Chemical Reactions

9

Chapter Outline

A fireworks display involves numerous different chemical reactions occurring at the same time.

In the previous two chapters we considered the properties of matter in various pure and mixed states. Nearly all of the subject matter dealt with interactions and changes of a *physical* nature. We now concern ourselves with the *chemical* changes that occur when various types of matter interact.

We first consider several types of chemical reactions and then discuss important fundamentals common to all chemical changes. Of particular concern to us will be how fast chemical changes occur (chemical reaction rates) and the extent to which chemical changes occur (chemical equilibrium).

9.1 TYPES OF CHEMICAL REACTIONS

A **chemical reaction** *is a process in which at least one new substance is produced as a result of chemical change.* An almost inconceivable number of chemical reactions are possible. The majority of chemical reactions (but not all) fall into five major categories: *combination* reactions, *decomposition* reactions, *single-replacement* reactions, *double-replacement* reactions, and *combustion* reactions.

Combination Reactions

A **combination reaction** *is a chemical reaction in which a single product is produced from two (or more) reactants.* The general equation for a combination reaction involving two reactants is

$$X + Y \longrightarrow XY$$

Figure 9.1 When a hot nail is stuck into a pile of zinc and sulfur, a fiery combination reaction occurs and zinc sulfide forms.

$$Zn + S \longrightarrow ZnS$$

In such a combination reaction, two substances join together to form a more complicated product (see Figure 9.1). The reactants X and Y can be elements or compounds or an element and a compound. The product of the reaction (XY) is always a compound. Some representative combination reactions that have elements as the reactants are

$$Ca + S \longrightarrow CaS$$
$$N_2 + 3H_2 \longrightarrow 2NH_3$$
$$2Na + O_2 \longrightarrow Na_2O_2$$

Some examples of combination reactions in which compounds are involved as reactants are

$$SO_3 + H_2O \longrightarrow H_2SO_4$$
$$2NO + O_2 \longrightarrow 2NO_2$$
$$2NO_2 + H_2O_2 \longrightarrow 2HNO_3$$

In organic chemistry (Chapters 12–17), combination reactions are called *addition reactions.* One reactant, usually a small molecule, is considered to be added to a larger reactant molecule to produce a single product.

Decomposition Reactions

A **decomposition reaction** *is a chemical reaction in which a single reactant is converted into two (or more) simpler substances (elements or compounds).* Thus a decomposition reaction is the opposite of a combination reaction. The general equation for a decomposition reaction in which there are two products is

$$XY \longrightarrow X + Y$$

Although the products may be elements or compounds, the reactant is *always* a compound.

At sufficiently high temperatures, all compounds can be broken down (decomposed) into their constituent elements. Examples of such reactions include

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

At lower temperatures, compound decomposition often produces other compounds as products.

$$CaCO_3 \longrightarrow CaO + CO_2$$
$$2KClO_3 \longrightarrow 2KCl + 3O_2$$
$$4HNO_3 \longrightarrow 4NO_2 + 2H_2O + O_2$$

In organic chemistry, decomposition reactions are often called *elimination reactions.* In many reactions, including some metabolic reactions that occur in the human body, either H_2O or CO_2 is eliminated from a molecule (a decomposition).

Decomposition reactions are easy to recognize because they are the only type of reaction in which there is only one reactant.

Single-Replacement Reactions

A **single-replacement reaction** *is a chemical reaction in which an atom or molecule replaces an atom or group of atoms from a compound.* There are always two reactants and two products in a single-replacement reaction. The general equation for a single-replacement reaction is

$$X + YZ \longrightarrow Y + XZ$$

A common type of single-replacement reaction is one in which an element and a compound are reactants, and an element and a compound are products. Examples of this type of single-replacement reaction include

$$Fe + CuSO_4 \longrightarrow Cu + FeSO_4$$
$$Mg + Ni(NO_3)_2 \longrightarrow Ni + Mg(NO_3)_2$$
$$Cl_2 + NiI_2 \longrightarrow I_2 + NiCl_2$$
$$F_2 + 2NaCl \longrightarrow Cl_2 + 2NaF$$

The first two equations illustrate one metal replacing another metal from its compound. The latter two equations illustrate one nonmetal replacing another nonmetal from its compound. A more complicated example of a single-replacement reaction, in which all reactants and products are compounds, is

$$4PH_3 + Ni(CO)_4 \longrightarrow 4CO + Ni(PH_3)_4$$

In organic chemistry, replacement reactions (both single and double) are often called *substitution* reactions. Substitution reactions of the single-replacement type are seldom encountered. However, double-replacement reactions are common in organic chemistry.

Double-Replacement Reactions

A **double-replacement reaction** *is a chemical reaction in which two substances exchange parts with one another and form two different substances.* The general equation for a double-replacement reaction is

$$AX + BY \longrightarrow AY + BX$$

Such reactions can be thought of as involving "partner switching." The AX and BY partnerships are disrupted, and new AY and BX partnerships are formed in their place.

When the reactants in a double-replacement reaction are ionic compounds in solution, the parts exchanged are the positive and negative ions of the compounds present.

$$AgNO_3(aq) + NaCl(aq) \longrightarrow AgCl(s) + NaNO_3(aq)$$
$$2KI(aq) + Pb(NO_3)_2(aq) \longrightarrow 2KNO_3(aq) + PbI_2(s)$$

Figure 9.2 A double-replacement reaction involving solutions of potassium iodide and lead(II) nitrate (both colorless solutions) produces yellow, insoluble lead(II) iodide as one of the products.

$$2KI(aq) + Pb(NO_3)_2(aq) \longrightarrow 2KNO_3(aq) + PbI_2(s)$$

In most reactions of this type, one of the product compounds is in a different physical state (solid or gas) from that of the reactants (see Figure 9.2). Insoluble solids formed from such a reaction are called *precipitates;* AgCl and PbI_2 are precipitates in the foregoing reactions.

Combustion Reactions

Combustion reactions are a most common type of chemical reaction. A **combustion reaction** *is a chemical reaction between a substance and oxygen (usually from air) that proceeds with the evolution of heat and light (usually from a flame).* Hydrocarbons—binary compounds of carbon and hydrogen (of which many exist)—are the most common type of compound that undergoes combustion. In hydrocarbon combustion, the carbon of the hydrocarbon combines with the oxygen of air to produce carbon dioxide (CO_2). The hydrogen of the hydrocarbon also interacts with the oxygen of air to give water (H_2O) as a product. The relative amounts of CO_2 and H_2O produced depend on the composition of the hydrocarbon.

$$2C_2H_2 + 5O_2 \longrightarrow 4CO_2 + 2H_2O$$
$$C_3H_8 + 5O_2 \longrightarrow 3CO_2 + 4H_2O$$
$$C_4H_8 + 6O_2 \longrightarrow 4CO_2 + 4H_2O$$

Hydrocarbon combustion reactions are the basis of an industrial society, making possible the burning of gasoline in cars, of natural gas in homes, and of coal in factories. Gasoline, natural gas, and coal all contain hydrocarbons. Unlike most other chemical reactions, hydrocarbon combustion reactions are carried out for the energy they produce rather than for the material products.

Examples of combustion reactions in which products other than CO_2 and H_2O are produced include

$$CS_2 + 3O_2 \longrightarrow CO_2 + 2SO_2$$
$$2H_2S + 3O_2 \longrightarrow 2SO_2 + 2H_2O$$
$$4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$$
$$2ZnS + 3O_2 \longrightarrow 2ZnO + 2SO_2$$

EXAMPLE 9.1
Classifying Chemical Reactions

Classify each of the following chemical reactions as a *combination, decomposition, single-replacement, double-replacement,* or *combustion* reaction.

a. $2KNO_3 \rightarrow 2KNO_2 + O_2$
b. $Zn + 2AgNO_3 \rightarrow Zn(NO_3)_2 + 2Ag$
c. $Ni(NO_3)_2 + 2NaOH \rightarrow Ni(OH)_2 + 2NaNO_3$
d. $3Mg + N_2 \rightarrow Mg_3N_2$

(continued)