Fundamentals of Chemistry and Matter

Chapter 7: Mass and Volume Relationships in Reactions (Stoichiometry)

Stoichiometry is the branch of chemistry that deals with the quantitative relationships between reactants and products in chemical reactions. It allows us to predict the amount of product formed from a given amount of reactant, or vice versa.

7.1 Stoichiometry of Reactions

- **Balanced Chemical Equations:** The foundation of stoichiometry. A balanced equation represents the conservation of mass and atoms during a chemical reaction. The coefficients in a balanced equation represent the mole ratio of reactants and products.
    - Example: 2H2(g) + O2(g) ➡️ 2H2O(l)
        - This means 2 moles of hydrogen react with 1 mole of oxygen to produce 2 moles of water.
        - It also means 2 molecules of hydrogen react with 1 molecule of oxygen to produce 2 molecules of water.
- **Mole Concept Revisited:** The mole is central to stoichiometry. It allows us to convert between mass, number of particles, and volume of gases.
    - 1 mole = Molar Mass (in grams)
    - 1 mole = 6.022 × 10^{23} particles (Avogadro's Number)
    - 1 mole of any gas at STP (0{°C}, 1 atm) = 22.4 L
    - 1 mole of any gas at RTP (25 {°C}, 1 atm) = 24 L
- **Calculations involving Moles, Mass, and Volume:**
    - **Mole-Mole Calculations:** Using the mole ratios from a balanced equation to find the moles of one substance given the moles of another.
    - **Mass-Mass Calculations:** Convert mass of reactant/product to moles, use mole ratio, then convert back to mass.
    - **Mass-Volume Calculations:** Convert mass to moles, use mole ratio, then convert moles of gas to volume (or vice versa).
    - **Volume-Volume Calculations (for gases):** Using Gay-Lussac's Law of Combining Volumes directly or converting volumes to moles.

      General Steps for Stoichiometric Calculations:

1. Write and balance the chemical equation.
2. Convert the given quantity (mass, volume, particles) of the known substance to moles.

3. Use the mole ratio from the balanced equation to find the moles of the unknown substance.
4. Convert the moles of the unknown substance to the required quantity (mass, volume, particles).

7.2 Study of Stoichiometry (Practical Applications)

- **Limiting Reactant (or Limiting Reagent):** In a chemical reaction, the reactant that is completely consumed first. It determines the maximum amount of product that can be formed. The other reactants are in "excess."
- **Theoretical Yield:** The maximum amount of product that can be produced from a given amount of reactants, calculated stoichiometrically.
- **Actual Yield:** The amount of product actually obtained from a chemical reaction in the laboratory. It is usually less than the theoretical yield due to incomplete reactions, side reactions, or loss during purification.
- **Percentage Yield:** A measure of the efficiency of a reaction.
    - Percentage Yield = ({Actual Yield} /{Theoretical Yield}) × 100\%

7.3 Volumetric Analysis: Titration, Molarity, Molar Solution

Volumetric analysis is a quantitative analytical technique used to determine the concentration of a substance by precisely measuring the volume of a solution of known concentration (a standard solution) required to react completely with it.

- **Titration:** The process of gradually adding a solution of known concentration (the **titrant**) from a burette to a solution of unknown concentration (the **analyte**) in a conical flask, until the reaction is complete. The **endpoint** is typically indicated by a color change of an indicator.
- **Molarity (M):** A common unit of concentration, defined as the **number of moles of solute per liter of solution**.
    - Molarity (M) = Moles of solute / Volume of solution (in Liters)
    - Units: mol/L or M.
- **Molar Solution:** A solution that contains one mole of solute dissolved in one liter of solution (e.g., a 1 M NaCl solution contains 1 mole of NaCl per liter).
- **Calculations in Volumetric Analysis:**
    - **Calculating Moles:**
        - Moles = Molarity × Volume (in Liters)
    - **Using Mole Ratios:** From the balanced chemical equation of the titration reaction.
    - **Example (Acid-Base Titration):**
        - Reaction: HCl(aq) + NaOH(aq) ➡️ NaCl(aq) + H_2O(l) (Mole ratio of HCl:NaOH is 1:1)
        - If 25.0 mL of 0.1 M HCl reacts completely with 20.0 mL of NaOH solution, find the concentration of NaOH.
            1. Moles of HCl = 0.1 { M} × (25.0/1000) { L} = 0.0025 { mol}
            2. From reaction, moles of NaOH = moles of HCl = 0.0025 { mol}
            3. Concentration of NaOH = Moles of NaOH / Volume of NaOH (L) = 0.0025 { mol} / (20.0/1000) { L} = 0.125 { M}

Chapter 8: Volumetric and Qualitative Analysis (Continued)

8.1 Volumetric Analysis (Advanced Topics)

- **Equivalence in Concentration:** At the **equivalence point** in a titration, the reactants have reacted completely in their stoichiometric ratio. For acid-base titrations, this means the moles of H^+ ions from the acid equal the moles of OH^- ions from the base.
    - For an acid-base reaction: n_a Ma Va = nb Mb Vb (where na, nb are basicity/acidity, Ma, Mb are molarities, Va, Vb are volumes). This is a simplified approach, direct mole calculation is usually clearer.
- **Standardization:** The process of accurately determining the concentration of a solution by titrating it against a primary standard.
    - **Primary Standard:** A highly pure, stable, readily available substance of known chemical formula, which can be weighed accurately to prepare a solution of precise concentration (e.g., anhydrous sodium carbonate, oxalic acid).
- **Purity in Substances:** Volumetric analysis can be used to determine the percentage purity of a sample by reacting it with a known concentration of another substance.
    - Calculate the theoretical amount of pure substance, then compare it to the actual mass of the impure sample.
- **Molar Mass (Determination):** Titration can be used to determine the molar mass of an unknown acid or base if its mass is known and it is titrated against a standard solution.
- **Water of Crystallization and Solubility of Substances (Revisited with Quantitative Analysis):**
    - **Water of Crystallization:** The amount of water of crystallization in a hydrated salt can be determined by heating a known mass of the hydrated salt to drive off the water, then calculating the mass loss. This links to concepts of percentage composition.
    - **Solubility of Substances:** Volumetric analysis can be used to determine the solubility of a sparingly soluble salt by titrating a saturated solution of the salt.

8.2 Qualitative Analysis

Qualitative analysis is the process of identifying the components (elements or ions) present in a sample. It focuses on *what* is present, rather than *how much* (which is quantitative analysis). It often involves a series of chemical tests leading to observable changes like precipitate formation, color changes, or gas evolution.

- **Identification of Cations (Metal Ions):**
    - Often involves adding specific reagents (e.g., sodium hydroxide, ammonia solution) and observing the color and solubility of the precipitates formed.
    - **Example Test:**
        - **Fe^{2+} (Iron(II) ions):** Add NaOH(aq) ➡️ dirty green precipitate, insoluble in excess.
        - **Fe^{3+} (Iron(III) ions):** Add NaOH(aq) ➡️ reddish-brown precipitate, insoluble in excess.
        - **Cu^{2+} (Copper(II) ions):** Add NaOH(aq) ➡️ light blue precipitate, insoluble in excess. Add aqueous ammonia ➡️ light blue precipitate, soluble in excess to give a deep blue solution.

        - **Zn^{2+} (Zinc ions):** Add NaOH(aq) ➡️ white precipitate, soluble in excess. Add aqueous ammonia ➡️ white precipitate, soluble in excess.
        - **Al^{3+} (Aluminium ions):** Add NaOH(aq) ➡️ white precipitate, soluble in excess. Add aqueous ammonia ➡️ white precipitate, insoluble in excess.
        - **Ca^{2+} (Calcium ions):** Add NaOH(aq) ➡️ white precipitate, insoluble in excess. Add aqueous ammonia ➡️ no precipitate. Test with ammonium oxalate solution for white precipitate.
        - **Pb^{2+} (Lead(II) ions):** Add NaOH(aq) ➡️ white precipitate, soluble in excess. Add aqueous ammonia ➡️ white precipitate, insoluble in excess. Add KI(aq) ➡️ yellow precipitate.
        - **NH_4^+ (Ammonium ions):** Warm with NaOH(aq), produces ammonia gas which turns damp red litmus blue.
- **Identification of Anions (Non-metal Ions):**
    - Involves testing for specific anions using characteristic reactions.
    - **Example Test:**
        - **CO_3^{2-} (Carbonate):** Add dilute acid ➡️ effervescence, gas turns limewater milky (CO2).
        - **SO_4^{2-} (Sulphate):** Add dilute HCl then BaCl2(aq) ➡️ white precipitate (BaSO4).
        - **Cl^- (Chloride):** Add dilute HNO3 then AgNO3(aq) ➡️ white precipitate (AgCl), soluble in excess aqueous ammonia.
        - **SO_3^{2-} (Sulphite):** Add dilute acid ➡️ gas with pungent smell (SO2), decolourizes acidified potassium permanganate.
        - **NO_3^- (Nitrate):** Brown ring test (complex procedure), or warm with Devarda's alloy and NaOH(aq) to produce ammonia gas.
- **Identification of Gases:**
    - **Hydrogen (H2):** Puts out a lighted splint with a "pop" sound.
    - **Oxygen (O2):** Relights a glowing splint.
    - **Carbon Dioxide (CO2):** Turns limewater milky.
    - **Ammonia (NH3):** Pungent smell, turns damp red litmus blue.
    - **Chlorine (Cl2):** Greenish-yellow gas, pungent smell, bleaches damp litmus paper.
    - **Sulphur Dioxide (SO2):** Pungent smell, turns acidified potassium permanganate (purple) colorless, turns acidified potassium dichromate (orange) green.
    - **Nitrogen Dioxide (NO2):** Reddish-brown gas, pungent smell.