EXPERIMENT 12N

8/7/2018

CALORIMETRY

MATERIALS: Styrofoam cup and lid, stir bar, magnetic stir plate, digital thermometer, 250 mL beaker, two 100 mL graduated cylinders, aluminum nugget, 1.0 M HCl, 2.0 M HCl, 1.0 M H_2SO_4, 1.0 M NaOH, 2.0 M NaOH.

PURPOSE: To determine the specific heat capacity of aluminum, and to determine the temperature change, heat of reaction, and enthalpy change for a series of acid-base neutralization reactions.

OBJECTIVES: By the end of this experiment, the student should be able to:

1. Experimentally determine a specific heat.
2. Calculate ΔH for a given reaction using thermodynamic data from tables.
3. Determine ΔH experimentally for a given reaction using a coffee cup calorimeter.
4. Predict how thermodynamic values change when varying the quantity or concentration of reactants.
5. Investigate factors that affect ΔT, q_{rxn}, and ΔH of a reaction.

PRE-LAB: Read the entire experiment and instructions, and complete the pre-lab assignment.

BACKGROUND:

The amount of heat absorbed or released by an object can be written as

$$q = C_{tot}\,\Delta T \tag{1}$$

where q is the heat absorbed or released, C_{tot} is the total heat capacity, and ΔT is the temperature change for the object. Equation 1 may also be expressed as

$$q = m\,C_{sp}\,\Delta T \tag{2}$$

where m is the mass of the object (or substance) absorbing or releasing the heat, and C_{sp} is the specific heat capacity (or simply specific heat) of the object. C_{sp} is just the heat capacity per gram. The value of C_{sp} depends on the object (or substance). For water, it is

$$C_{sp,\ water} = 4.184\ \text{J/g}\ ^{o}\text{C} \tag{3}$$

Because we are dealing with temperature <u>changes</u>, C_{sp} is identical for units involving Kelvin: $C_{sp,\ water}$ = 4.184 J/g K.

<u>Simple heat transfer</u>

Consider placing a hot aluminum nugget in a sample of cool water. The aluminum will lose heat and the water will gain heat. The heat transferred in this process can be measured using a calorimeter. Calorimeters can be very complicated and expensive (bomb calorimeters, isothermal calorimeters, differential scanning calorimeters, etc.). However, a simple calorimeter can be made from any well insulated cup, such as a Styrofoam coffee cup. Assuming we have an ideal system (no heat escapes and only the water absorbs the heat, not the coffee cup), the heat of the calorimeter (q_{cal}) approximates the heat transferred to the water (q_{water}). We will therefore use q_{water} henceforth. With this assumption, all of the heat lost by the Al is gained by the water:

$$q_{Al} = -q_{water} \tag{4}$$

It follows that for Al and water, equation 2 can be written as

$$q_{Al} = m_{Al}\,C_{sp,\ Al}\,\Delta T_{Al} \qquad\qquad q_{water} = m_{water}\,C_{sp,\ water}\,\Delta T_{water} \tag{5}$$

Note that ΔT in equation 5 must be written as T(final) – T(initial) for each substance.

Heat transfer in an acid-base neutralization reaction

The neutralization of an acid with a base in aqueous solution is an exothermic process. For example,

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l) \qquad \Delta_rH° \approx -56.84 \text{ kJ/mol}^{1} \tag{6}$$

The heat transferred in this process (q_{rxn}) can also be measured using a simple coffee cup calorimeter, such as described above. In this case, all of the heat evolved by the reaction is transferred to the solution:

$$q_{rxn} = -q_{soln} \tag{7}$$

where q_{soln} is the heat gained by the solution. q_{soln} can be measured as a temperature change where

$$q_{soln} = m_{soln}\, C_{sp,\, soln}\, \Delta T_{soln} \tag{8}$$

Since our solution is quite dilute and aqueous, and water has a very high specific heat, we will assume that the specific heat of the solution is the same as that of the water. Therefore,

$$C_{sp,\, soln} = 4.184 \text{ J/g °C}$$

The enthalpy change for a reaction, Δ_rH, is usually expressed in units of kJ/mol. When expressed in this way, Δ_rH is the amount of heat released or absorbed (at constant pressure) **per mole of reaction**. In this lab you will calculate Δ_rH as the enthalpy change associated with the formation of one mole of H_2O through the process of acid/base neutralization. The total amount of heat produced by a reaction is given by:

$$q_{rxn} = n\, \Delta_rH \tag{9}$$

where n is moles of reaction (moles of water produced). Knowing that $q_{cal} \approx q_{water} \approx q_{soln}$, we have

$$\Delta_rH = \frac{q_{rxn}}{n} = -\frac{q_{soln}}{n} \tag{10}$$

You will calculate q_{soln} using equation 8, and you will calculate the moles of water produced (n) using the moles of reactants added and the stoichiometry of the reaction. Assume that the reaction goes to completion. In some of the trials, one of the reactants is limiting, and we assume that reactant is completely consumed.

PROCEDURE:
Work in pairs

Part A. Specific Heat of Aluminum

1. Place about 75 mL of water in the 250 mL beaker.
2. Weigh an aluminum nugget on the top-loading balance, and record this mass in the Data Section. Place the aluminum nugget into the 75 mL of water.
3. Set up a tripod, screen, and Bunsen burner, and begin heating the 75 mL of water (containing the aluminum nugget). Bring it to a full boil (assumed to be 100°C), and record the temperature of the aluminum nugget in the Data Section (this temperature is the initial temperature of Al). *Note: Continue to step 4 while the water and aluminum are heating.*
4. While the water and aluminum are heating, measure out exactly 100 mL of water in the graduated cylinder and pour it into a clean, dry, Styrofoam cup. Record the volume in the Data Section.
5. Measure the temperature of the water in the Styrofoam cup and record it in the Data Section. *This is the initial temperature of the water.*
6. With the 75 mL water at a boil, use the tongs to remove the aluminum nugget and quickly place it in the Styrofoam cup and cover it with a lid, with thermometer inserted through the lid into the water. Swirl the cup of water and observe the temperature rise. Record the maximum temperature in the Data Section. *This is the final temperature.*

Clean-up/Disposal: Empty the Styrofoam cup of water BUT NOT THE SLUG down the drain.

[1] Peter Atkins and Julio de Paula, Physical Chemistry, 10th ed, W. H. Freeman and Company, New York, 2014.

Part B. Calorimetry in Acid-Base Neutralization Reactions

Caution: Hydrochloric acid, sulfuric acid, and sodium hydroxide are corrosive and toxic.

1. Construct a coffee-cup calorimeter: Place a Styrofoam cup on a magnetic stirrer. Add a magnet and cover the cup with a lid. Secure a thermometer to a clamp on a ring stand so that the thermometer extends through the lid and into the cup without touching the magnet. The combined cup, magnet, lid, and thermometer is your calorimeter.

2. **READ ALL STEPS BEFORE PROCEEDING.** For each of the five experimental conditions in the table,

    a. Accurately measure the appropriate amounts of acid and base in *separate* graduated cylinders. *Note: Use the same graduated cylinder for all acid measurements, and the other graduated cylinder for the base measurements.*
    b. Open the lid and pour the acid into the calorimeter. Replace the lid and monitor the temperature for 1 min, in order to ensure a stable initial temperature. Do not puncture the calorimeter with the thermometer. *Note: The lid must be on while the temperature is monitored in this step and all other subsequent steps*.
    c. Record the initial temperature.
    d. Add the base to the calorimeter and replace the lid.
    e. Monitor the temperature of the solution as it rises, and record the maximum temperature.
    f. Dispose of the reaction solution by pouring it down the drain and rinse the stir bar and calorimeter with distilled water. Pour out any excess water but there is no need to dry the cup between experiments.

Experiment	Acid Solution	Sodium Hydroxide Solution
1	50.0 mL 1.00 M hydrochloric acid	50.0 mL 1.00 M sodium hydroxide
2	100.0 mL 1.00 M hydrochloric acid	100.0 mL 1.00 M sodium hydroxide
3	50.0 mL 2.00 M hydrochloric acid	50.0 mL 2.00 M sodium hydroxide
4	25.0 mL 1.00 M hydrochloric acid	75.0 mL 1.00 M sodium hydroxide
5	25.0 mL 1.00 M sulfuric acid	75.0 mL 1.00 M sodium hydroxide

3. Calculate the ΔT for each experiment. Compare your ΔT values to those of the group next to you. If any ΔT values differ by more than 0.5°C, repeat that experiment together.

Clean-up/Disposal:
1. All solutions can be rinsed down the drain with plenty of water.
2. Rinse your calorimeter, stir bar, and any other glassware used.
3. Return equipment to their proper locations and clean up your lab area.

Name ____ Section ____________________

Partner ______________________________________ Date ______________________

DATA SECTION
Experiment 12N

Part A – Specific Heat of Aluminum

Initial Conditions	
mass of aluminum (g)	
initial temperature of aluminum (°C)	
volume of water (mL)	
initial temperature of water (°C)	
Final Conditions	
final temperature (°C)	

Part B – Calorimetry in Acid-Base Neutralization Reactions

Experiment	**Initial Temperature (°C)**	**Maximum Temperature (°C)**	**ΔT (°C)**
1			
2			
3			
4			
5			

DATA TREATMENT
Experiment 12N

Part A – Specific Heat of Aluminum

1. Calculate the specific heat of aluminum. Show all work, and remember to include correct units.

2. Calculate the percent error, given that the literature value[2] is 0.897 J g^{-1} $°C^{-1}$.

Part B – Calorimetry in Acid-Base Neutralization Reactions

Answer the questions below for experiment 1 only. *Show all work.*

1. Calculate the moles of H^+ initially present.

2. Calculate the moles of OH^- initially present.

3. Write the balanced chemical equation for the reaction between H^+(aq) and OH^-(aq).

4. Calculate the moles of H_2O produced.

[2] CRC Handbook of Chemistry and Physics, 96th edition, 2015 – 2016. http://www.hbcpnetbase.com (Accessed 22 July 2016).

5. Calculate the temperature change.

6. Calculate the <u>mass of solution</u> from the volume of solution.

7. Calculate q_{rxn}, in units of Joules. Include the correct sign (+/–).

8. Calculate the enthalpy change, $\Delta_r H$, for the reaction in question 3 (in *kilojoules per mole of water formed*).

9. Given that the literature reports $\Delta_r H$ = –55.84 kJ/mol for the reaction $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$,[3] calculate the percent error of your answer.

10. Record your answers for Experiment 1 in the table below.

11. Repeat the above calculations for experiments 2 – 5 and record your answers in the table below.
Note 1: Pay special attention to experiments having a limiting reactant.
Note 2: H_2SO_4 is a diprotic acid; for calculational purposes, assume both ionization steps are strong.

Experiment	**Initial mol H^+**	**Initial mol OH^-**	**mol H_2O produced**	**ΔT, (°C)**	**Mass of solution (g)**	**q_{rxn} (J)**	**ΔH_{rxn} (kJ/mol)**
1							
2							
3							
4							
5							

[3] Peter Atkins and Julio de Paula, Physical Chemistry, 10th ed, W. H. Freeman and Company, New York, 2014.

QUESTIONS

1. In Pre-Laboratory Question 3**,** you made temperature change predictions for four variations of Experiment 1. Does your experimental data support your predictions? For each incorrect prediction, describe the error in your initial reasoning.

2. a. Does doubling the volumes of 0.10 M acid and 0.10 M base in a neutralization reaction double the amount of heat released? If yes, explain *why* your observations show this behavior.

   b. Does doubling the concentrations (but not the volumes) of acid and base in a neutralization reaction double the amount of heat released? If yes, explain *why* your observations show this behavior.

3. a. Experiments 2 and 3 both produce twice as much heat as experiment 1. Explain why ΔT for experiment 2 was the same as that for experiment 1 and why ΔT for experiment 3 was twice that for experiment 1.

b. Experiments 1 and 4 each have a total reaction solution volume of 100.0 mL and use 1.00 M hydrochloric acid and 1.00 M sodium hydroxide. How do you account for their different q_{rxn} and ΔT?

c. Experiments 4 and 5 each use 25.0 mL of a 1.00 M strong acid and 75.0 mL of 1.00 M sodium hydroxide. How do you account for their different q_{rxn} and ΔT?

4. Despite changes in reaction conditions (volume, concentration, monoprotic vs. diprotic acid), $\Delta_r H$ (in kJ/mol) for each reaction was approximately the same. Explain why.

5. Based on a total reaction volume of 100.0 mL, what volumes of 1.00 M sulfuric acid and 1.00 M sodium hydroxide will produce the greatest amount of heat? *Show work.*

Name ____ Section ____________________

PRE-LABORATORY QUESTIONS
Experiment 12N

Read the Background and Procedure sections of the lab and answer the following questions <u>before</u> the lab period. Show your work for all calculations.

1. a. Write the molecular and **net** ionic equations for the reaction of aqueous hydrochloric acid and aqueous sodium hydroxide.

   b. Write the molecular equation for the reaction of aqueous sulfuric acid and aqueous sodium hydroxide.

2. a. When 50.0 mL of 1.00 M hydrochloric acid and 50.0 mL of 1.00 M sodium hydroxide react, the temperature rises 6.7°C. Use the total solution volume, density of water, and specific heat of water to calculate q_{soln}.

   b. Calculate q_{rxn} for this acid-base reaction.

   c. Calculate the moles of hydrogen ion and hydroxide ion initially present, and the moles of water produced in this reaction.

   d. Calculate the ΔH (in kJ/mol) for the reaction forming 1 mole of water.

3. The neutralization of 50.0 mL of 1.00 M hydrochloric acid with 50.0 mL of 1.00 M sodium hydroxide causes a 6.7°C increase in temperature. Predict how the following changes to the experimental protocol would affect the value of the change in temperature. Explain your answers.

Hint: According to equations given in the lab handout,

$$\Delta T_{soln} = \frac{q_{soln}}{m_{soln}C_{sp\ soln}} = -\frac{q_{rxn}}{m_{soln}C_{sp\ soln}} = -\frac{n\Delta_r H}{m_{soln}C_{sp\ soln}}$$

Since $\Delta_r H$ and $C_{sp\ soln}$ are constants, the temperature change depends on the moles of water produced (moles of reaction) and the mass of the solution. Assume the density of each solution is 1.0 g/mL.

a. Using 100.0 mL of 1.00 M hydrochloric acid and 100.0 mL of 1.00 M sodium hydroxide

b. Using 50.0 mL of 2.00 M hydrochloric acid and 50.0 mL of 2.00 M sodium hydroxide

c. Using 25.0 mL of 1.00 M hydrochloric acid and 75.0 mL of 1.00 M sodium hydroxide

d. Using 25.0 mL of 1.00 M sulfuric acid and 75.0 mL of 1.00 M sodium hydroxide (Be careful; think about the value of n.)