REACTION MECHANISMS IN ENVIRONMENTAL ORGANIC CHEMISTRY

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CHAPTER 2

HYDROLYSIS

A. INTRODUCTION

In general terms, hydrolysis is defined as a chemical transformation in which an organic molecule, RX, reacts with water, resulting in the formation of a new covalent bond with OH and cleavage of the covalent bond with X (the leaving group) in the original molecule. The net reaction is the displacement of X by OH⁻ (Harris, 1981; Mill and Mabey, 1988)

$$RX + H_2O \rightarrow ROH + X^- + H^+ \qquad (2.1)$$
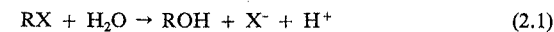
Hydrolysis is an example of a larger class of reactions referred to as nucleophilic displacement reactions in which a nucleophile (an electron-rich species containing an unshared pair of electrons) attacks an electrophilic atom (an electron-deficient reaction center). Hydrolytic processes encompass several types of reaction mechanisms that can be defined by the type of reaction center (i.e., the atom bearing the leaving group, X) where hydrolysis occurs. The reaction mechanisms encountered most often are direct and indirect nucleophilic substitution and nucleophilic addition-elimination.

The chemical structures of hydrolyzable functional groups that are prevalent in environmental chemicals, and the reaction products resulting from their hydrolysis, are listed in Table 2.1. For these classes of chemicals, hydrolysis may be the dominant pathway for their transformation in aquatic ecosystems. Hydrolytic processes are not limited to the bodies of water such as rivers, streams, lakes, and oceans usually associated with the term aquatic ecosystems. Hydrolysis of organic chemi-

Table 2.1.   Examples of Hydrolyzable Functional Groups

1. Halogenated Aliphatics

   Nucleophilic substitution

   $RCH_2X \xrightarrow{H_2O, OH^-} RCH_2OH + HX$
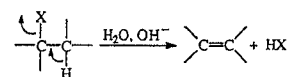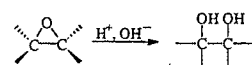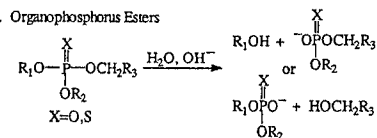
   Elimination

    $+ HX$
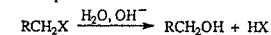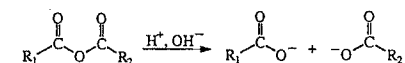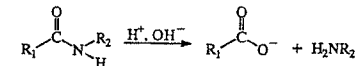
2. Epoxides

3. Organophosphorus Esters
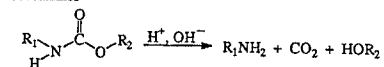

   $X = O, S$

4. Carboxylic Acid Esters
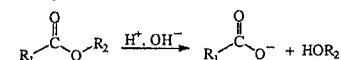
5. Anhydrides

6. Amides

7. Carbamates

    $R_1NH_2 + CO_2 + HOR_2$

8. Ureas

    $R_1NH_2 + CO_2 + H_2NR_2$
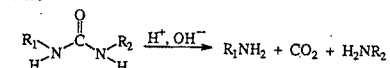
cals also can occur in fogwater, biological systems, groundwater systems, and the aqueous microenvironment associated with soils and sediments.

B. HYDROLYSIS KINETICS

1. Specific Acid and Base Catalysis

In addition to nucleophilic attack by H_2O (neutral hydrolysis), we find that hydrolytic reactions are sensitive to specific acid and specific base catalysis (i.e., catalysis by hydronium ion, H^+, and hydroxide ion, OH^-, respectively). Accordingly, hydrolysis kinetics must take into account the potential for H_2O to dissociate. Even at pH 7.0, where the concentration of H^+ and OH^- is only 10^{-7} M, specific acid and specific base catalysis can significantly accelerate hydrolysis kinetics. Specific acid and base catalysis occurs because the hydronium ion and hydroxide ions provide an alternative mechanism for hydrolysis that is energetically more favorable. In specific acid catalysis, hydronium ion is thought to provide a reaction pathway of lower energy by withdrawing electron density from the atom bearing the leaving group, X, thus making it more susceptible to nucleophilic attack by H_2O. Specific base catalysis occurs because OH^- is a much more reactive nucleophile than H_2O (typically by a factor of about 10^4: Streitwieser, 1962). Accordingly, a hydrolysis reaction involving nucleophilic attack by OH^- will occur at a faster rate than the pathway involving nucleophilic attack by H_2O alone.

Taking into consideration specific acid and base catalysis (the concentration of a catalyst is reflected in the rate law but is not reflected in the equilibrium constant), the hydrolysis rate term for hydrolyzable chemicals can be described by:

$$d[RX]/dt = k_{hyd}[RX] = k_a[H^+][RX] + k_n[RX] + k_b[OH^-][RX] \qquad (2.2)$$

where [RX] is the concentration of the hydrolyzable compound, k_{hyd} is the observed or measured hydrolysis rate constant, and k_a, k_n, and k_b are the rate constants for the acid-catalyzed, neutral, and base-catalyzed processes. Assuming that the individual rate processes for the acid, neutral, and base hydrolyses obey first-order kinetics with respect to the hydrolyzable chemical, RX, it is possible to write the following equation for k_{hyd}:

$$k_{hyd} = k_a[H^+] + k_n + k_b[OH^-] \qquad (2.3)$$

From the equilibrium term for the ionization of water, K_w:

$$K_w = [OH^-][H^+] = 1 \times 10^{-14} \qquad (2.4)$$

it is possible to substitute for [OH⁻] in Equation 2.4, giving:

$$k_{hyd} = k_a[H^+] + k_n + k_b(K_w/[H^+]) \qquad (2.5)$$

Because k_{hyd} is a pseudo first-order rate constant at a fixed pH (i.e., the hydrolysis is independent of RX concentration), the half-life for hydrolysis can be calculated from Equation 2.6.

$$t_{1/2} = \ln2/k_{hyd} \qquad (2.6)$$

2. pH Dependence

It is apparent from Equation 2.5 that the overall rate constant for hydrolysis, k_{hyd}, depends on pH and the magnitude of the rate constants for the individual processes. Plots of log k_{hyd} versus pH are very useful for determining the contribution of the acid, neutral, and base terms for hydrolysis of a compound of interest at a specific pH. Figure 2.1 illustrates the log k_{hyd} versus pH plot for several chemicals of interest. These data demonstrate that the relationship between hydrolysis kinetics and pH is dependent on the nature of the hydrolyzable functional group. For example, over typical environmental pH values (4 to 8), the neutral hydrolysis rate term for ethylene oxide and methyl chloride will dominate. Only below pH 4 will the acid-catalyzed rate term for ethylene oxide contribute to the overall hydrolysis rate term. Likewise, base-catalyzed hydrolysis of ethylene oxide and methyl chloride will not
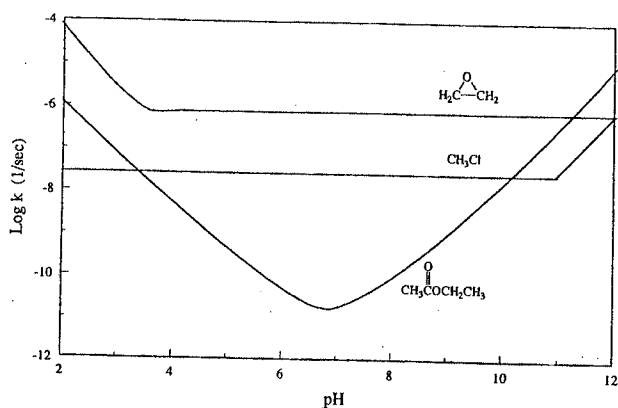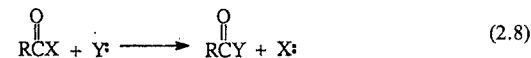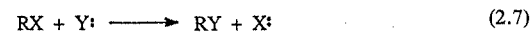

Figure 2.1.   pH-rate profiles for the hydrolysis of ethylene oxide, methyl chloride and ethyl acetate (Data taken from Mabey and Mill, 1978).

compete with neutral hydrolysis until pH 11, which is well above the pH range of natural aquatic ecosystems. By contrast, the neutral hydrolysis of ethyl acetate occurs over a much narrower pH range (6 to 7). Either below or above this pH range, the rate terms for acid- or base-catalyzed hydrolysis will dominate.

C. HYDROLYSIS REACTION MECHANISMS

Reaction mechanisms for hydrolysis can be classified according to the type of reaction center involved. The primary distinction is made between reaction at saturated and unsaturated centers. With respect to carbon-centered functional groups, which will be the primary focus of this chapter, hydrolysis involves reactions at sp^3 (saturated) or sp^2 (unsaturated) hybridized carbons. Nucleophilic reactions at sp^3 carbons are termed nucleophilic substitution (2.7). The reaction at sp^2 carbons is termed nucleophilic addition-elimination or acyl substitution (2.8).

$$RX + Y\colon \longrightarrow RY + X\colon \qquad (2.7)$$

$$\underset{\overset{\|}{RCX}}{\overset{O}{}} + Y\colon \longrightarrow \underset{\overset{\|}{RCY}}{\overset{O}{}} + X\colon \qquad (2.8)$$

Because both the nucleophile, Y:, and the leaving group, X:, are Lewis bases, these are examples of Lewis acid-base reactions in which one Lewis base replaces another in the Lewis acid-base adduct (Jensen, 1978).

1. Nucleophilic Substitution

The limiting cases of nucleophilic substitution have been described as the ionization mechanism (S_N1, substitution-nucleophilic-unimolecular) and the direct displacement mechanism (S_N2, substitution-nucleophilic-bimolecular: Gleave et al., 1935). The S_N1 and S_N2 mechanisms describe the extremes in nucleophilic substitution reactions. Pure S_N1 and S_N2 reaction mechanisms, however, are rarely observed. More often a mix of these reaction mechanisms are occurring simultaneously.

S_N1 Mechanism

The S_N1 mechanism begins by a rate-determining heterolytic dissociation of the substrate to an sp^2 hybridized carbocation (commonly referred to as a carbonium ion) and the leaving group (2.9):

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