Skills to Develop

• Explain and identify metathesis reactions.
• Apply metathesis reactions in gravimetric analysis and volumetric analysis.
• Apply metathesis reactions for making chemicals.

Key Words

• metathesis, precipitation, neutralization, gas formation
• gravimetric and volumetric analyses

A reaction such as

\[ \text{NaCl}_{(aq)} + \text{AgNO}_3_{(aq)} \rightarrow \text{AgCl}_{(s)} + \text{NaNO}_3_{(aq)} \]

in which the cations and anions exchange partners is called metathesis. In actual fact, the chemistry takes place in several steps. When the chemicals (sodium chloride and silver nitrate) are dissolved, they become hydrated ions:

\[ \text{NaCl}_{(s)} + 12 \text{H}_2\text{O} \rightarrow [\text{Na(H}_2\text{O)}_6]^+ + [\text{Cl(H}_2\text{O)}_6]^- \]
\[ \text{AgNO}_3_{(s)} + 12 \text{H}_2\text{O} \rightarrow [\text{Ag(H}_2\text{O)}_6]^+ + [\text{NO}_3(H}_2\text{O)}_6]^- \]

When the silver ions and chloride ions meet in solution, they combine and form a solid, which appears as a white precipitate:

\[ [\text{Ag(H}_2\text{O)}_6]^+ + [\text{Cl(H}_2\text{O)}_6]^- \rightarrow \text{AgCl}_{(s)} + 12 \text{H}_2\text{O} \]

The above equation shows the net ionic reaction, whereas the bystander ions \([\text{Na}^+]\) and \([\text{NO}_3^-]\) are not shown. Bystander ions are also called spectator ions. Metathesis reactions not only take place among ionic compounds, they occur among other compounds such as Sigma Bond Metathesis and Olfin Metathesis. Metathesis reaction is a type of chemical reaction, which includes combination, decomposition, and displacement.

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### Types of Metathesis Reactions

What happens when you pour two solutions of different electrolytes together? The mixture will have all ions from the two electrolytes. Ions of the same charge usually repel each other, but ions of opposite charge may form a stable molecule or solid. When a solid is formed such as \([\text{AgCl}]\), a precipitate is formed. From the observation point of view, metathesis reactions can be further divided into three classes:

- **Precipitation reaction:** products formed are not soluble, forming solids which we call precipitates. The solid silver chloride \([\text{AgCl}]\) mentioned above is a precipitate. Since the solid can be collected and dried, precipitation reactions are often used in gravimetric analysis, chemical analysis by mass or weight.
- **Neutralization reaction:** products formed are neutral water molecules, and the net ionic reaction is actually \([\text{H}^+ + \text{OH}^- \rightarrow \text{H}_2\text{O}]\). With proper indicators or pH monitoring, equivalence points are easily detected. Thus, neutralization reactions are used for volumetric analysis, quantitative determination by
volume measurement.

- **Gas formation reaction:** methesis reaction may lead to the formation of a neutral molecule that has low boiling point as well as low solubility in water. Thus, a gas is formed. For example: $2 \text{H}^+ + \text{CO}_3^{2-} \rightleftharpoons \text{H}_2\text{O} + \text{CO}_{2\text{(g)}}$

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**Why do ions exchange partners?**

Cations are always attracted to anions, but the hydration and hydrogen bonding keep the ions of electrolytes in solution. When two solutions are mixed, cations of one electrolyte meet anions of the other. If they form a more stable substance such as a solid or neutral molecules, exchange or metathesis reaction takes place. The new couples form a precipitation, gas, or neutral molecules. These reactions can be employed for gravimetric or volumetric analysis (determine the quantities present in a sample).

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**What substances are soluble?**

You have to work with these materials to know them well. Here are two basic rules regarding solubility:

- Most nitrates are soluble. So are alkali and ammonium halides.
- Most carbonates, phosphates, sulfites, sulfides, $\text{Ca(OH)}_2$, and $\text{AgCl}$ are some of the substances that are only sparingly soluble (less than 0.1 g per 100-mL water).

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**Gravimetric Analysis**

The quantitative determination of a component by measuring the mass of a compound formed with the component using a chemical reaction is called gravimetric analysis. Some examples are given here to show how gravimetric analysis is carried out.

**Example 1**

To determine % of $\text{MgSO}_4$ in epsom salts, you treat it with $\text{BaCl}_2$, because of the following reaction:

$\text{MgSO}_4 + \text{BaCl}_2 \rightarrow \text{MgCl}_2 + \text{BaSO}_4$

You can dry the substance $\text{BaSO}_4$ formed and weigh the resulting solid to determine the quantity of $\text{BaSO}_4$ (mol. wt. 120.37) formed. Suppose you started with 1.0000 g of epsom salts, and got 0.5000 g of $\text{BaSO}_4$ (mol. wt. 233.39). Calculate the percentage of $\text{MgSO}_4$ in the sample.

**Hint** - Use the following one-line method to do the conversion quickly:

$$\text{mol}\,\text{BaSO}_4 \times \frac{1\,\text{mol}\,\text{MgSO}_4}{1\,\text{mol}\,\text{BaSO}_4} \times \frac{120.37\,\text{g}\,\text{MgSO}_4}{1\,\text{mol}\,\text{MgSO}_4} = 0.2579 \, \text{g}\,\text{MgSO}_4$$
The sample is \(\frac{0.2579 \text{ g}}{1.0000 \text{ g}} \times 100\% = 25.79\% \text{ MgSO}_4\).

The numerators and denominators of the factors are equivalent under the conditions of the problem. Thus, these are conversion factors, and the factors convert the weight of \(\text{BaSO}_4\) to that of \(\text{MgSO}_4\).

Note the strategy of the analysis, and the methods of calculation for study purposes.

**Skill learned:**
Performing quantitative analysis is an important skill, and this link gives the procedures.

**Example 2**

A sample weighing 3.77 g containing \(\text{CaCl}_2\) and \(\text{AlCl}_3\) dissolved in water was treated with \(\text{AgNO}_3\), and the dry \(\text{AgCl}\) collected weighs 13.07 g. Calculate the weight and mole percentages of \(\text{CaCl}_2\) in the sample.

**Formula wt:** \(\text{CaCl}_2, 111.1; \text{AlCl}_3, 133.5; \text{AgCl}, 163.4.

**Hint -**
Since both compounds contain \(\text{Cl}^-\), this problem required some thinking. Consider all quantities in moles.

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Here is a place for the application of the skills learned in algebra. You can assume \(x\) to be the weight (g) of \(\text{CaCl}_2\), then \((3.77 - x)\) g must be \(\text{AlCl}_3\). Convert these into moles, and the sum of the moles of \(\text{Cl}^-\) ions from both salts must be equal to the (0.080) moles observed. Thus, we have

\[
\frac{x \text{ g CaCl}_2}{111.1 \text{ g/mol CaCl}_2} \times \frac{2 \text{ mol Cl}^-}{1 \text{ mol CaCl}_2} + \frac{(3.77 - x) \text{ g AlCl}_3}{133.5 \text{ g/mol AlCl}_3} \times \frac{3 \text{ mol Cl}^-}{1 \text{ mol AlCl}_3} = 0.080 \text{ mol Cl}^-.
\]

Simplify the above equation to give

\[
0.0180 \times x + 0.0847 - 0.0225 \times x = 0.080.
\]

The solution gives

\[
x = 1.04 \text{ g CaCl}_2, \text{ and } 3.77 - 1.04 = 2.73 \text{ g AlCl}_3.
\]

By definition, the weight percent of \(\text{CaCl}_2 = \frac{1.04}{3.77} \times 100\% = 27.59\%\).

In order to calculate mole percent, the quantities are converted into moles:

\[
\frac{1.04 \text{ g CaCl}_2}{111.1 \text{ g/mol CaCl}_2} = 0.0094 \text{ mol CaCl}_2
\]

\[
\frac{2.73 \text{ g AlCl}_3}{133.5 \text{ g/mol} = 0.0204 \text{ mol AlCl}_3}
\]

Thus, the mole percentage of \(\text{CaCl}_2 = \frac{0.0094}{0.0094 + 0.0204} = 31.5\%\).
Skill learned:
Determine the weight and mole percentages of a mixture.

Confidence Building Problems

1. **What is the product when solids of \(\ce{AgNO3}\) and \(\ce{NaCl}\) are mixed?**

   Hint: no reaction

   **Skill:**
   Solids do not react until moisture is present.

2. **What is the product when solutions of \(\ce{AgNO3}\) and \(\ce{NaCl}\) are mixed?**

   Hint: solid \(\ce{AgCl}\) formed

   **Skill:**
   Metathesis reaction takes place in solution!

3. **An impure \(\ce{AgNO3}\) sample weighing 1.00 g dissolving in water is treated with \(\ce{NaCl}\) to give 0.600 g \(\ce{AgCl}\). Calculate the percentage of \(\ce{AgNO3}\) in the sample.**

   Hint: 71.1%

   
   \[
   \text{mass of } \ce{AgCl} \times \frac{1 \text{ mol } \ce{AgCl}}{143.4 \text{ g } \ce{AgCl}} \times \frac{1 \text{ mol } \ce{AgNO_3}}{1 \text{ mol } \ce{AgCl}} \times \frac{169.9 \text{ g } \ce{AgNO_3}}{1 \text{ mol } \ce{AgNO_3}} = \ ? \text{ g } \ce{AgNO_3}
   \]

   **Skill:**
   Determine the percentage of an impure substance.

4. **Is there any reaction between \(\ce{AgNO3}\) and \(\ce{NaNO3}\) solution?**

   Hint: no reaction

   The resulting solution consists of \(\ce{Ag^+}\), \(\ce{Na^+}\), and \(\ce{NO_3^-}\) ions.

   **Skill:**
   Explain the species of an electrolyte.

5. **When solutions of \(\ce{H2SO4}\) and \(\ce{NaCl}\) are mixed, what is evolved in the vapour? Give the formula.**

   Hint: \(\ce{HCl}\)

   \(\ce{HCl}\) has a much higher vapour pressure than \(\ce{H2SO4}\).

   **Skill:**
Use this reaction to make \(\text{HCl}\).

6. **A 1.140 g mixture of \(\text{NaCl}\) and \(\text{CaCl}_2\) dissolved in water is mixed with sufficient solution of \(\text{AgNO}_3\) to give 2.868 g of dry \(\text{AgCl}\). Calculate the WEIGHT percentage of \(\text{NaCl}\). Use two significant digits.**

   \(\text{Na} = 23.0; \text{Cl} = 35.5; \text{Ca} = 40; \text{Ag} = 107.9\)

   **Hint:** 51% by weight

   \[
   \text{mass of AgCl} = 0.0200 \text{ mol (Cl}^-\text{ or AgCl)}
   \]

   Assume \(x\) g \(\text{NaCl}\), then you have \((1.140 - x)\) g of \(\text{CaCl}_2\).

   The equation

   \[
   \frac{x\ \text{g NaCl}}{58.5\ \text{g/mol}} + \frac{2(1.140 - x)\ \text{CaCl}_2}{111.1\ \text{g/mol}} = 0.0200\ \text{mol}
   \]

   Solve for \(x = \text{?} \text{ g}\)

   **Skill:**
   
   Determine the percentage of a mixture by one measurement.

7. **A 1.140 g mixture of \(\text{NaCl}\) and \(\text{CaCl}_2\) dissolved in water is mixed with sufficient solution of \(\text{AgNO}_3\) to give 2.868 g of dry \(\text{AgCl}\). Calculate the MOLE percentage of \(\text{NaCl}\).**

   \(\text{Na} = 23.0; \text{Cl} = 35.5; \text{Ca} = 40; \text{Ag} = 107.9\)

   **Hint:** 66% by mole

   **Skill:**
   
   Determine the mole percentage of a mixture.

8. **When 0.10 mol each of \(\text{NaCl}\) and \(\text{CaCl}_2\) dissolved in water is treated with \(\text{AgNO}_3\), how many moles of \(\text{AgCl}\) should be collected?**

   **Hint:** 0.3 mol

   **Skill:**
   
   Apply the limiting reagent concept in chemical analysis.

9. **What is the weight of 0.30 mol \(\text{AgCl}\)? (formula wt. \(\text{AgCl}\), 163.4)**

   **Hint:** 49 g \(\text{AgCl}\)

   **Skill:**
   
   Use \(\text{AgNO}_3\) as a reagent for gravimetric analysis for chloride.
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