**Thermochemistry: The Heat of Neutralization**

**Safety**  
Solid NaOH is a severe contact hazard. Avoid touching it! HCl and NaOH solutions are both contact hazards. Wear goggles at all times since NaOH is a severe danger to eyes. Rinse off any spilled solutions with water or neutralizer. Wash your hands thoroughly before leaving lab.

Note: There are two concentrations of HCl on the reagent shelf: 1.00 M and 2.00 M. Be sure to check the concentration required in each procedure below.

**Procedure**

1. **Neutralization of HCl solution with NaOH solution:** You will use two coffee-cup calorimeters and an accurate digital thermometer. Place about 50 mL (measure it exactly) of 2.00 M HCl in one calorimeter and about 50 mL (measured exactly) of 2.00 M NaOH in the other. Record the exact volumes of solutions used in your data table on page 5. Allow the solutions to stand for a couple of minutes, and record the initial temperatures as accurately as possible, rinsing and drying the thermometer between readings. Now pour the NaOH solution into the HCl calorimeter, replace the lid and thermometer, and swirl the calorimeter to mix the solutions. Start timing when the NaOH solution is added, and read and record the temperature every 30 seconds. Continue swirling and recording the temperatures until the temperature has reached a maximum and has decreased slightly for at least three consecutive readings or has stayed the same temperature for four consecutive readings. Rinse the calorimeters.

2. **Heat of dissolution of NaOH:** Measure 100 mL of distilled water (record the exact volume in your data table) into one of the calorimeters, and allow it to come to a constant temp. The stockroom has estimated 4g samples of NaOH pellets for you. Obtain one vial from the instructor’s station and weigh it (including lid and contents). Add the complete contents of the vial to your distilled water in the calorimeter with continuous vigorous swirling. Continue swirling and recording the temperatures until the temperature has reached a maximum and has decreased slightly for at least three consecutive readings or has stayed the same temperature for four consecutive readings. Be sure that the NaOH pellets dissolve as soon as possible after addition. Reweigh the empty vial (including lid) and subtract this mass from the total mass (pellets, vial, and lid) to obtain the exact weight of NaOH used.

3. **Heat of reaction of solid NaOH and 1.00 M HCl:** Add the second vial (weighed) of NaOH pellets to 100.0 mL of 1.00 M HCl using the same technique as above. Again record the mass of the empty vial and lid when your reaction is complete to determine the exact mass of NaOH used. Continue swirling and recording the temperatures until the temperature has reached a maximum and has decreased slightly for at least three consecutive readings or has stayed the same temperature for four consecutive readings.

**Calculations:**

In general, the heat gained by the contents of the calorimeter is given by

\[ q_{\text{contents}} = \text{mass} \times (\text{specific heat}) \times \Delta T \]

Use the quantities described below to calculate the heat of each reaction.

The sources of heat exchanged by the neutralization and dissolution processes are the reactions under study. So the heat generated by the reaction equals the heat gained by the contents of the calorimeter, but the q values have opposite signs. Thus,

\[ q_{\text{rxn}} = - q_{\text{contents}} \]

\[ q_{\text{rxn}} = - \text{mass} \times (\text{sp. ht.}) \times \Delta T \]
You will have to assign $q_{\text{rxn}}$ as a negative value. It has the opposite sign as $q_{\text{contents}}$.

Calculations for Reaction 1:
- **Mass:** You combined aqueous HCl with aqueous NaOH. Since these are dilute solutions, assume they have the same density as water (1.00 g/mL). For the measured volume of each solution you used, calculate the mass of each solution. (Hint: If you had used 50.0 mL of water how much would the water weigh? Answer: 50.0 g). Add the mass of HCl and the mass of NaOH to give the total mass used, this will be the mass you will use to calculate heat of reaction, $q$.
- **Specific heat:** The specific heat for reaction 1 can be assumed to be close to that of pure water (4.184 J/g·°C).
- **$\Delta T$:** $\Delta T$ is the change in temperature of the solution ($T_f - T_i$). $T_f$ will be the highest temperature recorded. Watch significant figures when calculating $\Delta T$.

- $q_{\text{rxn}} = - \text{mass} \times (\text{sp. ht.}) \times \Delta T$
- $\Delta H_{\text{rxn}} = \frac{q_{\text{rxn}}}{\text{moles}}$

Calculations for Reaction 2:
- **Mass:** You combined solid NaOH with water. Find the mass of water used by assuming the density to be 1.00 g/mL. Add the mass of solid NaOH and the mass of water to give the total mass used.
- **Specific heat:** The specific heat for the dissolution of NaOH will use the specific heat of NaOH, 3.90 J/g·°C.
- **$\Delta T$:** $\Delta T$ is the change in temperature of the solution ($T_f - T_i$). $T_f$ will be the highest temperature recorded. Watch significant figures when calculating $\Delta T$.

- $q_{\text{rxn}} = - \text{mass} \times (\text{sp. ht.}) \times \Delta T$
- $\Delta H_{\text{rxn}} = \frac{q_{\text{rxn}}}{\text{moles}}$

Calculations for Reaction 3:
- **Mass:** You combined solid NaOH with dilute aqueous HCl. Use the density of water again to approximate the mass of HCl. Add the mass of solid NaOH and the mass of HCl to give the total mass used.
- **Specific heat:** The specific heat for reaction 3 can be assumed to be close to that of pure water (4.184 J/g·°C).
- **$\Delta T$:** $\Delta T$ is the change in temperature of the solution ($T_f - T_i$). $T_f$ will be the highest temperature recorded.

- $q_{\text{rxn}} = - \text{mass} \times (\text{sp. ht.}) \times \Delta T$
- $\Delta H_{\text{rxn}} = \frac{q_{\text{rxn}}}{\text{moles}}$

Enthalpy values are typically reported in kJ/mol, so $\Delta H_{\text{rxn}}$ can be obtained by dividing the experimentally determined heat of reaction by moles:

$$\Delta H_{\text{rxn}} = \frac{q_{\text{rxn}}}{\text{moles}}$$

For reactions 1 & 3, you will need to calculate the $\Delta H$ value in terms of **kilojoules released per mole of water formed**. To determine the number of moles of water formed or NaOH dissolved, you will need to consider which reactant was the limiting reactant.
DATA
Record time and temperature data for all three reactions in a table below like the one below until the temperatures decrease for three consecutive readings.

<table>
<thead>
<tr>
<th>Time and Temperature Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, °C</td>
</tr>
<tr>
<td>Minutes</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Before mixing reagents</td>
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<tr>
<td>0</td>
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<td>0.5</td>
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<tr>
<td>7.5</td>
</tr>
<tr>
<td>8.0</td>
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</tbody>
</table>

**Mass Data Tables:** Record the exact volume, concentration, and/or mass of each reactant used in all three reactions. For the HCl and NaOH solutions (reactions 1 and 3), you will use the density of the solutions to determine the mass of the solution.

**Data for reaction 1: HCl(aq) + NaOH(aq)**

<table>
<thead>
<tr>
<th>Volume HCl(aq)</th>
<th>Mass HCl(aq)</th>
<th>Concentration HCl</th>
<th>Volume NaOH(aq)</th>
<th>Mass NaOH(aq)</th>
<th>Concentration NaOH(aq)</th>
<th>Total mass</th>
</tr>
</thead>
</table>

**Data for reaction 2: NaOH(s) + H₂O(l)**

<table>
<thead>
<tr>
<th>Mass NaOH(s)</th>
<th>Volume H₂O(l)</th>
<th>Mass H₂O(l)</th>
<th>Total mass</th>
</tr>
</thead>
</table>

GCC CHM 151LL: Thermochemistry: The Heat of Neutralization © GCC, 2016 page 3 of 7
CALCULATIONS and RESULTS
For each reaction you should include the following information and ALL calculations in your lab notebook:

- Title the start of each reaction’s calculation section
- Write the balanced chemical equation for the reaction
- Initial temperature of the solution/reactants
- Final temperature (highest temperature during the reaction), $T_f$
- $\Delta T = (T_f - T_i)$
- Total mass of the final solution (sum of component masses)
- Specific heat of the solution
- $q_{rxn}$
- Number of moles of each reactant
- Number of moles of water formed based on the limiting reagent
- $\Delta H$ (kJ/mol H$_2$O)

For EACH trial, show the following work for full credit:
1. (2 pts each trial) Balanced Chemical Equation
2. (2 pts each trial) $\Delta T$ Calculation
3. (2 pts each trial) $q_{rxn}$ Calculation
4. (2 pts each trial) Mole Calculations
5. (2 pts each trial) $\Delta H$ Calculation
Pre-Lab Questions

Write your answers on this page and turn it in to your instructor before starting this experiment.

1. What molarity of NaOH and HCl will be used for part 1 in this week’s lab?

2. What substance will be weighed out on the balance for part 2 and part 3?

3. When the thermometer in a calorimeter is observed to be increasing in temperature, is the system gaining heat or losing heat?

4. Is $T_{\text{Final}}$ the highest temperature recorded or the very last temperature recorded?
Discussion Questions
Write your answers on these pages and attach them to your report.

1) (6 pts) Rewrite the balanced chemical equations for the three reactions carried out in lab. Beside each reaction, write the \( \Delta H \) (per mole) you calculated for that reaction. The value you determined for reaction 3 is your first actual value of \( \Delta H \) for the reaction between solid NaOH and aqueous HCl.

1.

2.

3.

2) (6 pts) Rewrite the three chemical reactions. Manipulate the first two chemical equations so that they add up to give the third equation (Hess’s Law). Show explicitly how the first two reactions cancel to equal the third reaction. Add the enthalpies (per mole) of the first two equations to calculate the enthalpy of the third equation (Hess’s Law) – this will determine your second actual \( \Delta H \) value for the reaction of solid NaOH plus aqueous HCl.

1.

2.

3.

3) (5 pts) Determine the percent difference between the two actual values \( \Delta H \) for the third reaction, the one you determined directly and the one you get from Hess’s Law.

\[
\text{% difference} = \left(\frac{\text{First actual} - \text{Second actual}}{\text{First actual}}\right) \times 100
\]
4) (6 pts) To calculate an accepted or theoretical value of ΔH/mol for the third reaction, calculate it using $\Delta H^\circ$. Show all of your calculations. Pay close attention to the states of matter of the third reaction when using $\Delta H^\circ$. Hint: You book does not have a value for NaCl(aq). Think about what individual species represents NaCl(aq).

5) (6 pts) Using the theoretical value of ΔH from 4), calculate the percent error for actual value #1 and actual value #2. Which one is more accurate?