Unit - 2
Stoichiometry

Stoichiometry:
The quantitative relationship between reactant and product in a chemical reaction is given by stoichiometry. Hence, stoichiometry is the relative number of atoms and molecules which are involved in the chemical reaction.

OR

The branch of chemistry which deals about the relative number of atoms and molecules involved in chemical combination is called stoichiometry.

1. Dalton's Atomic Theory
Postulates:

a. All matter consist of smallest discrete, indivisible particles called atom, which is the smallest unit of matter which can take part in chemical reaction

b. Atoms of same elements are identical in all respect but differ from atoms of other element.

c. Atoms cannot be created nor be destroyed or cannot be transform into atom of other elements.

d. Atoms of different element can combine with each other in fixed simple whole number ratio to form compound molecule.

e. The relative number and types of atom are constant in a given compound.

f. A chemical reaction is a rearrangement of atoms.

Laws of Stoichiometry (Law of Chemical Combination)

1. Law of Conservation of mass
2. Law of definite or Constant ~~Properties~~ Porportion
3. Law of Multiple Proportion
4. Law of reciprocal Proportion
5. Law of Gaseous Volumes

1. Law of Conservation of Mass

It states that, in a chemical reaction total mass of reactants is equal to the total mass of product. Hence, during chemical combination mass is neither gained nor lost. ~~Th~~ i.e. mass is conserved

Experimental Verification : Landolt's Experiment

Hans Heinrich Landolt, a German chemist proved the law of conservation of mass experimentally by using H-type glass tube filled with silver nitrate solution in limb A and hydrochloric acid in limb B as in the figure. The tube was sealed and weighed and the solutions were mixed tilting the tube up and down, then they reacted to give white precipitate of silver chloride and nitric acid.

The weight of the tube along with solution after reaction was taken. Finally, it was found that the weight of the tube with solution before reaction was same after the reaction which is in favour of the law of conservation of mass.

$$AgNo_3\,(aq) + HCl\,(aq) \longrightarrow AgCl\downarrow + HNO_3\,(aq)$$

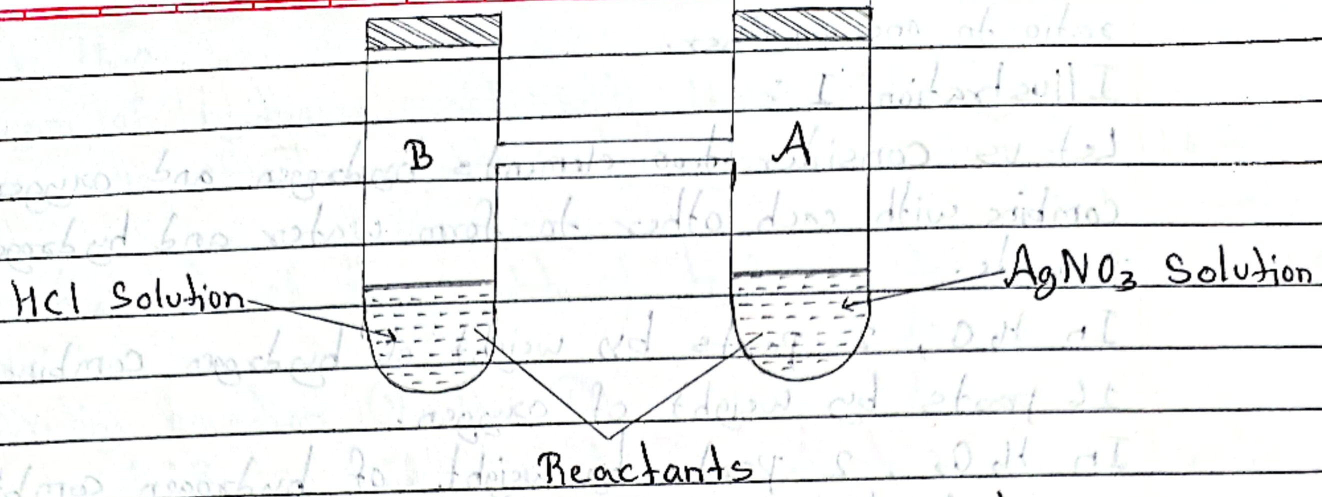

figure 2.1 : Landolt's Experiment

2. Law of Definite or Constant Proportions

The law of definite proportion states that a pure chemical compound always contains the same element combined together in ~~a~~ the same proportion by weight whether that compound is taken from different source or origin.

For example : ~~Taking an example of~~ If pure samples of water be taken from different source such as rain water, tap water etc. After analysis it is found that each sample contains Hydrogen and oxygen element combined together in the ratio 1:8 by mass.

Limitation : This law is not applicable for same compound molecules containing different isotopes. For example Water containing three different ~~isos~~ isotopes i.e. H_2O, D_2O and T_2O.

3. The law of Multiple Proportions

It states that "When one element combines with another element to form two or more different compounds, then the weight of one of the element which combines with the constant weight of other bears the simple whole-number ratio to one another.

Illustration I :

Let us consider two elements hydrogen and oxygen that combine with each other to form water and hydrogen ~~peroxide~~ Peroxide.

In H_2O, 2 parts by weight of hydrogen combine with 16 parts by weight of oxygen.

In H_2O_2, 2 parts by weight of hydrogen combine with 32 parts by weight of oxygen.

Thus,

The weight of oxygen (16 parts and 32 parts) combined with the same weight of hydrogen (2 parts) bears to each other in a simple whole-number ratio = 16 : 32 = 1:2

4. The law of reciprocal Proportions:

It states that "When two different elements combine seperately with the same weight of third element, the ratio in which they do so will be same or some simple multiple of the ratio in which they unite with each other".

Illustration

The combination of three different elements, carbon, hydrogen and oxygen forms carbondioxide, water and methane.

In CO_2

12 gm of carbon combines with 32 gm of oxygen

1 gm of carbon combines with 32/12 gm of oxygen

In CH_4

12 gm of carbon combines with 4 gm of hydrogen

1 gm of carbon combines with 4/12 gm of hydrogen

The ratio of the weight of hydrogen and oxygen which combine seperately with the same weight of carbon is 4 : 32 or 1 : 8 —— (1)

In H_2O

2 gm of hydrogen reacts with 16 gm of oxygen.

The ratio of the weight of hydrogen to oxygen = 2:16 or

= 1:8 —(ii)

So the ratio of the weight of hydrogen to oxygen is 1:8.

Now,

Dividing equation (i) by (ii)

$\frac{1:8}{1:8} = 1:1$ which is a simple whole no. ratio.

Hence, this data proves the law of reciprocal proportion.

5. Gay Lussac's Law of Gaseous Volume

It states that "under the similar conditions of temperature and pressure, the volume of gas reactant and gas product bears a simple whole number ratio".

Illustration:

Hydrogen combines with nitrogen to give ammonia gas

$$\underset{3\ vol}{Hydrogen} + \underset{1\ vol}{Nitrogen} \longrightarrow \underset{2\ vol}{Ammonia}$$

The ratio of hydrogen, nitrogen and ammonia is 3:1:2 which is a simple whole number ratio that illustrates the gaseous Volume.

Solved Numerical

1. 1.81 gm of Copper was obtained by heating 2.26 gm of Copper oxide. In a separate experiment, 2.23 gm of Copper was dissolved on nitric acid, Copper nitrate so formed was ignited to give 2.67 gm of Copper oxide. Show that the above experimental data explain the law of definite proportion.

Solution:

Case I

Weight of Copper oxide = 2.26 gm

Weight of Copper = 1.81 gm
Weight of Oxygen = 2.26 - 1.81
= 0.45 gm
Ratio of Copper to oxygen = 4:1
Case II
Weight of Copper oxide = 2.67 gm
Weight of Copper = 2.23 gm
Weight of oxygen = 2.67 - 2.13
= 0.54 gm
Ratio of weight of Copper to oxygen = 4:1
Here,
the ratio of the weight of copper to oxygen is the same. It illustrate the law of definite/constant proportion.

2. 3.2 gm of sulphur combines with 3.2 gm of oxygen to form a compound under one set of condition. In another experiment 1.2 gm of sulphur combines with 1.2 gm of oxygen to form other compound which law is illustrated by this data?
Solution:
Case I
Weight of Sulphur = 3.2 gm
Weight of Oxygen = 3.2 gm
Ratio of ~~Co~~ sulphur to oxygen = 1:1
Also,
Case II
Weight of sulphur = 1.2 gm
Weight of oxygen = 1.2 gm
Ratio of sulphur to oxygen = 1:1
Here,
the ratio of the weight of ~~cop~~ sulphur to oxygen is the same. So it illustrate the law of definite proportion.

3. A sample of common salt having mass 0.25 gm contains 0.15 gm chlorine, similarily 0.25 gm of another sample contains 0.14 gm chlorine. Which chemical law do this data illustrate?

Solution:

Case I

Weight of common salt = 0.25 gm

Weight of chlorine = 0.15 gm

Weight of sodium = 0.25 - 0.15

= 0.10 gm

Ratio of weight of chlorine to sodium = 3:2

Also,

Case II

Weight of common salt = 0.25 gm

Weight of chlorine = 0.14 gm (approx 0.15 gm)

Weight of sodium = 0.25 - 0.15

= 0.10 gm

Ratio of weight of chlorine to sodium = 3:2

Here,

The ratio of weight of chlorine to sodium is the same in both cases. So, this experiment illustrate the law of definite proportion.

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4. A metals forms two oxides A and B. 3 gm of A and B contains 0.72 gm and 1.16 gm oxygen respectively. Calculate the masses of the metal which combine with 1 gm of oxygen in each case. Which law does it illustrate?

Solution:

In oxide A

Weight of oxide A = 3 gm

Weight of oxygen = 0.72 gm

Weight of metal = 3 - 0.72 = 2.28 gm

Now, 2.28 gm of metal combines with 0.72 gm of oxygen

1 gm of metal combines with $\frac{0.72}{2.28}$ gm of oxygen

$= 0.31$

In oxide B

Weight of oxide B = 3 gm

Weight of oxygen = 1.16 gm

Weight of metal = 3 - 1.16

= 1.84 gm

Now,

1.84 gm of metal combines with 1.16 gm of oxygen.

1 gm of metal combines with $\frac{1.16}{1.84}$ gm of oxygen

= 0.63 gm

Thus,

The ratio of weight of oxygen which combines with fixed weight of metal (1 gm) in both cases is 0.31 : 0.63

$= \frac{0.31}{0.31} : \frac{0.63}{0.31}$

$= 1 : 2$

Here, 1:2 is a simple whole no. ratio. This proves the law of multiple proportion.

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5. Carbon dioxide contains 27.27% of carbon, carbon disulphide contains 15.97% of carbon and sulphur dioxide contains 50% of sulphur. Show that these data are in agreement ~~of~~ with the law of reciprocal proportions.

Solutions:

In Carbon dioxide:

% of Carbon = 27.27

% of Oxygen = 72.73

27.27 gm of carbon combine with 72.73 gm of oxygen
1 gm of carbon combines with 2.667 gm of oxygen.

In carbon disulphide
% of carbon = 15.97
% of sulphur = 84.03
15.97 gm of carbon combine with 84.03 gm of sulphur
1 gm of carbon combine with 5.262 gm of sulphur.
Now,
The weight of sulphur and oxygen which combine with the fixed weight of carbon is in the ratio 5.262 : 2.667 or 2:1.

In sulphur dioxide
% of sulphur = 50
% of oxygen = 50
50 gm of sulphur combine with 50 gm of oxygen
Ratio of sulphur to oxygen = 50:50
= 1:1
The ratio of 2:1 is a simple multiple of the ratio 1:2. So these data are in agreement with the law of reciprocal proportion.

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6. Nitric oxide (NO gas) contains 46.66% ~~per~~ nitrogen and 53.34% oxygen, water contains 11.21% hydrogen and 88.79% oxygen. Ammonia contains 17.78% hydrogen and ~~82.22~~ 82.22% nitrogen. Show these data proves the law of reciprocal proportions.

Solution:
In nitric oxide
% of nitrogen = 46.66%
% of oxygen = 53.34%
~~46.66 gm of nitrogen combines with 53.34 gm of oxygen~~

~~1 gm of nitrogen combines with 1.143 gm of oxygen~~

~~In Water~~
~~% of hydrogen~~
~~% of~~

53.34 gm of oxygen combines with 46.66 gm of nitrogen
1 gm of oxygen combines with 0.874 gm of nitrogen

In Water
% of hydrogen = 11.21
% of oxygen = 88.79
88.79 gm of oxygen combine with 11.21 gm of hydrogen.
1 gm of oxygen combine with 0.126 gm of hydrogen
Now,
The weight of nitrogen and hydrogen which combines with the fixed weight of oxygen is in the ratio 0.874 : 0.126 = 6 : 1

In Ammonia
% of Hydrogen = 17.78
% of Nitrogen = 82.22

Mole Concept

A mole is defined as a collection of particles of anything (atoms, ions, electrons, protons etc.) equal in number to the number of atoms present in 1 gm ~~of~~ atom of C-12 isotope.

$$\begin{tikzcd}
6.023 \times 10^{23} \arrow[r, leftrightarrow, "\text{in terms of}", "\text{number}"'] & \text{1 mole (1 mol)} \arrow[r, leftrightarrow, "\text{in terms of}", "\text{volume}"'] \arrow[d, leftrightarrow, "\text{in terms of mass}"] & \text{22.4 L gas at NTP} \\
& \text{Molecular Weight} &
\end{tikzcd}$$

In terms of atom,

$$\text{number of moles} = \frac{\text{weight in gm}}{\text{atomic weight}}$$

In terms of mass,

$$\text{number of moles} = \frac{\text{Weight in gm}}{\text{Molecular weight}}$$

In terms of ions,

$$\text{number of Moles} = \frac{\text{Weight in gm}}{\text{ionic weight}}$$

In terms of gases,

$$\text{number of moles} = \frac{\text{Volume of NTP}}{\text{22.4 litres}}$$

1 mole of H atoms $= 6.023 \times 10^{23}$ atoms $= 1.008$ gm

1 mole of H_2 molecules $= 6.023 \times 10^{23}$ molecules $= 2.016$ gm

1 mole of H_2O $= 6.023 \times 10^{23}$

1 mole of SO_4 ions $= 6.023 \times 10^{23}$

1. Calculate the number of mole of oxygen atom present in 8 gm of it.

Solution:

Weight in gm = 8 gm

Atomic weight of oxygen = 16 gm

Number of mole = ?

We know,

$$\text{No. of mole} = \frac{\text{Weight in gm}}{\text{Atomic weight}}$$

$$= \frac{8}{16}$$

$$= 0.5 \text{ mole}$$

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2. Calculate the number of moles of sodium atom present in 46 gm of it.

Solution:

Weight in gm = 46 gm

Atomic weight of sodium = 22

Number of mole = ?

We know,

$$\text{Number of mole} = \frac{\text{weight in gm}}{\text{Atomic weight}}$$

$$= \frac{46}{22}$$

$$= \cancel{2.09\ 2\ \text{mole}}$$

$$= 2 \text{ mole}$$

3. Calculate the number of moles of ozone molecules in 24 gm of it.

solution:

Weight in gram = 48 gm

Atomic weight of ozone (O_3) = 48 gm

We know,

$$\text{Number of mole} = \frac{\text{Weight in gm}}{\text{Atomic weight}}$$

$$= \frac{48}{48}$$

$$= 1 \text{ mole}$$

4. Pure water sample having a mass of 0.36 gm is taken, answer the following questions

i. How many moles of water are present?

$$\text{Number of moles} = \frac{\text{Weight in gm}}{\text{Molecular weight}}$$

$$= \frac{0.36}{18}$$

$$= 0.02 \text{ mole}$$

ii. How many molecules ~~are~~ of water are present?

1 mol of water = 6.023×10^{23} molecules

0.02 mol of water = $6.023 \times 10^{23} \times 0.02$

$= 1.2046 \times 10^{22}$ molecules

iii. How many atoms of hydrogen are present?

1 mol of water = $2 \times 6.023 \times 10^{23}$ atoms

0.02 mol of water = $2 \times 6.023 \times 10^{23} \times 0.02$

$= 2.4092 \times 10^{22}$ atoms

iv. How many volume of water is present at NTP?

1 mol of water at NTP = $22.4\,l$

0.02 mol of water at NTP = 22.4×0.02

$= 0.448\, l$

5. Which of the following has the largest number of molecules and how? 7 gm of nitrogen or 1 gm of hydrogen.

Solution.

In 7 gm of nitrogen

Number of moles $= \frac{7}{28}$

$= 0.25$ mol

Number of molecules $= 0.25 \times 6.023 \times 10^{23}$

$= 1.50 \times 10^{23}$ molecules

In 1 gm of hydrogen

Number of ~~molecules~~ moles $= \frac{1}{2}$

$= 0.5$ mole

No. of molecules $= 0.5 \times 6.023 \times 10^{23}$

$= 3.0115 \times 10^{23}$

So, 1 gm of hydrogen has large number of molecules because its number of moles is large.

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6. What mass of 60% pure sulphuric acid is required to decompose 25 gm of $CaCO_3$?

Solution:

$$\underset{\substack{1\text{ mol} \\ 100\text{ gm}}}{CaCO_3} + \underset{\substack{1\text{ mol} \\ 98\text{ gm}}}{H_2SO_4} \longrightarrow CaSO_4 + H_2O + CO_2$$

100 gm of $CaCO_3$ is decomposed by 98 gm of H_2SO_4

Given,

H_2SO_4 is 60% pure

Let mass of 60% pure H_2SO_4 = x gm

$x \times 60\% = 24.5$

$x \times \frac{60}{100} = 24.5$

$\therefore x = 40.833$ gm

Avogadro's Law

It states that under similar conditions of temperature and pressure, equal volume of all gases contains equal number of molecules

Application of Avogadro's Hypothesis

1. Relation between molecular mass and Vapour density

Molecular mass or molecular weight of a substance is the mass or weight of one molecule of the substance as compared to the mass of an atom of hydrogen.

i.e.

$$\text{Molecular mass} = \frac{\text{Mass of 1 molecules of gaseous subst.}}{\text{mass of 1 atom of Hydrogen}}$$

The vapour density of a gas is defined as ratio of the mass or weight of a certain volume of a gas to the mass or weight of the same volume of hydrogen gas under similar conditions of temperature and pressure.

i.e.

$$\text{V.D} = \frac{\text{Mass of certain vol. of subst. in gaseous state}}{\text{Mass of same vol. of Hydrogen under similar conditi-}}$$

Applying Avogadro's Hypothesis,

Let us suppose a certain volume of gas contains 'n' molecule it means, same volume of hydrogen also contains n molecules.

$$\text{V.D} = \frac{\text{Mass of 'n' molecules of gaseous substance}}{\text{mass of n molecules of hydrogen}}$$

Let,

$n = 1$ then,

$$V.D = \frac{\text{Mass of 1 molecules of the gaseous substance}}{\text{mass of 1 molecule of hydrogen}}$$

$$\text{or, } V.D = \frac{\text{mass of 1 molecules of gaseous substance}}{2 \times \text{mass of 1 atom of hydrogen}}$$

from equation (i) and (ii), we can write,

$$V.D = \frac{\text{molecular mass}}{2}$$

Molecular mass = 2 × vapour density

Thus, molecular wt. of any gas is twice of its vapour density.

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2. Relation between molecular mass and volume of gas

we know that,

1 cc of hydrogen at NTP = 0.000089 gm

Also,

we know that,

Molecular wt. = 2 × V.D

but,

$$V.D = \frac{\text{wt. of 1 ltr. of gas at NTP}}{\text{wt. of 1 ltr. of } H_2 \text{ gas at NTP}}$$

So,

$$\text{molecular wt.} = \frac{2 \times \text{wt. of 1 ltr. of gas at NTP}}{\text{wt. of 1 ltr. of } H_2 \text{ at NTP}}$$

we know,

wt. of 1 ltr. of H_2 gas at NTP = 0.089 gm

therefore,

$$\text{molecular wt.} = \frac{2 \times \text{wt. of 1 ltr. of gas}}{0.089}$$

$$= 22.4 \times \text{wt. of 1 ltr. of gas}$$

$$= \text{wt. of 22.4 ltr. of gas}$$

Hence, the gram molecular volume of all gases at NTP occupies 22.4 ltr.

Date: / /

3. Relationship between Molecular mass and number of molecules.

According to Avogadro law, under similar condition of Temperature and pressure, equal volume of all gases contains equal no. of molecules.

That means,

If we consider 22.4 l gas at NTP or gram molecular volume of gas then it contains 6.023×10^{23} molecules. which is called Avagadro's number and it is denoted by N_A.

$$1 \text{ mole} = 1 \text{ gram atom or } 1 \text{ gram mole} = 6.023 \times 10^{23}$$
$$= 22.4 \, l \text{ at NTP}$$

4. Limiting Reactant and Excess Reactant

The reactant which is present in lesser amount and that limits the formation of product is called limiting reactant.

The reactant which is present in higher amount is called excess reagent. The excess ~~regent~~ reagent cannot be completely consumed during the course of reaction and left over unreacted, while the limiting reagent limits the product formation due to present in lesser amount in reactant mixture

Numerical Problems.

1. 3 gram of hydrogen react with 29 gm of oxygen to give water.

a. Which is the limiting reagent?

b. Calculate the amount of water formed.

c. Calculate the mass of unreacted reagent left over.

Solution:

The reaction involved is;

$$2H_2 + O_2 \longrightarrow 2H_2O$$

4gm   32gm   36 gm

By Question;

Hydrogen = 3 gm

Oxygen = 29 gm

a. We know,

4 gm of H_2 Completely reacts with 32gm O_2.

3 gm of H_2 Completely react with $\frac{32}{4} \times 3 = 24$

Here, 3 gm of H_2 Completely reacts with 24 gm of O_2.
so, according to question H_2 is limiting reagent.

Again,

b. We know,

4 gm ~~of~~ of H_2 gives 36 gm of H_2O

3 gm of H_2 gives $\frac{36}{4} \times 3$ gm of H_2O

$= 27$ gm

c. Also,

Amount of excess reagent (O_2) left over is;

$= 29 - 24$ gm

$= 5$gm

2. In this reaction :

$CaCO_3 + 2HCl \longrightarrow CaCl_2 + CO_2 + H_2O$

6.088 gm $CaCO_3$ reacted with 2.852 gm HCl. What mass of $CaCO_3$ remains unreacted?

Solution :

The reaction involved is;

$CaCO_3 + 2HCl \longrightarrow CaCl_2 + CO_2 + H_2O$

100 gm   73 gm

We know,

100 gm of $CaCO_3$ Completely reacts with 73 gm HCl.

6.088 gm of $CaCO_3$ Completely react with $\frac{73}{100} \times 6.088$ gm

$= 4.44$ gm

Hence, the amount of HCl is less than the required. So, it is limiting reagent.

Again,

73 gm HCl consumes 100 gm $CaCO_3$

2.85 gm HCl consumes $\frac{100}{73} \times 2.85$ gm of $CaCO_3$

$= 3.904$ gm

Now,

Mass of $CaCO_3$ unreacted $=$ 6.088 gm $-$ 3.904 gm

$=$ 2.184 gm

3. 17 gm of Ammonia is treated with 45 gm of oxygen to produce NO and H_2O. (i) Which is the limiting reactant?

ii. Calculate the number of moles of unreacted reagent left over.

iii. What volume of NO are produced at NTP.

iv. Calculate the mass of H_2O produced

Solution:

The reaction involved is;

$$4NH_3 + 5O_2 \longrightarrow 4NO + \cancel{6H} \; 6H_2O$$

68 160 120 108

Here,

i. 68 gm NH_3 completely reacts with 160 gm of O_2

17 gm NH_3 completely reacts with $\frac{160}{68} \times 17$ O_2

$= 40$ gm

Since, the amount of oxygen is greater than required amount. So, ammonia is limiting reagent.

Also,

ii. We know,

~~68 gm an NH_3~~ the given mass of O_2 = 45 gm

the reacted mass of O_2 = 40 gm

the mass left over = 45 − 40

= 5 gm

Now, No. of mole = $\frac{5}{32}$ = 0.15 mole

iii. We know,

68 gm NH_3 gives $4 \times 22.4 = 89.6\,l$ at NTP

17 gm NH_3 gives $\frac{89.6}{68} \times 17$

= 22.4 litre

Again,

iv. 68 gm of NH_3 gives 108 gm of H_2O

17 gm of NH_3 gives $\frac{108}{68} \times 17$ gm

= 27 gm