Molecular Formula: Example

- A compound is found to contain 85.63% C and 14.37% H by mass. In another experiment its molar mass is found to be 56.1 g/mol. What is its molecular formula?

CHAPTER 3

Chemical Equations & Reaction Stoichiometry

Objectives

- Understand how to write chemical equations
- Perform calculations based on chemical equations
- Calculate percent yields from chemical reactions
- Understand the concept of sequential reactions

Equations

- Consider a simple equation:

$$2 \times 3 = ?$$

- The question is: what happens to 2 if we multiply it by 3?

$$2 \times 3 = 6$$

- The answer: it is converted to 6

- In chemistry, we try to answer similar problems using chemical equations

Chemical Equations

$$CH_4 + O_2 \rightarrow ?$$

- We ask: what happens to methane when it reacts with oxygen (burns)?
- We know the answer from the chemical experiment

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

- The only thing we have to check is the Law of Conservation of Matter

Chemical Equations

- The Law of Conservation of Matter:

  in any physical or chemical change the total mass of matter remains constant

which means

  the number of atoms of each element involved remains unchanged

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

unbalanced equation

Chemical Equations

- We need to:

(1) balance the equation

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

(2) make sure that we have the same number of atoms for each element on the left and on the right side

$$\underbrace{CH_4 + 2O_2}_{\text{reactants}} \rightarrow \underbrace{CO_2 + 2H_2O}_{\text{products}}$$

Chemical Equations

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

- Symbolic representation of a chemical reaction that shows:
  - reactants on the left side
  - products on the right side
  - relative amounts of each using stoichiometric coefficients

Balancing Chemical Equations

- $Fe + O_2 \rightarrow Fe_3O_4$
- $Al + H_2SO_4 \rightarrow Al_2(SO_4)_3 + H_2$
- $C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O$

Quantitative Aspects

- Let's go back to

$$2 \times 3 = 6$$

- If we multiply both sides of the equation by some number, they still will be equal

$$8 \times (2 \times 3) = 8 \times 6$$

- We can treat chemical equations in the same way

Quantitative Aspects

- What happens in the reaction between methane and oxygen numerically?

$$CH_4 \quad + \quad 2O_2 \rightarrow \quad CO_2 \quad + \quad 2H_2O$$

1 molecule 2 molecules 1 molecule 2 molecules

- We can multiply both left and right sides by the same number – they will remain equal:

$$CH_4 \quad + \quad 2O_2 \rightarrow \quad CO_2 \quad + \quad 2H_2O$$

(1 molecule 2 molecules 1 molecule 2 molecules) x 8

8 molecules 16 molecules 8 molecules 16 molecules

Example 1

- How many O_2 molecules are required to react with 81 atoms of Fe?

$$Fe + \quad O_2 \rightarrow \quad Fe_3O_4$$

Quantitative Aspects

- Let's multiply the equation by Avogadro's number:

$$CH_4 \quad + \quad 2O_2 \rightarrow \quad CO_2 \quad + \quad 2H_2O$$

1 molecule	2 molecules	1 molecule	2 molecules
6.022×10^{23} molecules	$2 \times (6.022 \times 10^{23}$ molecules)	6.022×10^{23} molecules	$2 \times (6.022 \times 10^{23}$ molecules)
"	"	"	"
1 mole	2 moles	1 mole	2 moles

- In the same way as we talk about chemical equations in terms of molecules, we can consider them in terms of moles

Example 2

- How many moles of H_2 is produced when 70 moles of aluminum react with excess sulfuric acid?

$$Al + \quad H_2SO_4 \rightarrow \quad Al_2(SO_4)_3 + \quad H_2$$

Quantitative Aspects

- Since we know the molar mass of each substance we can also establish the mass relationships:

$$CH_4 \quad + \quad 2O_2 \rightarrow \quad CO_2 \quad + \quad 2H_2O$$

$$\begin{array}{lcccc} & \text{1 mole} & \text{2 moles} & \text{1 mole} & \text{2 moles} \\ \times & (16.0\ \text{g/mol} & 32.0\ \text{g/mol} & 44.0\ \text{g/mol} & 18.0\ \text{g/mol}) \\ \hline & 16.0\ g \ + & 64.0\ g \ = & 44.0\ g \ + & 36.0\ g \end{array}$$

- The total mass of products should be the same as the total mass of reactants

Example 3

- What mass of CO is required to react with 146 g of iron(III) oxide?

$$Fe_2O_3 + \quad CO \rightarrow \quad Fe + \quad CO_2$$

Example 4

- What mass of carbon dioxide can be produced by the reaction of 0.540 mole of iron(III) oxide with excess carbon monoxide?

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

Example 5

- What mass of iron(III) oxide reacted with excess carbon monoxide if carbon dioxide produced by the reaction had a mass of 8.65 grams?

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

Limiting Reactant Concept

- Example: A box contains 87 bolts, 110 washers, and 99 nuts. How many sets, each consisting of one bolt, two washers, and one nut, can you construct from the contents of one box?
- 87 bolts →
- 110 washers →
- 99 nuts →

Example 6

- What is the maximum mass of sulfur dioxide that can be produced by the reaction of 95.6 g of carbon disulfide with 110. g of oxygen?

$$CS_2 + O_2 \rightarrow CO_2 + SO_2$$

Example 7

- Calculate the mass of carbon tetrachloride which can be produced by the reaction of 10.0 g of carbon with 100.0 g of chlorine. Determine the mass of excess reagent left unreacted.

$$C + Cl_2 \rightarrow CCl_4$$

Percent Yields from Reactions

- Theoretical yield is calculated by assuming that the reaction goes to completion
- It is the maximum yield possible for the given reaction

BUT

- in many reactions the reactants are not completely converted to products
- a particular set of reactants may undergo two or more reactions simultaneously
- sometimes it is difficult to separate the desired product from other products in the reaction mixture

Percent Yields from Reactions

- Actual yield is the amount of a specified pure product actually obtained from a given reaction
- Percent yield:

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

- There are many reactions that do not give the 100% yield
- When calculating the percent yield, always make sure that the actual and theoretical yields are expressed in the same units

Example 8

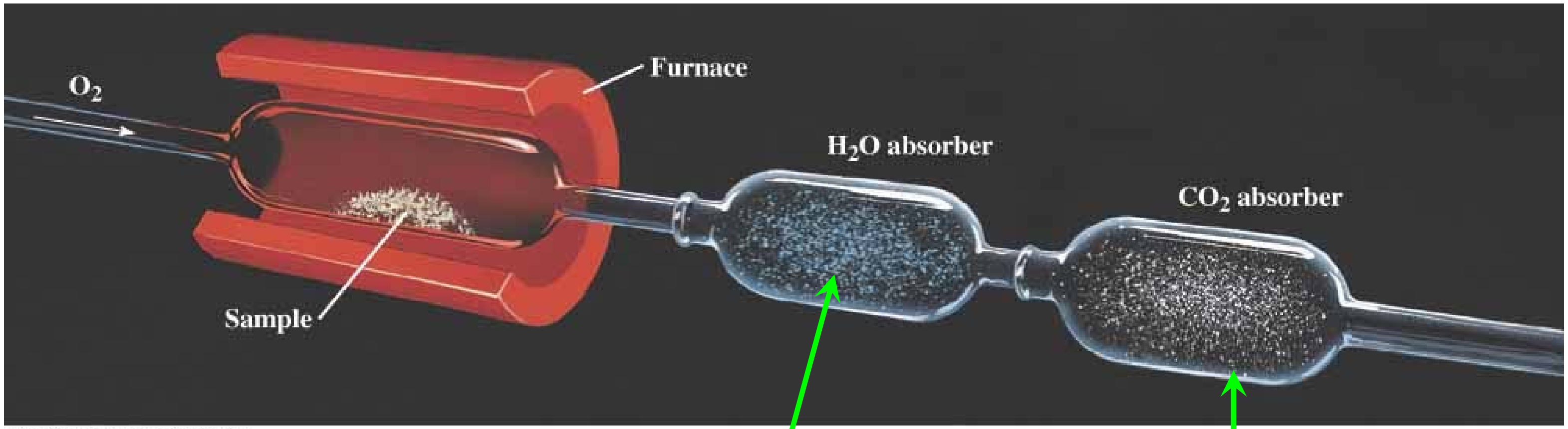
- A 10.0 g sample of ethanol, C_2H_5OH, was boiled with excess acetic acid, CH_3COOH, to produce 14.8 g of ethyl acetate, $CH_3COOC_2H_5$. What is the percent yield?

Example 9

- 10.6 g of Fe reacts with 25 g of Br_2 to form 18 g of $FeBr_3$. What is the percent yield?

Sequential Reactions

- A set of reactions required to convert starting materials into the desired product
- The amount of the desired product from each reaction is taken as the starting material for the next reaction.



magnesium perchlorate

sodium hydroxide

Example 10

- 13 g of decane, $C_{10}H_{22}$, is burned in a C-H combustion train. The CO_2 gas formed reacts with sodium hydroxide, NaOH, and is converted into sodium carbonate, Na_2CO_3. What mass of Na_2CO_3 will be formed if all reactions proceed to completion?

Example 11

- What mass of $(NH_4)_3PO_4$ can be produced in the result of the following reactions if we start with 10 moles of N_2 and excess **hydrogen**?

$$N_2 + \quad H_2 \rightarrow \quad NH_3 \quad (\text{yield} = 44\%)$$

$$NH_3 + \quad H_3PO_4 \rightarrow \quad (NH_4)_3PO_4 \quad (\text{yield} = 95\%)$$

Solutions

- We carry out many reactions in solutions
- Remember that in the liquid state molecules move much easier than in the solid, hence the mixing of reactants occurs faster
  - Solute is the substance which we dissolve
  - Solvent is the substance in which we dissolve the solute
  - In aqueous solutions, the solvent is water

Concentration of Solutions

- The concentration of a solution defines the amount of solute dissolved in the solvent
- We will express the concentration of a solution in one of the two most common ways:
    - percent by mass
    - molarity

Percent by mass of solute

$$\% \text{ by mass of solute} = \frac{\text{mass of solute}}{\text{mass of solution}} \times 100\%$$

$$\text{mass of solution} = \text{mass of solute} + \text{mass of solvent}$$

- What does it tell us?
  - The mass of solute in 100 mass units of solution

$$\omega(\text{solute}) = \frac{m(\text{solute})}{m(\text{solution})} \times 100\%$$

  - usually expressed as "% w/w"

Example 1

- What is the concentration of the solution obtained by dissolving 25 g of NaOH in 300.0 mL of water?

Example 2

- What mass of NaOH is required to prepare 250.0 g of solution that is 8.00% w/w NaOH?

Example 3

- Calculate the mass of 8.00% w/w NaOH solution that contains 32.0 g of NaOH.

Example 4

- What volume of 12.0% KOH contains 40.0 g of KOH? The density of the solution is 1.11 g/mL.

Molarity, or Molar Concentration

$$\text{molarity} = \frac{\text{number of moles of solute}}{\text{number of liters of solution}}$$

$$M = \frac{n(\text{solvent})}{V(\text{solution})} \left[\frac{\text{mol}}{\text{L}} \text{ or } \frac{\text{mmol}}{\text{mL}} \right]$$

- <u>Always divide</u> the number of moles of the solute <u>by the volume of the solution</u>, not by the volume of the solvent

Example 5

- Calculate the molarity of a solution that contains 12.5 g of sulfuric acid in 1.75 L of solution.

Example 6

- Determine the mass of calcium nitrate required to prepare 3.50 L of 0.800 M $Ca(NO_3)_2$.

Dilution of Solutions

$$M = \frac{n(\text{solute})}{V(\text{solution})} \Rightarrow n(\text{solute}) = M \times V(\text{solution})$$

- Solution 1: concentration = M_1
  volume = V_1
  $\boxed{n = M_1 \times V_1}$

- We add more solvent (dilute the solution)
  concentration = M_2
  volume = V_2
  $\boxed{n = M_2 \times V_2}$

- The amount of solute remains the same
  (we didn't add more solute to the solution)

Dilution of Solutions

$$\boxed{M_1 \times V_1 = M_2 \times V_2}$$

- If we know any 3 of these 4 quantities, we can calculate the other one
- The relationship is appropriate for dilutions but not for chemical reactions

Example 7

- If 10.0 mL of 12.0 M HCl is added to enough water to give 100. mL of solution, what is the concentration of the solution?

Example 8

- What volume of 18.0 M sulfuric acid is required to make 2.50 L of a 2.40 M sulfuric acid solution?

Using Solutions in Chemical Reactions

- Combine the concepts of molarity and stoichiometry to determine the amounts of reactants and products involved in reactions in solution.

Example 9

- What volume of 0.500 M $BaCl_2$ is required to completely react with 4.32 g of Na_2SO_4?

Example 10

- What volume of 0.200 M NaOH will react with 50.0 mL of 0.200 M aluminum nitrate, $Al(NO_3)_3$? What mass of $Al(OH)_3$ will precipitate?

Example 11

- What is the molarity of a KOH solution if 38.7 mL of the KOH solution is required to react with 43.2 mL of 0.223 M HCl?

Example 12

- What is the molarity of a barium hydroxide solution if 44.1 mL of 0.103 M HCl is required to react with 38.3 mL of the $Ba(OH)_2$ solution?

Reading Assignment

- Read Chapter 3
- Learn Key Terms (p. 112)
- Take a look at Lecture 5 notes (will be posted on the web not later than Monday morning)
- If you have time, read Chapter 4
- **Homework #1 due by 9/13**