THERMOCHEMISTRY

Thermodynamics
Study of energy and its interconversions

• Energy is **TRANSFORMED** in a chemical reaction (**POTENTIAL** to **KINETIC**)
• **HEAT** (energy transfer) is also usually produced or absorbed
  - **SYSTEM**: part of the universe being studied
  - **SURROUNDINGS**: everything else

First Law of Thermodynamics

**TOTAL ENERGY IN THE UNIVERSE IS CONSTANT...**

Energy cannot be created or destroyed but it can be converted or transformed!

AKA Law of Conservation of Energy

Energy
Ability to produce change or do work

• **Joule (J)** is the SI unit for energy
• Another common unit is calorie (cal)
• 1 calorie = 4.184 Joules
• 1 kilocalorie = 1000 calories

Potential Energy
• Stored energy from the interactions of charged particles
• Increases with charge or decreases with diameter

Kinetic Energy
• Energy of motion that depends on mass and speed: \[ KE = \frac{1}{2}mv^2 \]
• Greater the mass or speed, more KE of an object

Heat (q)
Quantity of thermal energy

• Heat transfers spontaneously from a warmer object to a colder one (energy transfer)
• Due to **molecular collisions**... Faster moving particles collide with slower moving ones and transfer some of their energy, changing the speed of both molecules (can also be transferred to the surroundings)
Heat Transfer

**EXOTHERMIC**
Energy is released (exits) / Feels warm

**ENDOTHERMIC**
Energy is absorbed (enters) / Feels cold

State Functions

Depend only on the change between the initial and final states of a system, not on the process by which the change occurs

- Ex: Adding a catalyst has no effect on the overall energy change
- Enthalpy ($\Delta H$), entropy ($\Delta S$), and free-energy ($\Delta G$) are all state functions

Standard State Conditions

- When quantities given on a test, they are given under these conditions
- Indicated by a little superscript circle (°)

\[
\Delta H = \Delta H^\circ \\
\Delta S = \Delta S^\circ \\
\Delta G = \Delta G^\circ
\]

- All gases are at 1 atm
- All liquids and solids are pure
- All solutions are at 1 M
- Energy of formation of an element in its normal state is defined as zero
- Temperature used is room temperature (25° C)

Enthalpy (H)

Flow of energy (HEAT EXCHANGE) at constant pressure when two systems are in contact

**UNITS ARE TYPICALLY kJ/mol!!**

Enthalpy (H)

Flow of energy (HEAT EXCHANGE) at constant pressure when two systems are in contact

- Heat RELEASED (Exo) = NEGATIVE values
- Heat ABSORBED (Endo) = POSITIVE values

- Enthalpy of Reaction ($\Delta H_{\text{rxn}}$): heat released or absorbed by a reaction (kJ/mol)
- Enthalpy of Formation ($\Delta H_f$): heat released or absorbed when ONE MOLE of a compound is formed from elements
- Enthalpy of Fusion ($\Delta H_{fus}$): heat absorbed to melt (overcome IMFs) of ONE MOLE of solid
- Enthalpy of Vaporization ($\Delta H_{vap}$): heat absorbed to boil (overcome IMFs) of ONE MOLE of liquid

Also known as “HEAT OF...”
IMFs

Don’t forget that phase changes always involve the overcoming of IMFs not the breaking of bonds!!

Fusion (melting), vaporization, and sublimation REQUIRE AN INPUT OF ENERGY to overcome the IMFS

Freezing, condensation, and deposition RELEASE ENERGY as IMFs form

Enthalpy Change ($\Delta H$)

Difference between the potential energies of the products and reactants

- State function
- $\Delta H = q$ at constant pressure
- Can be calculated in different ways:
  - Stoichiometry
  - Calorimetry (next lesson)
  - Tables of Standard Values
  - Hess’s Law
  - Bond Energy (been there)

Freezing, condensation, and deposition RELEASE ENERGY as IMFs form

Enthalpy Change ($\Delta H$)

Difference between the potential energies of the products and reactants

- EXAMPLE (Stoichiometry):
  
  Upon adding potassium hydroxide pellets to water the following reaction takes place:
  
  $$\text{KOH}(s) \rightarrow \text{KOH}(aq) + 43 \text{ kJ/mol}$$

  When 14.0 g of KOH are added to water, what is the enthalpy change for the dissolution? Does the beaker get warmer or colder?

Heat of Formation ($\Delta H^\circ_f$)

- $\Delta H^\circ_f$ for a pure element (including diatomics) is ZERO... you’ll see in many AP problems that they just don’t give you any values for pure elements so you must know this!

- If $\Delta H^\circ_f$ is NEGATIVE, then energy is RELEASED when compound is formed and product is more STABLE than its elements

- If $\Delta H^\circ_f$ is POSITIVE, then energy is ABSORBED when compound is formed and product is LESS stable than its elements

$\Delta H = \sum \Delta H^\circ_f \text{PRODUCTS} - \sum \Delta H^\circ_f \text{REACTANTS}$

Heat of Formation ($\Delta H^\circ_f$)

- EXAMPLE (Tables):
  
  Given the information below, calculate the $\Delta H^\circ_{\text{rxn}}$ for the following reaction:
  
  $$3 \text{Al}(s) + 3 \text{NH}_4\text{ClO}_4(s) \rightarrow \text{Al}_2\text{O}_3(s) + 2 \text{AlCl}_3(s) + 3 \text{NO(g)} + 6 \text{H}_2\text{O(g)}$$

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\Delta H^\circ_f$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{NH}_4\text{ClO}_4(s)$</td>
<td>-295</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3(s)$</td>
<td>-1676</td>
</tr>
<tr>
<td>$2 \text{AlCl}_3(s)$</td>
<td>-704</td>
</tr>
<tr>
<td>$3 \text{NO(g)}$</td>
<td>90.0</td>
</tr>
<tr>
<td>$6 \text{H}_2\text{O(g)}$</td>
<td>-242</td>
</tr>
</tbody>
</table>

Just like bond enthalpy... pay attention to the BALANCED equation!!
**Bond Enthalpy**

*Energy required to break the bond between two covalently bonded atoms (aka Bond Energy)*

- Bonds **BREAKING** = Endothermic
- Bonds **FORMING** = Exothermic
- Takes energy to **BREAK**… Released when **FORM**
- Change in enthalpy (energy) for a reaction can be found using the bond energies:
  \[ \Delta H_{\text{rxn}} = \sum (\text{energies of bonds BROKEN}) - \sum (\text{energies of bonds FORMED}) \]

**Enthalpy Summary**

- \( \Delta H = "+" \)… Reaction is **ENDOTHERMIC** and heat energy is **ADDED** to the system
- \( \Delta H = "-" \)… Reaction is **EXOTHERMIC** and heat energy is **LOST** from the system
- Nature tends to go towards the **LOWEST** energy state!

**Hess’s Law**

*If a reaction can be described as a series of steps, then \( \Delta H \) for the overall reaction is simply the sum of the \( \Delta H \) values for all steps*

**THREE RULES:**

1) Flip the equation… Flip the sign
2) Multiply or divide the equation by a \( \# \)… Multiply or divide enthalpy value by same
3) When several equations are summed up to get a new equations… Add enthalpy values of the component equations

**Practice**

*Calculate the standard change of enthalpy for the thermite reaction below using the information given:*

\[ 2 \text{Al}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + 2 \text{Fe}(s) \]

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \Delta H ) (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Fe}_2\text{O}_3(s) )</td>
<td>-826</td>
</tr>
<tr>
<td>( \text{Al}_2\text{O}_3(s) )</td>
<td>-1676</td>
</tr>
</tbody>
</table>

**Bond Enthalpy**

*Energy required to break the bond between two covalently bonded atoms*

**EXAMPLE (Bond Energy):**

Calculate the energy change that accompanies the following reaction given the data below:

\( \text{H}_2(\text{g}) + \text{F}_2(\text{g}) \rightarrow 2 \text{HF}(\text{g}) \)

<table>
<thead>
<tr>
<th>Bond</th>
<th>Bond Energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-H</td>
<td>432</td>
</tr>
<tr>
<td>F-F</td>
<td>154</td>
</tr>
<tr>
<td>H-F</td>
<td>565</td>
</tr>
</tbody>
</table>

**Hess’s Law**

*If a reaction can be described as a series of steps, then \( \Delta H \) for the overall reaction is simply the sum of the \( \Delta H \) values for all steps*

**EXAMPLE (Hess’s):**

Calculate the \( \Delta H \) for this overall reaction given the following:

\[ 2 \text{H}_3\text{BO}_3(\text{aq}) \rightarrow \text{B}_2\text{O}_3(\text{s}) + 3 \text{H}_2\text{O}(\text{l}) \]

\( \Delta H = -0.02 \text{ kJ/mol} \)

\[ \text{H}_2\text{B}_4\text{O}_7(\text{aq}) \rightarrow \text{HBO}_2(\text{aq}) + \text{H}_2\text{O}(\text{l}) \]

\( \Delta H = -11.3 \text{ kJ/mol} \)

\[ \text{H}_2\text{B}_4\text{O}_7(\text{aq}) \rightarrow 2 \text{B}_2\text{O}_3(\text{s}) + \text{H}_2\text{O}(\text{l}) \]

\( \Delta H = 17.5 \text{ kJ/mol} \)
**Practice**

- **EXAMPLE:**

  Determine the $\Delta H_f$ of $C_6H_{12}O_6$ given the reaction below and the following information:
  
  $$C_6H_{12}O_6(s) + 6 \text{O}_2(g) \rightarrow 6 \text{CO}_2(g) + 6 \text{H}_2\text{O}(g) + 2800 \text{kJ}$$

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\Delta H_f^\circ$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CO}_2(g)$</td>
<td>-393.5</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}(g)$</td>
<td>-285.8</td>
</tr>
</tbody>
</table>

**Practice**

- **EXAMPLE:**

  Calculate the $\Delta H$ for the reaction below using the information given:
  
  $$2 \text{C}(s) + \text{H}_2(g) \rightarrow \text{C}_2\text{H}_2(g)$$

  $$\text{C}_2\text{H}_2(g) + \frac{5}{2} \text{O}_2(g) \rightarrow 2 \text{CO}_2(g) + \text{H}_2\text{O}(l) \quad \Delta H = -1299.6 \text{kJ}$$

  $$\text{C}(s) + \text{O}_2(g) \rightarrow \text{CO}_2(g) \quad \Delta H = -393.5 \text{kJ}$$

  $$\text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) \quad \Delta H = -285.8 \text{kJ}$$

**Heat Capacity ($C_p$)**

*Amount of heat needed to increase the temperature of an object by 1°C*

- **Extensive Property**... depends on how much! (Ex: ice cube vs. iceberg)

- **SPECIFIC HEAT CAPACITY** ($C$ or $C_p$): amount of heat needed to raise 1 g of a substance by 1°C

  - Water has a **HIGH** $C_p$ (4.184 J/g°C)... need more heat to raise the temperature
  - Metals have a **LOW** $C_p$... less heat needed to raise the temperature

**Specific Heat**

*Different materials store different amounts of heat energy.*

- Water takes about 30 times longer to heat than gold, meaning it stores about 30 times more calories.

**Specific Heat Problems**

- Units are usually J/g°C or cal/g°C

- Equation: $q = mc\Delta T$

  $$q = \text{HEAT (Joules)}$$
  $$m = \text{MASS (grams)}$$
  $$c = \text{SPECIFIC HEAT}$$
  $$\Delta T = \text{FINAL Temp - INITIAL Temp (°C)}$$
Specific Heat Problems

• **EXAMPLE:**
  When 435 J of heat is added to 3.4 g of olive oil at 21°C, the temperature increases to 85°C. What is the specific heat of the olive oil?

\[
q = mc \Delta T
\]

\[
435 \text{ J} = (3.4 \text{ g}) \cdot c \cdot (85°C - 21°C)
\]

\[
c = 2.0 \text{ J/g°C}
\]

Practice

• **EXAMPLE:**
  How many calories does 32.0 g of water absorb when it is heated from 25.0°C to 80.0°C?

Calorimetry

*Process of measuring heat based on observing the temperature change when a body absorbs or discharges energy as heat*

• **CALORIMETER:** device used to measure heat (ex: foam cup... good insulators)

  *“Coffee Cup” Calorimetry*
  aka Constant Pressure Calorimetry

\[
q = \Delta H
\]

At these conditions... We assume NO heat is lost to the surroundings

Calorimetry

*Process of measuring heat based on observing the temperature change when a body absorbs or discharges energy as heat*

**Sealed vessel** that withstands high pressures! (Constant pressure)

\[
+q_{\text{sys}} = -q_{\text{surr}}
\]

Heat gained by system will be **SAME** as heat lost by surroundings (and vice versa)

**HEAT LOST** by substance = **HEAT GAINED** by water!

*Conservation of Energy!!*
Practice

• EXAMPLE:
An unknown metal with a mass of 75.8 grams is heated to a temperature of 80.0°C. It is then placed in 79.4 grams of water that is at a temperature of 18.5°C. The temperature of the water and metal then rise to a temperature of 23.5°C. What is the specific heat of the metal?

Calorimetry

Process of measuring heat based on observing the temperature change when a body absorbs or discharges energy as heat

• Can also use this to find the enthalpy of a reaction

*NOTE: There are SO MANY variations of these problems... the wording is key... you will need to be “on your toes” and THINKING!!

Calorimetry

Process of measuring heat based on observing the temperature change when a body absorbs or discharges energy as heat

• GENERAL STEPS:
1) Use \( q = mc\Delta T \) ... if mass not given, density can be used (assume density of water) to determine TOTAL mass of solutions being mixed and usually assume specific heat of the solution is 4.184 J/g°C
2) Solve for \( q \), remember this is the heat of the resulting solution so the heat due to the reaction is OPPOSITE sign
3) Determine moles of substance formed (might need to do limiting problem if asking about product)
4) \( q / \text{mol} \) gives \( \Delta H_{\text{reaction}} \) (kJ/mol)

Practice

• EXAMPLE:
An experiment was conducted in which 5.19 g of Na\(_2\)CO\(_3\) was dissolved in 75.0 g of distilled water. A temperature increase of the system of 3.80°C was observed. Find the molar enthalpy of dissolution of Na\(_2\)CO\(_3\).

*TAKE NOTE...
If the solid is just DISSOLVING (heat of solution / dissolution), then ADD the water and solid mass together for the total mass in the specific heat equation!!

Calorimetry

Process of measuring heat based on observing the temperature change when a body absorbs or discharges energy as heat

• EXAMPLE:
In a calorimeter, 100.0 mL of 1.0 M NaOH and 100.0 mL of 1.0 M HCl are mixed. Both solutions were originally at 24.6°C. After the reaction, the final temperature is 31.3°C. Assume all solutions have a density of 1.0 g/cm\(^3\) and a specific heat of 4.184 J/g°C. Calculate the energy change (kJ) for the reaction.

Practice

• EXAMPLE:
An experiment was conducted in which 5.19 g of Na\(_2\)CO\(_3\) was dissolved in 75.0 g of distilled water. A temperature increase of the system of 3.80°C was observed. Find the molar enthalpy of dissolution of Na\(_2\)CO\(_3\).

*TAKE NOTE...
If the solid is being BURNED / COMBUSTED / REACTED, then just use the mass of the water ONLY for the total mass in the specific heat equation!!
Practice

• EXAMPLE:
An experiment was conducted in which 5.19 g of Na$_2$CO$_3$ was dissolved in 75.0 g of distilled water. A temperature increase of the system of 3.80°C was observed. Find the molar enthalpy of dissolution of Na$_2$CO$_3$.

Practice

• EXAMPLE:
When 1.00 L of 2.00 M Ba(NO$_3$)$_2$ at 25°C is mixed with 1.00 L of 0.5 M Na$_2$SO$_4$ at 25°C in a calorimeter, the white solid BaSO$_4$ forms and the temperature of the mixture increases to 28.1°C. Assuming the specific heat is 4.184 J/g °C and that the density of the final solution is 1.0 g/mL, calculate the enthalpy change per mole of BaSO$_4$ formed.

Practice

• EXAMPLE:
Gallium, a metal often used to make computer chips, can be purified by melting. Using the information given below, how much energy in kJ is required to melt 2.0 moles of gallium originally at 293 K?

<table>
<thead>
<tr>
<th>Molar heat capacity of solid</th>
<th>25.86 J mol$^{-1}$K$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of fusion</td>
<td>5.59 kJ mol$^{-1}$</td>
</tr>
<tr>
<td>Heat of vaporization</td>
<td>256 kJ mol$^{-1}$</td>
</tr>
<tr>
<td>Melting point</td>
<td>303 K</td>
</tr>
</tbody>
</table>

Second Law of Thermodynamics

UNIVERSE IS CONSTANTLY INCREASING THE DISPERAL (DISORDER) OF MATTER AND ENERGY

Entropy (S)

• GREATER the disorder, GREATER the entropy

• Zero entropy is a solid crystal at 0 K (no disorder at all)

• Never reached 0 K so all substances have a positive value for entropy, but overall processes can be negative!

DISORDER is preferred / favored... NATURE TENDS TOWARD CHAOS!!
Entropy (S)

Measure of the randomness or disorder of the system

- Liquids = Higher entropy values than solids
- Gases = Higher entropy values than liquids
- Particles in solution = Higher entropy than solids
- Two moles of gas = Higher entropy than one mole of gas

As temperature increases, S increases!

To calculate standard entropy change for a reaction:

$$\Delta S^\circ = \Sigma S^\circ_{PRODUCTS} - \Sigma S^\circ_{REACTANTS}$$

- Units usually J/mol \cdot K
- Pay attention to the balanced equation
- "+" \( \Delta S = \) disorder increases (FAVORED)
- \( \Delta S = 0 \) at equilibrium!
Entropy (S)

Measure of the randomness or disorder of the system

**EXAMPLE:**
Calculate the entropy change at 25°C for the reaction below using the given data:

\[2 \text{SO}_2(g) + \text{O}_2(g) \rightarrow 2 \text{SO}_3(g)\]

<table>
<thead>
<tr>
<th>Substance</th>
<th>(S^*) (J/mol K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{SO}_2(g)</td>
<td>248.1</td>
</tr>
<tr>
<td>\text{O}_2(g)</td>
<td>205.3</td>
</tr>
<tr>
<td>\text{SO}_3(g)</td>
<td>256.5</td>
</tr>
</tbody>
</table>

Thermodynamically Favored

Processes or reactions that involve both a DECREASE in internal energy (\(\Delta H^\circ < 0\)) and an INCREASE in entropy (\(\Delta S^\circ > 0\)) are...

**THERMODYNAMICALLY FAVORED!**

*Note the terms spontaneous and nonspontaneous were used to describe favored and unfavored reactions previously... **DO NOT USE THEM ON THE EXAM!!**

Gibb's Free Energy (G)

Measure of whether or not a process will proceed without the input of outside energy

- \(\Delta G\) ultimately determines whether a reaction is thermodynamically favorable or not
- “\(\Delta G\) = Thermodynamically FAVORED
- “\(\Delta G\) = Thermodynamically UNFAVORED
- \(\Delta G = 0\)... At EQUILIBRIUM

**EXAMPLE:**
Calculate the free energy change for the following reaction using the data given:

\[2 \text{H}_2\text{O}(l) + \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}_2(l)\]

<table>
<thead>
<tr>
<th>Substance</th>
<th>(\Delta G^\circ) (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{H}_2\text{O}(l)</td>
<td>-237.1</td>
</tr>
<tr>
<td>\text{H}_2\text{O}_2(l)</td>
<td>-120.4</td>
</tr>
</tbody>
</table>
Gibb's Free Energy (G)
Measure of whether or not a process will proceed without the input of outside energy

- Nature moves towards two states... LOW energy and HIGH disorder
- How to determine favorability of a process relating free energy (G), enthalpy (H), and entropy (S):

\[ \Delta G = \Delta H - T \Delta S \]

- \( T \) = absolute temperature (K)
- Convert \( T \Delta S \) term to kJ/mol

Gibb's Free Energy (G)
Measure of whether or not a process will proceed without the input of outside energy

- Nature moves towards two states... LOW energy and HIGH disorder
- How to determine favorability of a process relating free energy (G), enthalpy (H), and entropy (S):

\[ \Delta G = -RT \ln K \]

- \( R = 8.3145 \text{ J/mol·K} \)
- \( K = \text{equilibrium constant} \)

Sign of \( \Delta G \) can be used to predict whether \( K \) is > or < than 1... How?

Favorability

<table>
<thead>
<tr>
<th>( \Delta H )</th>
<th>( \Delta S )</th>
<th>T</th>
<th>( \Delta G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>+</td>
<td>Low</td>
<td>ALWAYS Favored</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>High</td>
<td>ALWAYS Favored</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>Low</td>
<td>NEVER Favored</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>High</td>
<td>NEVER Favored</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>Low</td>
<td>Not Favored at Low</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>High</td>
<td>Favored at High</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Low</td>
<td>Favored at Low</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>High</td>
<td>Not Favored at High</td>
</tr>
</tbody>
</table>

At LOW temp \( \Delta H \) wins... At HIGH temp \( \Delta S \) wins!

Misconceptions

- If \( \Delta G > 0 \), the process cannot occur... NOT TRUE! External sources of energy can be used to drive change (Ex: Electric current applied to charge a dead battery)
- If \( \Delta G \) is large and negative, the process must proceed at a measurable rate... NOT TRUE! Kinetics related to HIGH ACTIVATION ENERGIES are important and play a role (Ex: held together by strong bonds or IMFs, collision orientation, \( E_a \))