This question can also be solved using a direct and quick method thus;

$$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_2$$

Mole ratio: 1 1 1 1

Gram formula: 1 x 65, 1 x 98 1x 161 1 x 2

Mass: 65g 98g 161g 2g

From the equation, 1mol of Zn react with 1mol of H_2SO_4

i.e. 65g Zn98g ——— H_2SO_4

Xg ——— 73.9g

Cross multiply and make Xg subject

$$Xg = \frac{65g/mol \ x73.9g}{98g/mol} = 49.01g$$

The result obtained from the last example tells us that 49.01g of zinc mixed completely with 73.9g of H_2SO_4.However, if any of this reactant is reduced for example Zn to 35.0g, it will limit the amount of product that will be formed. In any stoichiometric problem, it is also important to determine which reactant is limiting in order to accurately determine the amount of product that will be formed.

Example 5.9

What mass of zinc tetraoxosulphate (VI) can be produced when 35.0g of zinc is allowed tocompletely react with 73.9g of tetraoxosulphate (VI) acid? (Zn = 65, S =32, O=16)

$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_2$

Solution

Question summary

The question is asking what quantity of zinctetraoxosulphate (VI) will be produced by completely reacting 35.0g zinc with 73.9g of tetraoxosulphate (VI) acid.

From the equation, one mole of zinc will react completely with one mole of tetraoxosulphate (VI) acid and we were giving the reacting mass of both Zn and H_2SO_4. We can then use these values to calculate the number of mole of the reactants.

Number of moles of H_2SO_4 $= \frac{73.9\text{g}}{98\text{g}/mol} = 0.754 mol\ of\ H2SO4$

Number of moles of Zn$= \frac{35.\text{g}}{65\text{g}/mol} = 0.54 mol\ of\ Zn$

From the equation one mole of each reactant will completely react with the other. It becomes obvious that zinc is the limiting reagent. Also, since one mole of zinc will produce one mole of zinc tetraoxosulphate (VI), then the mole of zinc should be used to calculate quantity of zinc tetraoxosulphate (VI) that will be produced.

Mass ($ZnSO_4$) = molecular mass x number of moles

Mass ($ZnSO_4$) = 98g/mol x 0.54 moles

Mass ($ZnSO_4$) = 52.78g

5.3OTHER METHODS OF EXPRESSING CONCENTRATION OF SOLUTIONS

There are other methods of expressing the concentration of solutions or solvents which are notcommonly used. Some of them are tabulated here in Table 5.1.

Table 5.1 summary of Concentration Expression

Unit	Symbol	Definition	Relationship
Molarity	M	Number of moles of solute per litre of solution	$M = \frac{n}{\text{Litre (L) of solution}}$
Molality	M	Number of moles of solute per kilogram of solution	$m = \frac{n}{\text{Kg solvent}}$
Mole Fraction	X	Ratio of the moles of solute to the total	$X = \frac{n2}{n1+n2}$

		moles of solute plus solvent	
Normality	N	Number of equivalent of solute per litre of solution	**N**=$\frac{equivalent}{\text{litre of solvent}}$
Percent by weight	Wt %	Parts by weight of solute per 100 parts by weight of solution.	Wt %=$\frac{g2}{g1+g2}$ X 100
Percent by Volume	Vol%	Parts by weight of solute per 100 parts by volume of solution	Vol%=$\frac{V2}{V1+V2}$ X 100

PRACTICE QUESTIONS

1. What volume will the following gases occupy at STP

i) 42g of N_2

ii) 16g of O_2

iii) 0.2mol of CO_2

iv) 3.02×10^{23} molecules of CO

v) 1.20×10^{23} molecules of CH_4

2. (a) How many moles are present in 1g of sodium hydroxide?

(b) What is the mass of 1.0mol of oxygen atoms?

3. Using 12g of copper, what mass of Copper (ii) trioxonitrate (v) will be formed in the reaction

$3Cu + 8HNO_3 \longrightarrow 3Cu(NO_3)_2 + 2NO + 4H_2O$

Cu = 63.5, O = 16, N = 14, H= 1)

4. How many moles are contained in 47g of magnesium trioxonitrate (v) $Mg(N0_3)_2$

(a) How many molecules of $Mg(NO_3)_2$ are in the sample

(b) How many moles are there in:

(i) 6g of magnesium

(ii) 6g of oxygen gas