Reaction Stoichiometry

PURPOSE

To determine the stoichiometry of acid-base reactions by measuring temperature changes which accompany them.

GOALS

- To learn to use the MicroLab Interface.
- To practice generating reaction tables.
- To determine the limiting reagent in a reaction through a measured quantity.

INTRODUCTION

In this lab, you will be investigating reaction stoichiometry by doing a series of mixing experiments using acids and bases in different amounts. By following temperature changes upon mixing, you will be able to relate the amount of heat given off in the reaction to the moles of acid and base that react. The first set of experiments uses the neutralization of HCl with sodium hydroxide:

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O \tag{1}$$

The second set of experiments involves the reaction between phosphoric acid and sodium hydroxide:

$$H_3PO_4(aq) + 3\ NaOH(aq) \rightarrow Na_3PO_4(aq) + 3\ H_2O \tag{2}$$

Chemical reactions form the core of the study of chemistry. We represent reactions in a shorthand notation called a balanced chemical equation. Although the balanced equation does not tell us anything about the mechanism of the reaction (how the atoms come together and how bonds are formed or broken), it does give us information on the stoichiometry of the reaction; that is, the relative **amounts** of reactants and products involved. The coefficients in the balanced equation allow us to determine how much product can form from a given amount of starting material on a per particle or per mole basis.

Reaction stoichiometry is based on the balanced chemical equation for any given reaction. The ratios of the coefficients of the balanced reaction represent the ratios of particles or moles of reacting and/or produced compounds. For example, consider the following chemical equation:

$$2\ Al + 6\ HCl \rightarrow 2\ AlCl_3 + 3\ H_2 \tag{3}$$

The stoichiometry indicates that for every 2 moles of Al that react, 6 moles of HCl would be required and 2 moles of $AlCl_3$ and 3 moles of H_2 would be obtained.

As an example, how many moles of HCl would be required for the reaction of 65.5 g of Al and how many grams of $AlCl_3$ could be produced?

$$\text{moles HCl needed} = 65.5\ \cancel{\text{g Al}} \times \frac{1\ \cancel{\text{mol Al}}}{27.0\ \cancel{\text{g Al}}} \times \frac{6\ \text{mol HCl}}{2\ \cancel{\text{mol Al}}} = 7.28\ \text{mol HCl} \qquad (4)$$

$$\text{grams AlCl}_3\ \text{produced} = 65.5\ \cancel{\text{g Al}} \times \frac{1\ \cancel{\text{mol Al}}}{27.0\ \cancel{\text{g Al}}} \times \frac{2\ \cancel{\text{mol AlCl}_3}}{2\ \cancel{\text{mol Al}}} \times \frac{133\ \text{g AlCl}_3}{1\ \cancel{\text{mol AlCl}_3}} = 323\ \text{g AlCl}_3 \qquad (5)$$

The reactants are seldom added in the exact ratios shown in the balanced equation, so one of them is present in an amount that is insufficient to react with all of the others. This substance then limits how much product can be obtained, so it is called the limiting reactant. When the limiting reactant is consumed, the reaction stops even if other reactants are still available. In the above example, if only 6.00 moles of HCl were available, it would be the limiting reactant because 7.28 moles are necessary to react with the given amount of Al. When 6.00 moles of HCl had reacted, the reaction would stop and the unreacted excess Al would be present in the product as a contaminant. Note that if a limiting reactant is present, then all calculations of product amounts must be based on that reactant.

For the example noted, the mass of $AlCl_3$ that can be produced if only 6.00 moles of HCl is available is:

$$\text{grams AlCl}_3\ \text{produced} = 6.00\ \cancel{\text{mol HCl}} \times \frac{2\ \cancel{\text{mol AlCl}_3}}{6\ \cancel{\text{mol HCl}}} \times \frac{133\ \text{g AlCl}_3}{1\ \cancel{\text{mol AlCl}_3}} = 266\ \text{g AlCl}_3 \qquad (6)$$

Note that this amount is significantly less than the 323 g of $AlCl_3$ which would have been produced if the required 7.28 mole of HCl were available.

The amount of product that calculations like these predict is called the theoretical yield. For the conditions noted in determining the grams of $AlCl_3$ produced in equation (6), the theoretical yield of $AlCl_3$ is 266 g. If 266 g were obtained, then the actual yield would be 100%. However, for a number of reasons, 100% yields in chemical reactions are a rarity. The amount actually obtained is called the **actual yield**, and the ratio of actual to theoretical yield, expressed as a percentage, is the **percent yield**. This can be calculated in mass or moles but the same units must be used for both:

$$\text{Percent yield} = \frac{\text{actual yield (g or mol)}}{\text{theoretical yield (g or mol)}} \times 100\% \qquad (7)$$

For example, if 255 g $AlCl_3$ were obtained for the reaction of 6.00 moles of HCl instead of 266 g $AlCl_3$, the percent yield would be:

$$\frac{255 \cancel{\text{ g AlCl}_3}}{266 \cancel{\text{ g AlCl}_3}} \times 100\% = 95.9\% \tag{8}$$

A reaction table is an excellent way to track the amounts of all substances in a chemical reaction. The following is the reaction table for the reaction 65.5 g (2.43 mol) of Al and 6.5 moles of HCl:

	2 Al	+	6 HCl	→	2 $AlCl_3$	+	3 H_2	
Initial	2.43		6.50		0		0	moles
Δ	–2.17		–6.50		+2.17		+3.25	moles
Final	0.26		0.00		2.17		3.25	moles

In this table:

Initial: The starting amounts expressed in moles or mmoles.

Δ (or change): The amount of change that occurs in the reaction expressed in moles or mmoles. Note that as the reaction proceeds, the reactant side decreases (hence the − sign) and the product side increases (the + sign). **IT IS ON THIS LINE WHERE THE REACTION STOICHIOMETRY AND LIMITING REACTANT ARE ACCOUNTED FOR**. This has been indicated in the table by the use of all of the HCl and the use of the stoichiometric amount of Al along with the stoichiometric equivalents of the products based on the HCl being the limiting reactant.

Final: The amount of material remaining after the reaction is complete or equilibrium is established. It is the algebraic sum of INITIAL + Δ.

As noted in the opening paragraph, acid-base reactions will be used in this experiment. The acids and bases used in this experiment are solutes in aqueous solution. To generate a reaction table, it will be necessary to convert from concentration to moles of material. The concentrations will be given in Molarity (M = moles/liter = millimoles/milliliter). The volumes of acid or base solution will be measured in milliliters (mL). The product of the volume in mL and the concentration in M will give the amount of acid or base in millimoles (mmol). For example, if one used 20 mL of 1.3 M NaOH solution, the millimoles of NaOH would be:

$$20.\ \text{mL NaOH solution} \times \frac{1.3\ \text{mmol NaOH}}{1.0\ \text{mL solution}} = 26\ \text{mmol NaOH} \tag{9}$$

Acid-base reactions are normally exothermic; that is, they give off heat. The heat given off by the reaction ends up in the "surroundings." For our purposes in this experiment, the surroundings will be the total aqueous solution that is formed after mixing. To accurately compare different mixtures, you will add water to some of the mixing experiments to make the **total** volume in each experiment the same. This way, the reaction is heating the same total volume of solution in each case.

The amount of heat given off by a reaction depends on the amount of product formed. (Literally, the number of moles of bonds broken and formed during the reaction.) Logically, the more moles of product formed, the more heat is given off. However, as stated earlier, **the number of moles of product actually formed is dictated by the limiting reactant.** Therefore, the amount of heat given off by the reaction, and the subsequent temperature change, is dictated by the limiting reactant too.

In this experiment, you will determine the stoichiometry of two acid-base reactions by measuring the temperature changes that accompany them.

EQUIPMENT

4 150 mL beakers

3 50 mL graduated cylinder

1 MicroLab Interface

1 MicroLab Thermistor Instruction Sheet

1 thermistor

1 deionized water squirt bottle

1 ring stand

1 clamp

REAGENTS

60 mL 1.5 M $HCl(aq)$

45 mL 1.0 M $H_3PO_4(aq)$

150 mL 1.5 M $NaOH(aq)$

SAFETY

You will be working with hydrochloric acid, $HCl(aq)$; phosphoric acid, $H_3PO_4(aq)$; and $NaOH(aq)$. These chemicals are corrosive. If you spill one of them on a surface, wipe it up with paper towels and rinse with water, being careful not to touch the liquid. If you spill some on yourself, immediately rinse the area with lots of water. If any gets in your eyes, flush them with water at the eyewash and have someone notify the TA.

WASTE DISPOSAL

The solutions used in this experiment can be flushed down the sink with plenty of water.

PRIOR TO CLASS

Please read the following sections of Lab Safety and Practices: Good Lab Practices[1] and Measurements[2].

Please read the following section in Lab Equipment: Volumetric Glassware[3].

[1] ../practices/manual.html
[2] ../measurements/manual.html
[3] ../equipment/manual.html#volumetric glassware

Please review the following video: Safety[4].

Please complete WebAssign prelab assignment. Check your WebAssign Account for due dates. Students who do not complete the WebAssign prelab are required to bring and hand in the prelab worksheet.

LAB PROCEDURE

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

1 Open the MicroLab program.

2 Calibrate the thermistor as described in the MicroLab instructions provided in the lab.

3 After the calibration is complete, set the MicroLab collection increment to 2 seconds using the instructions provided.

4 In separate **appropriately labeled** 150 mL beakers, obtain the total amount of acid and base solutions you will need for each set of experiments: 60 mL HCl, 45 mL H_3PO_4 and 150 mL NaOH. **Record their concentrations** in Table A.

5 Label a graduated cylinder for acid, another for base and a third for deionized water. **Use them consistently for the liquid designated.** For each experiment, add the NaOH solution and the deionized water together in a 150 mL beaker, and immerse the thermistor part way into the liquid being careful not to touch the thermistor to the bottom or sides of the vessel.

6 Add the appropriate amount of NaOH solution (20 mL) and deionized water (20 mL) for the first run to a 150 mL beaker. Do not, at this point, handle the beaker since we only want to measure the heat evolved from the reaction. Use a clamp to hold the thermistor in place in the beaker to prevent it from touching the bottom and prevent the beaker from tipping over.

7 Measure the initial temperature of the base (NaOH solution, diluted with water). You may need to wait ~2 minutes to be sure the temperature has stabilized. Record its temperature to the nearest 0.01°C in Table B.

8 Add the appropriate amount of acid solution and swirl the beaker gently. If you swirl too vigorously, you may spill the acid and base on your hand. **Do not stir with the thermistor** as it can easily break. After the temperature stops changing (~30 sec), stop the temperature collection program. Record this final temperature to the nearest 0.01°C in Table B. Note: After stabilizing, the temperature may slowly, over the course of many minutes, decrease toward room temperature. Record the first stable temperature as your final temperature.

9 Dispose of the solution from the first run and rinse the reaction beaker and thermistor thoroughly with deionized water from your squirt bottle.

10 Obtain temperature change data for the other 5 mixing experiments by repeating steps 6 - 9. Remember to record both your initial and final temperatures for each experiment in Tables B and C.

[4] ../movies/labsafety.html

11 Close the MicroLab software. Rinse all of your glassware with water, dry it and return it to the set-up area where you found it.

12 Before leaving, enter your results in the WebAssign 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.

