Solubility Rules

PURPOSE

To develop a set of solubility rules.

GOALS

- To observe trends in solubility and exceptions to these trends.
- To write chemical formulas based on cation/anion charges.
- To learn to write net ionic equations.

INTRODUCTION

Chemical reactions can be classified into five major classes:

1 Combination or Synthesis (formation) reactions:

Two substances combine to form a compound. The generic expression is:

$$A + B \rightarrow C \tag{1}$$

Examples of such reactions include:

$$2\ Ca + O_2 \rightarrow 2\ CaO \tag{2}$$

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3 \tag{3}$$

2 Decomposition reactions:

The opposite of a combination reaction, a compound breaks apart to form two or more products. The generic expression is:

$$AB \rightarrow A + B \tag{4}$$

Examples of such reactions include:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{5}$$

$$2\ H_2O \rightarrow 2\ H_2 + O_2 \tag{6}$$

3 Single Displacement Reactions:

One element, ion, or functional group displaces another element, ion, or functional group from a compound. The generic expression is:

$$\mathrm{A + BC \rightarrow AC + B} \tag{7}$$

Some examples include:

$$\mathrm{Cu + 2\ HNO_3 \rightarrow Cu(NO_3)_2 + H_2} \tag{8}$$

$$\mathrm{Zn + 2\ HCl \rightarrow ZnCl_2 + H_2} \tag{9}$$

4 Double Displacement or Metathesis Reactions:

The atoms or ions in two or more different substances change places to form new compounds. The generic expression is:

$$\mathrm{AB + CD \rightarrow AD + CB} \tag{10}$$

Some examples include:

$$\mathrm{HC_2H_3O_2}(aq) + \mathrm{NaOH}(aq) \rightarrow \mathrm{NaC_2H_3O_2}(aq) + \mathrm{H_2O} \tag{11}$$

$$\mathrm{Pb(NO_3)_2}(aq) + 2\ \mathrm{KI}(aq) \rightarrow \mathrm{PbI_2}(aq) + 2\ \mathrm{KNO_3}(aq) \tag{12}$$

Double displacement reactions fall into at least two major subclasses. Equation 11 shows one of them, a **neutralization** reaction between an acid and a base. Equation 12 shows another, a **precipitation** reaction. Soluble species (generally ions) react to form insoluble solid compounds that are called **precipitates**.

5 Electron Transfer or Redox reactions:

Electrons are transferred from one substance to another. These will be treated separately in this lab course.

In this experiment, we will work with **precipitation reactions** involving ions. Ionic solids dissolve in water by a process known as **dissolution**. If an appreciable amount of the solid dissolves, it is said to be **soluble**. The ions are **solvated** by water, and free to move independently of each other in the solution. When two aqueous solutions of ionic substances are mixed, the mobile ions in each solution interact with each other. Coulomb's law describes the interaction between the ions (charged particles).

$$F = k \cdot \frac{q_1 q_2}{\epsilon r^2} \tag{13}$$

where:

F is the force that acts between the two ions

k (Coulomb's constant) is 8.9875×10^9 N·m^2/C^2

q_1 and q_2 are the charges on the ions

r is the distance that separates them

ϵ (epsilon) is the dielectric constant of the solvent*

* Water has a large dielectric constant, which reduces the electrostatic interaction between the particles.

When the signs of the charges q_1 and q_2 are the same, $F > 0$ and the charges repel one another. When ions of opposite charge encounter one another, $F < 0$, and the ions are attracted to one another. When the attractive force between opposite charged ions is great enough to overcome the energetically favorable interaction between the ions and water, the ions combine to form a compound that is not soluble in water. We say that the compound "falls out" of solution, or **precipitates** (verb). The solid compound, which has formed, is called a **precipitate** (noun). As an initial hypothesis, we can state that precipitates will form when the attractive force between ions is large. This will be true when their charges (q_1 and q_2) are opposite in sign and large.

As noted previously, soluble ionic species are mobile and free to move independently of each other. The freedom is not absolute; the positive ions will not all congregate in one portion of the solution. Nonetheless, the ions are not tied to a position or to a specific **counterion** (ion of opposite charge). To express this, one may write a reaction in the form of a **total ionic equation**, as shown below:

$$\begin{aligned} &\mathrm{Pb}^{2+}(aq) + 2\ \mathrm{NO}_3^-(aq) + 2\ \mathrm{K}^+(aq) + 2\ \mathrm{I}^-(aq) \rightarrow \\ &\qquad \mathrm{PbI}_2(s) + 2\ \mathrm{K}^+(aq) + 2\ \mathrm{NO}_3^-(aq) \end{aligned} \tag{14}$$

This rather cumbersome equation includes several ions that appear in identical form on both sides of the equation. These ions are not directly involved in the chemical reaction and are called **spectator ions**. It is often convenient to write a reaction with a **net ionic equation**, which shows only those species that participate in the chemical reaction. The net ionic equation for the reaction shown in Equation 14 is shown below.

$$\mathrm{Pb}^{2+}(aq) + 2\ \mathrm{I}^-(aq) \rightarrow \mathrm{PbI}_2(s) \tag{15}$$

Net ionic equations are much simpler to write and interpret than total ionic equations. They are used frequently in inorganic chemistry. The spectator ions must, of course, be present. One does not find a bottle of lead(II) cations or iodide ions on a lab shelf! However, the reaction will work nicely regardless of whether the lead ion is introduced as lead nitrate, $Pb(NO_3)_2$, or as lead acetate, $Pb(C_2H_3O_2)_2$. Similarly, the iodide compound can be potassium iodide, KI, or sodium iodide, NaI. All of these compounds are soluble in water, and stable.

In this laboratory, you will perform a number of microscale chemical reactions to determine which anions form insoluble compounds with various cations. The results will be used to formulate a table of solubility rules.

Since the reactions will be done with ions in solution, the solutions must be prepared from compounds that are soluble. All nitrate salts are soluble. Therefore, the cations you will use will be solutions of their nitrate salts. In keeping with the usage of net ionic equations, only the cation, e.g., Ca^{2+}, will be listed in your data table. For anions, you will formulate a solubility rule which will allow you to guess what an appropriate spectator cation might be.

EQUIPMENT

1 250 mL beaker (for waste)

1 plastic 8 × 12 well plate

1 test tube rack

2+ small test tubes

REAGENTS

Anions (rows)

~3 drops 0.20 M NaCl

~3 drops 0.20 M $NaClO_4$

~3 drops 0.20 M NaOH

~3 drops 0.20 M Na_2CO_3

~3 drops 0.20 M Na_2SO_4

~3 drops 0.20 M Na_3PO_4

Cations (columns)

~3 drops 0.20 M NH_4NO_3

~3 drops 0.20 M KNO_3

~3 drops 0.20 M $Ca(NO_3)_2$

~3 drops 0.20 M $Sr(NO_3)_2$

~3 drops 0.20 M $Mg(NO_3)_2$

~3 drops 0.20 M $Al(NO_3)_3$

~3 drops 0.20 M $Fe(NO_3)_3$

~3 drops 0.20 M $Zn(NO_3)_2$

~3 drops 0.20 M $Pb(NO_3)_2$

~3 drops 0.20 M $AgNO_3$

SAFETY

Some of the cation solutions are toxic. Do not ingest them. If you spill any on yourself, wash well with soap and water. Avoid putting anything in your mouth while in lab, ex. chewing on fingernails, pens and pencils.

Silver solution will form dark spots on skin if spilled. The spots will not appear for about 24 hours, as the ions are slowly reduced to the metal. They are not hazardous, and will fade in a few days.

WASTE DISPOSAL

All of the solutions prepared in this experiment should be discarded in the waste container on the side shelf. You may wish to have a beaker in your work area to collect waste while you are doing the experiment. Make sure it is labeled. Use a squeeze bottle of deionized water to rinse the solutions into the beaker; use the minimum amount of water you can, to avoid creating large volumes of waste solution. The plates and test tubes can then be washed in the normal manner.

LAB PROCEDURE

Please print the worksheet for this lab. You will need this sheet to record your data.

Part A: Investigating Trends in Solubility

1 Obtain an 8×12 plastic well plate. You will be mixing ions in the well plate. The combinations of ions are listed in the grid in Table A.

2 In order to keep track of what you are doing, put your solutions into the well plate in the same order they are listed in Table A.

3 Add ***three drops*** of each solution listed to the well. (More is not better!) Be careful to drop the solution into the well without touching the grid or any solution that is already in the well. If the dropper touches another solution, the reagent in the dropper bottle will become contaminated. Place your cations (nitrate solutions) in columns. Place your anions (sodium solutions) in rows.

4 Record your observations in Table A. If a precipitate forms, put a **Y** in the space that corresponds to the two solutions that were mixed. If no reaction occurs (no precipitate forms), put an **N** in the appropriate space in the table. If you cannot see a result clearly in the well plate, repeat the experiment in a small clean test tube.

5 Make note of any observations other than precipitation below the table. For example, if a precipitate is colored or appears gelatinous, a comment to that effect should appear on your worksheet.

Part B: Investigating Some Exceptions to the Solubility Rules

1 In two of the unused wells of your well plate, mix the solutions listed in Table B, as you did for Part A.

2 Record your observations in Table B. If a precipitate forms, put **Y** in the space that corresponds to the two solutions that were mixed. If no reaction occurs (no precipitate forms), put an **N** in the appropriate space in the table. If you cannot see a result clearly in the well plate, repeat the experiment in a small clean test tube.

3 When you are finished, collect all your waste and deposit it in the waste container provided on the side shelf. Use a minimum amount of water to rinse residual solutions into the waste container. Then clean and dry all your equipment and return it to the set-up area where you found it.

4 Before leaving, go to a computer in the laboratory and enter your results in the In-Lab assignment. If all results are scored as correct, log out. If not all results are correct, try to find the error or consult with your lab instructor. When all results are correct, note them and log out of WebAssign. The In-Lab assignment must be completed by the end of the lab period. If additional time is required, please consult with your lab instructor.