SECTION 4.2

Double Displacement Reactions

X rays are highly useful for creating images of bones in the human body, but they generally do not show soft tissues clearly. To help doctors diagnose conditions involving the digestive tract, a patient may be asked to drink a liquid that contains tiny particles of barium sulfate, $BaSO_4(s)$. These particles block X rays, allowing organs such as the stomach to appear in high contrast on X-ray images, as shown in **Figure 4.7**.

Particles of barium sulfate can be produced by the reaction of barium chloride with sodium sulfate:

barium chloride	+	sodium sulfate	→	sodium chloride	+	barium sulfate
$BaCl_2(aq)$	+	$Na_2SO_4(aq)$	→	$2NaCl(aq)$	+	$BaSO_4(s)$

Notice that the positive ions, Ba^{2+} and Na^+, change partners. This reaction is called a **double displacement reaction**. A double displacement reaction involves the exchange of positive ions between two ionic compounds to form two new ionic compounds.

Key Terms

double displacement reaction
precipitate
neutralization

double displacement reaction a chemical reaction in which the positive ions of two ionic compounds exchange places, resulting in the formation of two new ionic compounds

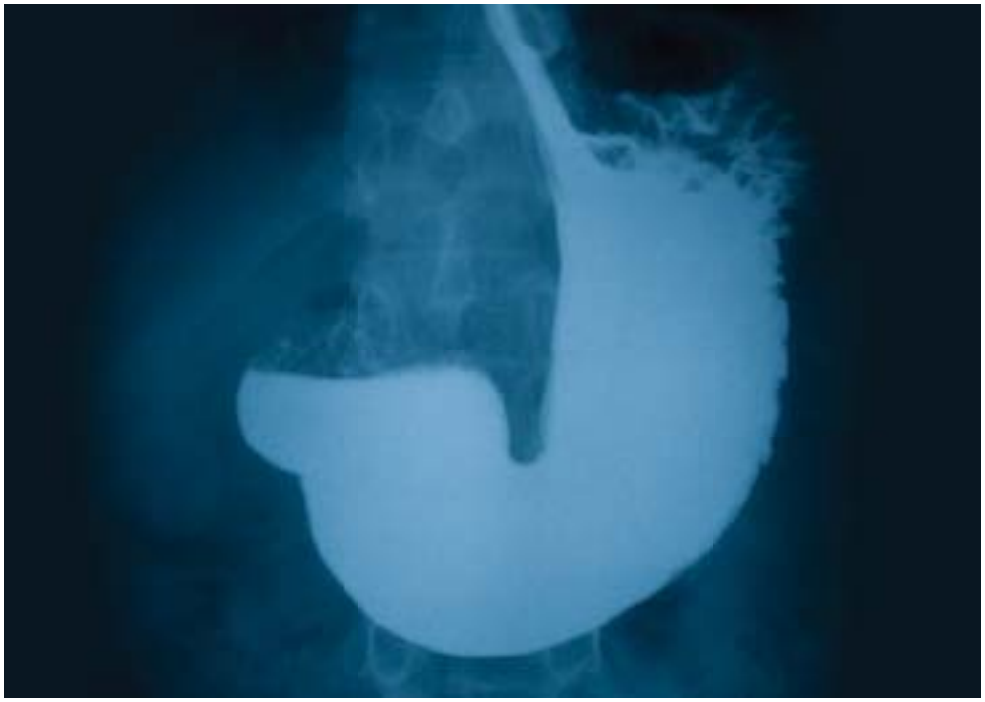

Figure 4.7 Drinking a liquid that contains barium sulfate allows organs to show up well on X-ray images. Barium sulfate, which is not soluble in water, can be produced by a double displacement reaction involving two soluble compounds, barium chloride and sodium sulfate.

Characteristics of Double Displacement Reactions

A double displacement reaction generally occurs between compounds that are in aqueous solution. The general form of a double displacement reaction is

In this equation, A and B are positively charged ions, or cations, and X and Y are negatively charged ions, or anions.

Types of Double Displacement Reactions

Just as there are different types of single displacement reactions, there are different types of double displacement reactions. On the following pages, you will learn about these double displacement reactions:

- a reaction that forms a solid
- a reaction that forms a gas
- a reaction that forms water

You will also learn about guidelines you can use to predict whether the products that are likely to form are solids, gases, or water.

Determining the Products of a Double Displacement Reaction

To determine the products of a double displacement reaction, you must first determine the ions that make up the reactants. For example, consider the reaction between lithium chloride and lead(II) nitrate:

$$LiCl(aq) + Pb(NO_3)_2(aq) \rightarrow$$

The reactants are composed of four ions. Lithium chloride is composed of lithium ions, Li^+, and chloride ions, Cl^-. Lead(II) nitrate is composed of lead(II) ions, Pb^{2+}, and nitrate ions, NO_3^-.

To determine the products of the reaction, simply change the pairs of ions. In this example, one of the products is lithium nitrate, formed from lithium ions pairing with nitrate ions. The other product is lead(II) chloride, formed from lead(II) ions pairing with chloride ions. When you write the formula of each ionic compound, remember to balance the charges of the ions. The final balanced equation for the reaction between lithium chloride and lead(II) nitrate is

$$\begin{array}{ccccccc} \text{lithium chloride} & + & \text{lead(II) nitrate} & \rightarrow & \text{lithium nitrate} & + & \text{lead(II) chloride} \\ 2LiCl(aq) & + & Pb(NO_3)_2(aq) & \rightarrow & 2LiNO_3(aq) & + & PbCl_2(s) \end{array}$$

A common use of lithium nitrate is the manufacture of fireworks and flares that produce a red colour. Lead(II) chloride is used to make glass that transmits infrared radiation for use as lenses in night-vision goggles, as shown in **Figure 4.8**.

Figure 4.8 Night-vision equipment detects infrared radiation. Such equipment can be used to observe the activities of animals, such as the lion and rhinoceros shown here, when there is insufficient visible light to see clearly.

Learning Check

7. What is the general form of a double displacement reaction?
8. In what state are the reactants of most double displacement reactions?
9. Explain whether describing a double displacement reaction as the exchange of cations between two compounds is correct.
10. When predicting the products of a double displacement reaction, why do you first need to determine the ions in each reactant?
11. Would you expect an element to form during a double displacement reaction? Explain your reasoning.
12. Potassium bromide can react with silver nitrate in a double displacement reaction to form an aqueous potassium compound and a solid silver compound.
    a. What are the names and formulas of the products that form during this reaction?
    b. Write a balanced chemical equation for this reaction.

A Reaction That Forms a Solid

A common observation during many double displacement reactions is the formation of a solid **precipitate**. In the previous example, the product, lead(II) chloride, is a precipitate. A precipitate is also formed during the reaction between silver nitrate and sodium chloride, shown in **Figure 4.9**. The balanced chemical equation for this reaction is

precipitate an insoluble solid that is formed by a chemical reaction between two soluble compounds

$$\begin{array}{ccccccc} \text{silver nitrate} & + & \text{sodium chloride} & \rightarrow & \text{silver chloride} & + & \text{sodium nitrate} \\ AgNO_3(aq) & + & NaCl(aq) & \rightarrow & AgCl(s) & + & NaNO_3(aq) \end{array}$$

The solid product, silver chloride, is the precipitate.

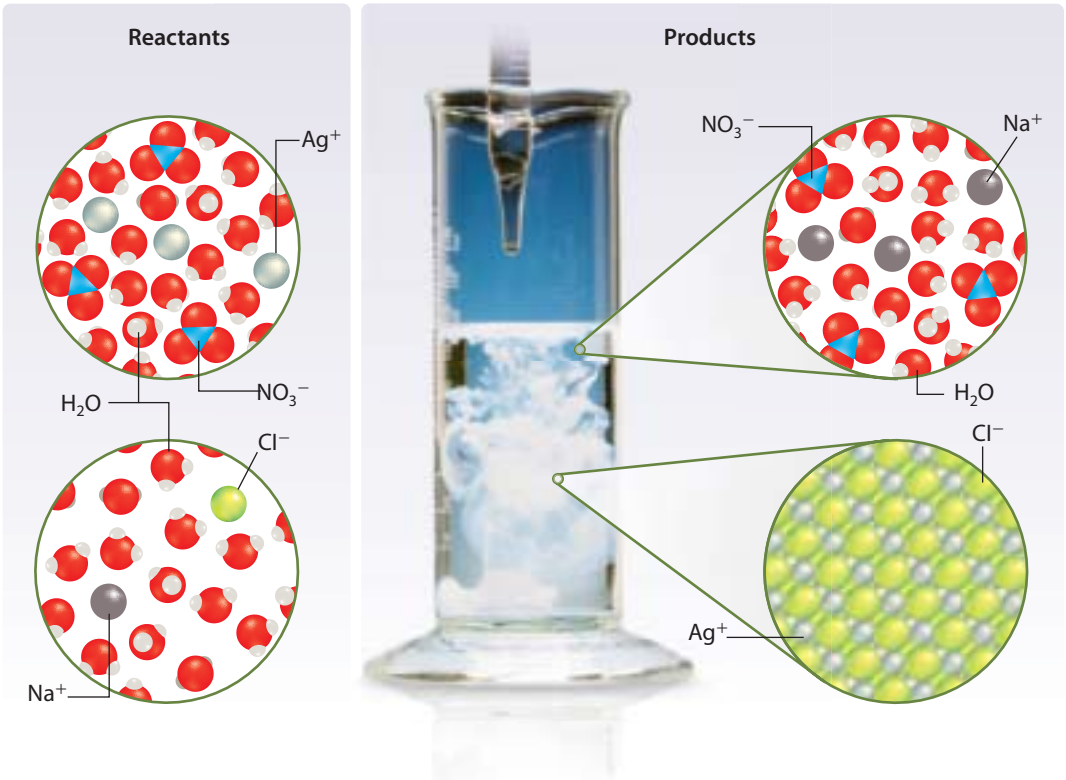

Figure 4.9 When aqueous solutions of silver nitrate and sodium chloride are mixed, a double displacement reaction occurs. A precipitate, silver chloride, is formed. The second product, sodium nitrate, remains in aqueous solution.

***Identify** the positive ions in this reaction, and describe what happens to them.*

Solubility Guidelines

How do chemists know whether a double displacement reaction is likely to produce a precipitate? A set of solubility guidelines has been assembled, based on the experimental results. These guidelines are shown in **Table 4.3**. Compounds that are insoluble or have low solubility in water form precipitates in double displacement reactions.

Solubility Guidelines

1. The hydrogen ion, ammonium ion, and all Group 1 (alkali metal) ions form soluble compounds with nearly all anions.
2. Nitrate and acetate ions form soluble compounds with nearly all cations.
3. Chloride, bromide, and iodide ions form compounds that have low solubility with silver, lead(II), mercury(I), copper(I), and thallium cations only.
4. Fluoride forms compounds that have low solubility with magnesium, calcium, barium, and lead(II) cations only.
5. The sulfate ion forms compounds that have low solubility with calcium, strontium, barium, and lead(II) cations only.
6. The sulfide ion forms soluble compounds only with the ions listed in guideline 1 and with Group 2 cations.
7. The hydroxide ion forms compounds that are soluble only with the cations listed in guideline 1, and with strontium, barium, and thallium cations.
8. Phosphate, carbonate, and sulfite ions form compounds that have low solubility with all cations except for those listed in guideline 1.

Table 4.3 Solubility of Common Ionic Compounds in Water

	Anion	+ Cation →	Solubility of Compound
1.	most	alkali metal ions (Li^+, K^+, Rb^+, Cs^+, Fr^+)	soluble
	most	hydrogen ion, H^+	soluble
	most	ammonium ion, NH_4^+	soluble
2.	nitrate, NO_3^-	most	soluble
	acetate (ethanoate), CH_3COO^-	Ag^+	low solubility
		most others	soluble
3.	chloride, Cl^- bromide, Br^- iodide, I^-	Ag^+, Pb^{2+}, Hg_2^{2+}, Cu^+, Tl^+	low solubility
		all others	soluble
4.	fluoride, F^-	Mg^{2+}, Ca^{2+}, Ba^{2+}, Pb^{2+}	low solubility
		most others	soluble
5.	sulfate, SO_4^{2-}	Ca^{2+}, Sr^{2+}, Ba^{2+}, Pb^{2+}	low solubility
		all others	soluble
6.	sulfide, S^{2-}	alkali ions and H^+, NH_4^+, Be^{2+}, Mg^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}	soluble
		all others	low solubility
7.	hydroxide, OH^-	alkali ions and H^+, NH_4^+, Sr^{2+}, Ba^{2+}, Tl^+	soluble
		all others	low solubility
8.	phosphate, PO_4^{3-} carbonate, CO_3^{2-} sulfite, SO_3^{2-}	alkali ions and H^+, NH_4^+	soluble
		all others	low solubility

"Soluble" here means that more than 1 g of a substance will dissolve in 100 mL of water at 25°C.

Sample Problem

Predicting the Precipitate in a Double Displacement Reaction

Problem

The double displacement reaction between magnesium chloride and lead(II) acetate forms a precipitate. Predict the products, and write a balanced chemical equation that identifies the precipitate.

What Is Required?

Determine the products that form when magnesium chloride and lead(II) acetate react, and write a balanced chemical equation that shows which product is a precipitate.

What Is Given?

You know the reactants: magnesium chloride and lead(II) acetate
You know the type of reaction: double displacement

Plan Your Strategy	Act on Your Strategy
Identify the ions that make up each reactant.	Magnesium chloride: • magnesium ions, Mg^{2+} • chloride ions, Cl^- Lead(II) acetate: • lead(II) ions, Pb^{2+} • acetate ions, CH_3COO^-
Switch the pairs of ions to determine the products.	One product is magnesium acetate (magnesium ions paired with acetate ions). The second product is lead(II) chloride (lead(II) ions paired with chloride ions).
Write a word equation for the reaction.	magnesium chloride + lead(II) acetate → magnesium acetate + lead(II) chloride
Use the solubility guidelines to determine the precipitate.	Magnesium acetate is not the precipitate because acetate ions form a soluble compound with magnesium ions. Lead(II) chloride is the precipitate because the compound formed from chloride ions and lead(II) ions has low solubility.
Write a balanced chemical equation for the reaction.	$MgCl_2(aq) + Pb(CH_3COO)_2(aq) \rightarrow Mg(CH_3COO)_2(aq) + PbCl_2(s)$

Check Your Solution

All the chemical formulas are correct, and the chemical equation is balanced. The products are correctly formed by switching the ions in the reactants. The precipitate is correctly identified, based on the solubility guidelines.

Practice Problems

Determine the products that form in the double displacement reaction between each pair of reactants, and identify the precipitate. Then write a balanced chemical equation.

11. potassium sulfate and calcium chloride

12. barium nitrate and sodium carbonate

13. iron(III) chloride and sodium hydroxide

14. rubidium sulfide and copper(II) iodide

15. zinc bromide and copper(I) acetate

16. lithium hydroxide and magnesium chloride

17. aluminum sulfate and lead(II) nitrate

18. lithium phosphate and magnesium chloride

19. calcium nitrate and magnesium sulfate

20. silver nitrate and magnesium chloride

A Reaction That Forms a Gas

Figure 4.10 The bubbling of this model volcano is caused by the formation of carbon dioxide gas, which is produced in the reaction between sodium hydrogen carbonate (commonly known as baking soda) and the acetic acid in vinegar.

Sometimes, the production of a gas, rather than a precipitate, indicates that a double displacement reaction has occurred. Many of these double displacement reactions are, in fact, two reactions that occur in rapid succession. A double displacement occurs, but then one of the products quickly decomposes into water and a gas. To predict the products in one of these reactions, you need to recognize the product that decomposes.

Formation of Carbon Dioxide

Have you ever made a vinegar and baking soda volcano like the one in **Figure 4.10**? Vinegar contains acetic acid, $CH_3COOH(aq)$, and baking soda is sodium hydrogen carbonate, $NaHCO_3(s)$. To determine the products, identify the ions and change the pairs of ions. The balanced chemical equation for the reaction is

acetic acid + sodium hydrogen carbonate → sodium acetate + carbonic acid (hydrogen carbonate)

$$CH_3COOH(aq) + NaHCO_3(s) \rightarrow NaCH_3COO(aq) + H_2CO_3(aq)$$

This cannot be the overall reaction because there is no carbon dioxide.

Decomposition of Carbonic Acid

In these reactions, the product to watch for is carbonic acid, $H_2CO_3(aq)$. Carbonic acid decomposes into liquid water and carbon dioxide gas according to the following equation:

carbonic acid → water + carbon dioxide

$$H_2CO_3(aq) \rightarrow H_2O(\ell) + CO_2(g)$$

Overall Chemical Reaction

Combining the double displacement reaction with the decomposition reaction gives the overall balanced equation:

acetic acid + sodium hydrogen carbonate → sodium acetate + water + carbon dioxide

$$CH_3COOH(aq) + NaHCO_3(s) \rightarrow NaCH_3COO(aq) + H_2O(\ell) + CO_2(g)$$

Suggested Investigation

Inquiry Investigation 4-B, Observing Double Displacement Reactions

Formation of Ammonia

Gaseous ammonia, $NH_3(g)$, forms in a similar way when a double displacement reaction is followed by a decomposition reaction. In this type of double displacement reaction, the product to look for is ammonium hydroxide, $NH_4OH(aq)$. For example, the equation for the double displacement reaction between ammonium chloride and sodium hydroxide is

ammonium chloride + sodium hydroxide → sodium chloride + ammonium hydroxide

$$NH_4Cl(aq) + NaOH(aq) \rightarrow NaCl(aq) + NH_4OH(aq)$$

Decomposition of Ammonium Hydroxide

Ammonium hydroxide decomposes to form water and ammonia according to the following equation:

ammonium hydroxide → water + ammonia

$$NH_4OH(aq) \rightarrow H_2O(\ell) + NH_3(g)$$

Overall Chemical Reaction

So, the overall equation for the chemical reaction that occurs is

ammonium chloride + sodium hydroxide → sodium chloride + water + ammonia

$$NH_4Cl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(\ell) + NH_3(g)$$

Predicting Products of Double Displacement Reactions That Form Gases

These two types of double displacement reactions, which form the gases carbon dioxide and ammonia, are important to remember when you need to predict products. They are summarized in **Table 4.4**.

Table 4.4 Double Displacement Reactions That Form Gases

Reactants	Products
acid + compound containing carbonate ion	ionic compound + water + carbon dioxide
compound containing ammonium ions + compound containing hydroxide ions	ionic compound + water + ammonia

Learning Check

13. What are the characteristics of a precipitate?

14. In **Figure 4.9**, why is silver chloride shown in a different form than the other compounds?

15. Do the solubility guidelines shown in **Table 4.3** apply to the solubility of compounds in all solvents, including alcohol and oil? Explain.

16. State the two types of reactions that occur when a double displacement reaction produces a gas. Give the general form of each reaction.

17. According to **Table 4.3**, which substance in each of the following pairs is more soluble?

a. $FeS(s)$ or $Ba(OH)_2(s)$

b. $TlCl(s)$ or $MgS(s)$

c. $H_3PO_4(s)$ or $SrCO_3(s)$

d. $PbSO_4(s)$ or $Na_2SO_3(s)$

18. Write a balanced chemical equation for the double displacement reaction between calcium carbonate, $CaCO_3(s)$, and hydrochloric acid, $HCl(aq)$.

A Reaction That Forms Water

When two solutions are mixed, the formation of a solid precipitate or a gas is evidence that a reaction has occurred. However, there is one type of double displacement reaction that occurs with no outward evidence of a reaction. This type of reaction forms water as a product, but, because the reactants are in aqueous solution, there is no visible sign that water molecules have formed.

Neutralization Reactions

Water can form when an acid and a base are combined in a process called **neutralization**. Water forms when hydrogen ions from the acid join with hydroxide ions from the base according to the following reaction:

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(\ell)$$

Because the hydrogen ions and hydroxide ions combine to form water, the amounts of these potentially harmful ions decrease. As a result, the solution that forms from a neutralization reaction may be neutral—neither acidic nor basic.

neutralization the process of making a solution neutral (pH = 7) by adding a base to an acidic solution or by adding an acid to an alkaline (basic) solution

Uses of Neutralization Reactions

Neutralization reactions between an acid and a base are important for treating acid or base spills. For example, when sulfuric acid, $H_2SO_4(aq)$, spilled from derailed tanker cars near Englehart, Ontario, a solution of the base calcium hydroxide, $Ca(OH)_2(aq)$, was used to help neutralize the acid during clean-up. The balanced chemical equation for this reaction is

$$\begin{array}{ccccccc} \text{sulfuric acid} & + & \text{calcium hydroxide} & \rightarrow & \text{calcium sulfate} & + & \text{water} \\ H_2SO_4(aq) & + & Ca(OH)_2(aq) & \rightarrow & CaSO_4(aq) & + & 2H_2O(\ell) \end{array}$$

Suggested Investigation

Inquiry Investigation 4-C, Observing a Neutralization Reaction

Inquiry Investigation 4-D, Modelling Neutralization Reactions Used in Scrubber Technology

Other Uses of Neutralization Reactions

Reactions between acids and bases are also important for optimizing soil conditions. For example, lettuce and celery grow better in neutral to basic soil, but strawberries and tomatoes grow better in acidic soil. **Figure 4.11** shows soil being tested to determine whether it is acidic, neutral, or basic. Depending on the types of plants that will be grown, substances can be added to the soil to neutralize acids or bases. On a smaller scale, when someone takes antacid tablets to treat acid indigestion, basic substances in the tablets help to neutralize the excess acid in the stomach. You will learn more about acids, bases, and neutralization in Unit 4.

Figure 4.11 Depending on the results of this soil test, lime, CaO(s), might be added to neutralize excess acids in the soil, or a substance such as ammonium sulfate might be added to neutralize bases.

Summarizing Double Displacement Reactions

Most double displacement reactions form a precipitate. Therefore, when you are asked to determine whether a reaction occurs, you will usually need to examine the solubility guidelines to determine whether one of the products is insoluble. Nevertheless, the double displacement reactions that form gases or water are important to remember. The flowchart in **Figure 4.12** summarizes the double displacement reactions you have studied in this section.

If one reactant …	+	the other reactant …	→	then the products include
is an aqueous salt	+	is an aqueous salt	→	**a precipitate**
is an acid	+	has carbonate ions	→	**water and carbon dioxide**
has ammonium ions	+	has hydroxide ions	→	**water and ammonia**
is an acid	+	has hydroxide ions	→	**water**

For any other reactant pairs, check the solubility guidelines. The product might include a precipitate.

Figure 4.12 Use this flowchart to help you predict the products of a double displacement reaction.

Sample Problem

Predicting Gases and Water in Double Displacement Reactions

Problem

Predict the products in each double displacement reaction, and write a balanced chemical equation.

a. sodium carbonate reacting with hydrobromic acid

b. sodium hydroxide reacting with hydrobromic acid

What Is Required?

Determine the products that form from the given reactants, and write a balanced chemical equation for each reaction.

What Is Given?

You know the reactants: **a.** sodium carbonate and hydrobromic acid

b. sodium hydroxide and hydrobromic acid

You know the type of reaction: double displacement

Plan Your Strategy	Act on Your Strategy
Identify the ions that make up each reactant.	**a.** Sodium carbonate: • sodium ions, Na^+ • carbonate ions, CO_3^{2-} Hydrobromic acid: • hydrogen ions, H^+ • bromide ions, Br^- **b.** Sodium hydroxide: • sodium ions, Na^+ • hydroxide ions, OH^- Hydrobromic acid: • hydrogen ions, H^+ • bromide ions, Br^-
Switch the pairs of ions to determine the products.	**a.** sodium bromide and hydrogen carbonate (carbonic acid) **b.** sodium bromide and water
Look for carbonic acid or ammonium hydroxide, which break down into water and a gas.	**a.** Carbonic acid will break down into water and carbon dioxide. **b.** Neither carbonic acid nor ammonium hydroxide is formed.
Write a word equation for each reaction.	**a.** sodium carbonate + hydrobromic acid → sodium bromide + water + carbon dioxide **b.** sodium hydroxide + hydrobromic acid → sodium bromide + water
Write and balance a chemical equation for each reaction.	**a.** $Na_2CO_3(aq) + 2HBr(aq) \rightarrow 2NaBr(aq) + H_2O(\ell) + CO_2(g)$ **b.** $NaOH(aq) + HBr(aq) \rightarrow NaBr(aq) + H_2O(\ell)$

Check Your Solution

All the chemical formulas are correct, and each chemical equation is balanced. The products are correctly formed by switching the ions of the reactants.

Practice Problems

Determine the products that form in the double displacement reaction between each pair of reactants. Then write a balanced chemical equation for the reaction.

21. potassium carbonate and hydrochloric acid

22. sulfuric acid and sodium carbonate

23. ammonium chloride and sodium hydroxide

24. rubidium hydroxide and hydrochloric acid

25. calcium carbonate and acetic acid

26. lithium hydroxide and ammonium bromide

27. sulfuric acid and lithium hydroxide

28. lithium hydrogen carbonate and acetic acid

29. calcium hydroxide and nitric acid

30. ammonium chloride and magnesium hydroxide

Section 4.2 REVIEW

Section Summary

- In a double displacement reaction, the positive ions in two compounds trade places to form two new compounds.
- The general form of a double displacement reaction is $AX + BY \rightarrow AY + BX$.
- A double displacement reaction generally produces a precipitate, a gas, or water.
- Solubility guidelines can be used to predict whether a product of a double displacement reaction will be a precipitate.
- Neutralization occurs when there is a double displacement reaction between an acid and a base. Water is a product of neutralization.

Review Questions

1. T/I The following general form of a double displacement reaction is incorrect:

$$CW + DZ \rightarrow CD + WZ$$

a. What is wrong with this general equation?

b. Write a correct equation using the reactants shown.

2. C Create a graphic organizer that you could use to predict the products of a double displacement reaction.

3. K/U What is a precipitate?

4. K/U What evidence would help you decide if a double displacement reaction has occurred?

5. T/I What two anions are almost never found in a precipitate formed during a reaction?

6. T/I What would be most likely to happen if you combined the solutions of two compounds in which the positive ions are alkali metals?

7. T/I What would be most likely to happen if you combined the solutions of two compounds that have the same anion?

8. C Suppose that you see an online video in which a person adds sodium nitrate to a sample of tap water and a precipitate forms. The person in the video concludes that there is lead in the water. Write a comment to address the error in this conclusion.

9. A To determine whether a rock sample is limestone, a geologist places several drops of hydrochloric acid on it. Limestone is calcium carbonate, $CaCO_3(s)$.

a. What evidence is the geologist expecting to see if the rock sample is limestone?

b. Write a balanced chemical equation for the reaction between hydrochloric acid and calcium carbonate.

10. A During a neutralization reaction, there is no visible evidence that a reaction is occurring. Describe a safe way by means of which you could determine whether a neutralization reaction is occurring.

11. T/I The photograph below shows the reaction between sodium hydroxide and copper(II) chloride.

a. What evidence of a double displacement reaction do you see?

b. What are the names of the products that formed?

c. Which product is the precipitate? Explain your reasoning.

d. Write a balanced chemical equation for the reaction.

12. T/I What gas forms in the reaction between ammonium bromide and sodium hydroxide? Write a balanced chemical equation for this reaction.

13. K/U What reactants are involved in a neutralization reaction?

14. K/U Which ions combine to form water during the reaction between an acid and a base?

15. T/I What products should form during the reaction between hydrochloric acid, $HCl(aq)$, and a solution of calcium hydroxide, $Ca(OH)_2(aq)$? Write a balanced chemical equation for the reaction.

16. C Analyze the following neutralization reaction:

$$3NaOH(aq) + H_3PO_4(aq) \rightarrow H_2O(aq) + Na_3PO_4(s)$$

In a brief paragraph, describe any errors you find and explain how you would correct them.