Chemical Reactions

Chapter 12: Rates of Reactions

The rate of a chemical reaction tells us how fast reactants are converted into products. Some reactions are very fast (like explosions), while others are very slow (like rusting). Understanding reaction rates is crucial in industry and daily life.

12.1 Rate of a Chemical Reaction

- **Definition:** The rate of a chemical reaction is the **change in concentration of a reactant or product per unit time**.
    - It can be measured by monitoring:
        - The decrease in the concentration (or mass/volume) of a reactant.
        - The increase in the concentration (or mass/volume) of a product.
        - Change in properties like pH, conductivity, or color.
    - Units: Typically mol/L·s or g/s or cm^3/s.

12.2 Collision Theory

The collision theory explains how chemical reactions occur and why reaction rates differ.

- **Postulates:**
    1. **Particles must collide:** Reactant particles must collide with each other for a reaction to occur.
    2. **Effective collisions:** Not all collisions lead to a reaction. Only "effective collisions" result in product formation.
    3. **Correct orientation:** Particles must collide with the correct geometric orientation for bonds to break and form.
    4. **Sufficient energy (Activation Energy):** Particles must collide with energy equal to or greater than the **activation energy (Ea)**. The activation energy is the minimum amount of energy required for reactants to be converted into products.

12.3 Factors Affecting Rates of Reaction

Several factors influence the frequency and effectiveness of collisions, thereby affecting the rate of reaction:

1. **Effect of the Nature of Reactants:**
    - **Bond Strength:** Reactions involving the breaking of fewer or weaker bonds tend to be faster.

    - **Physical State:** Reactions generally proceed faster between gases or in solutions (where particles are mobile) than between solids.
    - **Ionic vs. Covalent:** Reactions between ions in solution are typically very fast (e.g., precipitation reactions) because there's no need to break strong covalent bonds. Reactions involving breaking and forming covalent bonds are generally slower.
2. **Effect of Concentrations of Reactants:**
    - **Increase in Concentration ➡️ Increase in Reaction Rate.**
    - **Explanation:** A higher concentration means more reactant particles per unit volume. This leads to a greater frequency of collisions between reactant particles, increasing the chance of effective collisions.
3. **Effect of Surface Area of Contact:**
    - **Increase in Surface Area ➡️ Increase in Reaction Rate.**
    - **Explanation:** For reactions involving solids, increasing the surface area (e.g., using powdered reactants instead of large lumps) exposes more reactant particles to collisions. This increases the frequency of collisions.
4. **Effect of Temperature:**
    - **Increase in Temperature ➡️ Increase in Reaction Rate.**
    - **Explanation:** At higher temperatures, particles have higher average kinetic energy. This leads to:
        - More frequent collisions.
        - A significantly higher proportion of collisions having energy equal to or greater than the activation energy.
        - A general rule of thumb is that for every 10 {°C} rise in temperature, the reaction rate approximately doubles.
5. **Effect of Light:**
    - Some reactions are initiated or accelerated by light energy (photochemical reactions).
    - **Example:** Photosynthesis (CO2 + H2O {{light}} {Glucose} + O2) and the reaction between hydrogen and chlorine (H2(g) + Cl2(g) ↔{{light}} 2HCl(g)).
6. **Effect of a Catalyst:**
    - **Catalyst ➡️ Increase in Reaction Rate.**
    - **Explanation:** A catalyst speeds up a reaction by providing an alternative reaction pathway with a **lower activation energy** (Ea). It does not change the overall energy change (ΔH) of the reaction.

Chapter 13: Chemical Equilibrium

Many chemical reactions do not go to completion; instead, they reach a state where reactants and products coexist, and the forward and reverse reactions occur at equal rates. This state is called chemical equilibrium.

13.1 Equilibrium System and Reversible Reactions

- **Reversible Reactions:** As discussed earlier (Chapter 9), these are reactions that can proceed in both forward and reverse directions. They are represented by a double arrow (↔).
    - Example: N2(g) + 3H2(g) ↔ 2NH3(g)

- **Equilibrium System (Dynamic Equilibrium):** A state in a reversible reaction where:
    1. The rate of the forward reaction is **equal** to the rate of the reverse reaction.
    2. The concentrations of reactants and products remain **constant** (not necessarily equal) over time.
    3. The reaction is **dynamic**, meaning it's still occurring at the molecular level, but there is no net change in concentrations.

13.2 Equilibrium Constant (Kc)

- For a general reversible reaction: aA + bB ↔ cC + dD
- The **equilibrium constant (Kc)** is a ratio of the concentrations of products to reactants at equilibrium, each raised to the power of their stoichiometric coefficients.

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

- [] denotes molar concentration at equilibrium.

    - **Significance of K_c:**
        - A large Kc (Kc >> 1) indicates that products are favored at equilibrium (the reaction goes almost to completion).
        - A small Kc (Kc << 1) indicates that reactants are favored at equilibrium (very little product is formed).
        - Kc is constant for a given reaction at a specific temperature. It changes with temperature.

13.3 Le Chatelier's Principle

Le Chatelier's Principle states that:

- "If a change of condition (stress) is applied to a system in equilibrium, the system will shift in a direction that relieves the stress." This principle is invaluable for predicting how equilibrium will respond to changes in external conditions.

13.4 Effect of a Change in Temperature

- **Impact on Equilibrium Position and Kc:**
    - **Exothermic Reaction (ΔH < 0):**
        - **Increase Temperature:** Equilibrium shifts to the **left (reverse reaction)** to absorb the excess heat. Kc decreases.
        - **Decrease Temperature:** Equilibrium shifts to the **right (forward reaction)** to release heat. Kc increases.

    - **Endothermic Reaction (ΔH > 0):**
        - **Increase Temperature:** Equilibrium shifts to the **right (forward reaction)** to absorb the excess heat. Kc increases.
        - **Decrease Temperature:** Equilibrium shifts to the **left (reverse reaction)** to release heat. Kc decreases.

13.5 Effect of a Change in Pressure

- **Impact on Equilibrium Position (for gaseous reactions only):**
    - Pressure changes primarily affect reactions involving gases where there is a change in the total number of moles of gas.
    - **Increase Pressure:** Equilibrium shifts to the side with **fewer moles of gas** to reduce the pressure.
    - **Decrease Pressure:** Equilibrium shifts to the side with **more moles of gas** to increase the pressure.
    - **No Change in Moles of Gas:** If the number of moles of gaseous reactants equals the number of moles of gaseous products (e.g., $H_2(g) + Cl_2(g) \leftrightarrow 2HCl(g)$), a change in pressure has **no effect** on the equilibrium position.
- **Note:** Pressure changes do not affect the value of Kc.

13.6 Effect of a Change in Concentration

- **Impact on Equilibrium Position (but not Kc):**
    - **Increase Concentration of Reactant:** Equilibrium shifts to the **right (forward reaction)** to consume the added reactant.
    - **Decrease Concentration of Reactant:** Equilibrium shifts to the **left (reverse reaction)** to produce more reactant.
    - **Increase Concentration of Product:** Equilibrium shifts to the **left (reverse reaction)** to consume the added product.
    - **Decrease Concentration of Product:** Equilibrium shifts to the **right (forward reaction)** to produce more product.
- **Note:** Changing concentration changes the equilibrium position, but the value of Kc remains constant at a given temperature.
- **Effect of a Catalyst (Revisited):**
    - A catalyst speeds up both the forward and reverse reactions equally.
    - Therefore, a catalyst helps the system reach equilibrium **faster**, but it **does not change the position of equilibrium** or the value of Kc.

Chapter 14: Radioactivity and Nuclear Energy

This chapter explores the fascinating world of the atomic nucleus, focusing on unstable nuclei and the tremendous energy changes associated with nuclear reactions.

14.1 Radioactivity

- **Definition:** The spontaneous disintegration (decay) of unstable atomic nuclei, accompanied by the emission of radiation.

- **Characteristics of Radioactivity:**
    - **Spontaneous:** Occurs naturally without external energy input.
    - **Random:** It is impossible to predict when a specific nucleus will decay.
    - **Independent of physical conditions:** Not affected by temperature, pressure, or chemical state.
    - **Emits radiation:** Releases energy and particles.
- **Types of Radiation:**
    1. **Alpha (α) rays:**
        - **Nature:** Consist of two protons and two neutrons (a helium nucleus, ^42He^{2+}).
        - **Charge:** +2 (positive).
        - **Penetrating Power:** Very low (stopped by a sheet of paper or a few cm of air).
        - **Ionizing Power:** Very high (causes significant ionization).
        - **Deflection:** Deflected by electric and magnetic fields (towards the negative plate).
    2. **Beta (β) rays:**
        - **Nature:** High-speed electrons (^0{-1}e) emitted from the nucleus (when a neutron changes into a proton and an electron).
        - **Charge:** -1 (negative).
        - **Penetrating Power:** Moderate (stopped by a few mm of aluminium).
        - **Ionizing Power:** Moderate.
        - **Deflection:** Deflected by electric and magnetic fields (towards the positive plate).
    3. **Gamma (γ) rays:**
        - **Nature:** High-energy electromagnetic waves (photons), no mass or charge. Often emitted along with alpha or beta decay when the nucleus is left in an excited state.
        - **Charge:** 0 (neutral).
        - **Penetrating Power:** Very high (requires thick lead or concrete to stop).
        - **Ionizing Power:** Very low.
        - **Deflection:** Not deflected by electric or magnetic fields.
    4. **X-rays (Brief Mention):** Also electromagnetic radiation, but typically generated outside the nucleus by electron transitions or deceleration. High energy, but generally lower energy than gamma rays from nuclear decay.
- **Detection of Radiation:**
    - **Geiger-Müller (GM) counter:** Detects radiation by measuring the ionization it causes in a gas-filled tube.
    - **Cloud Chamber:** Shows the paths of charged particles as trails of condensed vapor.
    - **Photographic Film:** Darkens upon exposure to radiation.
- **Radioactive Disintegration (Nuclear Decay):** The process by which an unstable atomic nucleus loses energy by emitting radiation. This often results in the formation of a different nucleus.
    - **Half-life (t{1/2}):** The time taken for half of the radioactive nuclei in a sample to decay. It's a constant for a particular radioisotope and is independent of initial amount or external conditions.

    - **Radioactive Decay Series:** A sequence of nuclear decays that an unstable nucleus undergoes until it forms a stable nucleus.
- **Biological Effects of Radiation:**
    - Radiation can cause ionization in living cells, damaging DNA and other molecules.
    - **Acute effects:** Radiation sickness (nausea, vomiting, hair loss, death) from high doses.
    - **Chronic effects:** Increased risk of cancer, genetic mutations, birth defects.
- **Uses of Radioisotopes:**
    - **Medical:**
        - **Diagnosis:** Tracers (e.g., Iodine-131 for thyroid, Technetium-99m for imaging organs).
        - **Treatment:** Radiotherapy for cancer (e.g., Cobalt-60, Iodine-131).
    - **Industrial:**
        - **Sterilization:** Sterilizing medical equipment and food (e.g., Gamma rays).
        - **Thickness gauging:** Measuring the thickness of materials (e.g., Beta emitters).
        - **Smoke detectors:** Using Americium-241.
    - **Agricultural:**
        - Pest control, extending food shelf life, tracing nutrient uptake.
    - **Dating:** Carbon-14 dating for archaeological artifacts.

14.2 Nuclear Energy

Nuclear energy involves the release of enormous amounts of energy from the nucleus of an atom.

- **Artificial Transmutation:** The process of converting one element into another by bombarding its nucleus with high-energy particles (e.g., Rutherford's first artificial transmutation: ^42He + ^{14}7N ➡️ ^{17}8O + ^11H).
- **Binding Energy:** The energy required to break a nucleus into its individual protons and neutrons, or the energy released when a nucleus is formed from its constituent nucleons.
    - It is related to the **mass defect** (the difference between the mass of a nucleus and the sum of the masses of its individual nucleons). This mass difference is converted to energy according to Einstein's mass-energy equivalence equation: E = mc^2.
    - A higher binding energy per nucleon indicates greater nuclear stability.
- **Nuclear Fission:**
    - **Definition:** The process where a **heavy, unstable nucleus splits** into two or more smaller, more stable nuclei, usually accompanied by the release of neutrons and a vast amount of energy.
    - **Example:** Bombardment of Uranium-235 with a neutron:
        - ^10n + ^{235}{92}U ➡️ ^{141}{56}Ba + ^{92}{36}Kr + 3^10n + {Energy}
    - **Chain Reaction:** The neutrons released from fission can go on to strike other fissile nuclei, causing further fissions, leading to a self-sustaining chain reaction.
    - **Controlled Fission:** Used in nuclear power plants to generate electricity.
    - **Uncontrolled Fission:** Used in atomic bombs.
- **Nuclear Fusion:**
    - **Definition:** The process where **two light nuclei combine** to form a heavier, more stable nucleus, releasing an even greater amount of energy than fission.

    - **Example:** Fusion of deuterium and tritium (isotopes of hydrogen):
        - ^21H + ^31H ➡️ ^42He + ^10n + {Energy}
    - **Conditions:** Requires extremely high temperatures (millions of degrees Celsius) and pressures to overcome the electrostatic repulsion between the positively charged nuclei.
    - **Natural Occurrence:** Occurs naturally in the Sun and other stars, providing their energy.
    - **Future Energy Source:** Scientists are working on controlled fusion for power generation, as it is a clean and virtually limitless energy source, but it remains a significant technological challenge.
- **Nuclear Energy for Power:**
    - Nuclear power plants use controlled nuclear fission (typically of Uranium-235) to generate heat, which is then used to produce steam to drive turbines and generate electricity.
    - **Advantages:** Low carbon emissions (no greenhouse gases), high energy output from small amounts of fuel.
    - **Disadvantages:** Production of radioactive waste (requires long-term safe storage), risk of accidents (e.g., Chernobyl, Fukushima), security concerns related to nuclear materials.

Glossary of Terms

- **Reaction Rate:** Change in concentration of reactant/product per unit time.
- **Collision Theory:** Explains reaction rates based on particle collisions.
- **Activation Energy:** Minimum energy for a reaction to occur.
- **Catalyst:** Substance that speeds up a reaction without being consumed.
- **Reversible Reaction:** Reaction proceeding in both forward and reverse directions.
- **Chemical Equilibrium:** State where forward and reverse reaction rates are equal, and concentrations are constant.
- **Equilibrium Constant (Kc):** Ratio of product to reactant concentrations at equilibrium.
- **Le Chatelier's Principle:** Principle predicting how equilibrium responds to stress.
- **Electrode Potential:** Potential difference between a metal and its ions.
- **Electrochemical Cell:** Device converting chemical energy to electrical energy.
- **Electrochemical Series:** List of elements by their electrode potentials/reactivity.
- **Corrosion:** Deterioration of metal due to environmental reactions.
- **Electrolysis:** Using electrical energy to drive a non-spontaneous chemical reaction.
- **Electrolyte:** Substance that conducts electricity when molten or in solution (due to mobile ions).
- **Faraday's Laws of Electrolysis:** Quantitative laws relating electricity to chemical change.
- **Enthalpy (H):** Heat content of a system.
- **Enthalpy Change (ΔH):** Heat absorbed or released in a reaction.
- **Exothermic Reaction:** Releases heat ($\Delta H < 0$).
- **Endothermic Reaction:** Absorbs heat ($\Delta H > 0$).
- **Calorimetry:** Measurement of heat changes.
- **Hess's Law:** Total enthalpy change is independent of the pathway.
- **Lattice Energy:** Energy to separate ions in an ionic solid.
- **Bond Energy:** Energy to break one mole of a covalent bond.

- **Gibbs Free Energy (ΔG):** Predicts spontaneity of reactions.
- **Radioactivity:** Spontaneous disintegration of unstable nuclei.
- **Alpha (α) rays:** Helium nuclei.
- **Beta (β) rays:** High-speed electrons.
- **Gamma (γ) rays:** High-energy electromagnetic waves.
- **Half-life:** Time for half of a radioactive sample to decay.
- **Nuclear Fission:** Splitting of a heavy nucleus.
- **Nuclear Fusion:** Combining of light nuclei.