Unit 4: Thermochemistry and Nuclear Chemistry

Chapter 6: Energy Relationships in Chemical Reactions (pg. 198 to 202)

1. System: - any specific part of the universe that is of interest to us.
Surrounding: - the rest of the universe outside the system.
Open System: - a system that can exchange mass and energy (usually in the form of heat) with its surroundings.
Closed System: - a system that allows the exchange of energy (usually in the form of heat) but not mass with its surrounding.
Isolated System: - a system that does not allow the transfer of either mass or energy to or from its surroundings.
Thermal Energy: - energy associated with the random motion of atoms and molecules.
Chemical Energy: - energy stored within the structural units of chemical substances.
Potential Energy: - energy available by virtue of an object's positions.
Kinetic Energy: - energy available because if the motion of an object.
Law of Conservation of Energy: - the total quantity in the universe is constant ($\Sigma E_{\text{input}} = \Sigma E_{\text{output}}$).

2. Heat is the transfer of energy between two bodies that are of different temperature. Thermal energy on the other hand is the energy associated with the random motion of atoms and molecules. When thermal energy flows between objects of different temperatures, we get heat. Heat is transferred from an open or closed system that is hot to an open or closed system that is cold.

3. We commonly use J or kJ for energy units in chemistry

6. **(a)** Kinetic (on the way up) → Potential (at maximum height) → Kinetic (as it falls back).
(b) Chemical Potential (discharging battery) → Light and Thermal (light bulbs give off heat as well).
(c) Kinetic (ski lift moving up) → Potential (at the top of the hill) → Kinetic (skiing back down).
(d) Kinetic (striking a match involves movement) → Chemical Potential (reaction between match head and striking surface; burning of the rest of the match).

7. Thermochemistry: - the study of heat changes in chemical reactions.
Exothermic Process: - processes that give off heat to the surroundings.
Endothermic Process: - processes that absorb heat from the surroundings.

8. Thermochemistry is based on the law of conservation of energy.

9. Answers may vary. Examples of exothermic process are condensation of steam to water and burning hydrocarbons. Examples of endothermic process are melting of ice into water and photosynthesis.

10. Combination reactions or formation reactions tend to be exothermic because most compounds are at a lower energy states compared to their elemental reactants. That is why we see more chemicals in compound forms compared to pure elemental forms. Decomposition reactions are the reverse process of combination reactions. Hence, they will involve an input of energy (endothermic) as the stable compounds are forced to break apart into their elements.

11. The first law of thermodynamics is based on the law of conservation of energy. In the equation, $\Delta E = q + w$, ΔE stands for total internal energy of a system (+ means the system gained energy; − means the system lost energy). q stands for heat (+ means endothermic change on the system; − means exothermic change on the system). w stands for work (+ means work is done ***on*** the system, volume of the system decreased; − means work is done ***by*** the system, volume of the system increased).

21. Enthalpy (H): - a thermodynamic quantity used to describe heat changes taking place at constant temperature, pressure and volume.
Enthalpy of Reaction (ΔH): - the difference between the enthalpies of the products and the enthalpy of the reactants.
The heat of the reaction will equal to the enthalpy change when no work is done on or by the system (that is the system is at constant volume and pressure). $\Delta E = q + w$. For $w = -P\Delta V$ and $\Delta V = 0$, $\Delta E = q = \Delta H$.

22. The physical state of a substance affects the enthalpy change of the reaction. Solids have a lower energy state than liquids, and liquids have a lower energy state the gases.

23. In the thermochemical equation, $4\ NH_{3\ (g)} + 5\ O_{2\ (g)} \rightarrow 4\ NO_{\ (g)} + 6\ H_2O_{\ (g)}$ $\Delta H = -904$ kJ/mol, means that 904 kJ is generated for 4 moles of $NH_{3\ (g)}$ consumed, or 904 kJ is generated for 5 moles of $O_{2\ (g)}$ consumed, or 904 kJ is generated for 4 moles of $NO_{\ (g)}$ produced, or 904 kJ is generated for 6 moles of $H_2O_{\ (g)}$ produced. An alternate way of writing the equation would be

$$4\ NH_{3\ (g)} + 5\ O_{2\ (g)} \rightarrow 4\ NO_{\ (g)} + 6\ H_2O_{\ (g)} + 904\ \text{kJ}$$

Other ways of writing the equation by emphasizing a mole of a specific chemical are

$NH_{3\ (g)} + \frac{5}{4} O_{2\ (g)} \rightarrow NO_{\ (g)} + \frac{3}{2} H_2O_{\ (g)}$ $\Delta H = -226$ kJ/mol NH_3 used or NO produced
(Divide equation and ΔH by 4)

$\frac{4}{5} NH_{3\ (g)} + O_{2\ (g)} \rightarrow \frac{4}{5} NO_{\ (g)} + \frac{6}{5} H_2O_{\ (g)}$ $\Delta H = -180.8$ kJ/mol O_2 used
(Divide equation and ΔH by 5)

$\frac{2}{3} NH_{3\ (g)} + \frac{5}{6} O_{2\ (g)} \rightarrow \frac{2}{3} NO_{\ (g)} + H_2O_{\ (g)}$ $\Delta H = -150.7$ kJ/mol of H_2O produced
(Divide equation and ΔH by 6)

24. (a) If the equation is multiplied by 2, $\Delta H = -2905.6$ kJ.
(b) If the direction of the reaction is reversed, $\Delta H = 1452.8$ kJ.
(c) If water vapour instead of liquid water is formed as the product, $\Delta H = -1290.2$ kJ.
(For water, $\Delta H_{\text{vap}} = 40.65$ kJ/mol and since water vapour has a higher energy state,
$\Delta H = -1452.8 + 4$ ~~mol~~ (40.65 kJ/~~mol~~) = −1290.2 kJ)

25. $\Delta H = -4.213$ kJ/g CuS

29. Specific Heat (s): - the amount of heat energy required to raise the temperature of one gram of a substance by one degree Celsius. The units for specific heat are J/(g • °C) or kJ/(kg • °C). It is an intensive property.

Heat Capacity (C): - the amount of heat required to raise the temperature of a given quantity of substance by one degree Celsius. The units for specific heat are J/°C or kJ/°C. It is an extensive property.

30. Calorimetry is a method to measure heat change. A calorimeter is a device that measure heat change of a system. There are two types of calorimeter. The constant-volume calorimeter is also referred to as a bomb calorimeter. A sample is ignited and the heat gained by the calorimeter (container and water) is calculated by $C\Delta T$ (heat capacity of the calorimeter time difference in temperature of the water). We use C because it takes into account of the gain in heat by the calorimeter container itself and therefore will be more accurate. The value of heat capacity is determined by using a reference reaction with known heat change and divided by the ΔT of the water (that is, $C = \frac{\Delta H}{\Delta T}$). The other calorimeter is the constant-pressure calorimeter, which is commonly called the Styrofoam calorimeter. In this case, we ignore the gain in heat by the container, and we use the formula $q = ms\Delta T$ to calculate heat change of the system.

31. Choice **(d)** will take place when the two metals are brought into contact. Heat will flow from Cu to Al because Cu is at a higher temperature. The definition of heat is the transfer of thermal energy between two bodies that are at different temperatures.

33. $s = 0.237$ J/(g • °C)

35. $q = 3.31$ kJ released

37. $q = 24.76$ kJ/g of Mg ; $\Delta H = 601.9$ kJ/mol of Mg

39. The standard state condition is at 25°C and 1 atm.

40. In cases where the compounds can be directly synthesized from their elements at standard condition, we perform a calorimetry experiment to find out their ΔH°_{f}. For compounds that cannot be directly synthesized from their elements, we use a series of reactions with Hess's law (adding $\Delta \overset{\circ}{H}_{\text{rxn}}$ from these reactions) or the extended Hess's law, $\Delta H^{\circ}_{\text{rxn}} = \Sigma H^{\circ}_{\text{products}} - \Sigma H^{\circ}_{\text{reactants}}$, using known ΔH°_{f}.

41. Standard enthalpy of reactions refers to the molar change of enthalpy of reaction at standard conditions.

42. $\Delta H^{\circ}_{\text{rxn}} = \Sigma H^{\circ}_{\text{products}} - \Sigma H^{\circ}_{\text{reactants}}$
$\Delta H^{\circ}_{\text{rxn}}$ = Standard Enthalpy of Reactions
$\Sigma H^{\circ}_{\text{products}}$ = Sum of ΔH°_{f} of all products = $n\Delta H^{\circ}_{f,\text{ product 1}} + n\Delta H^{\circ}_{f,\text{ product 2}} + n\Delta H^{\circ}_{f,\text{ product 3}} + \ldots..$
$\Sigma H^{\circ}_{\text{products}}$ = Sum of ΔH°_{f} of all reactants = $n\Delta H^{\circ}_{f,\text{ reactant 1}} + n\Delta H^{\circ}_{f,\text{ reactant 2}} + n\Delta H^{\circ}_{f,\text{ reactant 3}} + \ldots..$

45. $CH_{4\ (g)}$ and $H_{\ (g)}$. All the other choices are elements in their most stable form $\Delta H^{\circ}_{f} = 0$). The most stable form of hydrogen is $H_{2\ (g)}$.

47. ΔH°_f of $H_2O_{(l)}$ is more negative because the $H_2O_{(g)}$ formed would have to release more heat to become $H_2O_{(l)}$. Hence, forming $H_2O_{(l)}$ from $H_{2\,(g)}$ and $O_{2\,(g)}$ involved a larger amount of heat released.

49. This is because $H_2O_{2\,(l)}$ is not decomposing into its elements, $H_{2\,(g)}$ and $O_{2\,(g)}$, but rather into $H_2O_{(l)}$ and $O_{2\,(g)}$. Since $H_2O_{(l)}$ has a more negative ΔH°_f than $H_2O_{2\,(l)}$, hydrogen peroxide has a tendency to decompose into water and oxygen.

51. $\Delta H^\circ_{\text{rxn}} = 177.8$ kJ/mol

55. **(a)** −724 kJ/mol **(b)** -1.37×10^3 kJ/mol **(c)** -2.01×10^3 kJ/mol

61. $\Delta H^\circ_{\text{rxn}} = 0.30$ kJ/mol

63. $\Delta H^\circ_{\text{rxn}} = -238.7$ kJ/mol

67. $\Delta H^\circ_f = -44.35$ kJ/mol

71. **(a)** Although we cannot measure $\Delta H^\circ_{\text{rxn}}$ for this reaction, the reverse process, is the combustion of glucose. We could easily measure $\Delta H^\circ_{\text{rxn}}$ for this combustion in a bomb calorimeter.

$$C_6H_{12}O_{6\,(s)} + 6\ O_{2\,(g)} \rightarrow 6\ CO_{2\,(g)} + 6\ H_2O_{(l)}$$

(Note that for cellular respiration as well as photosynthesis, H_2O is in liquid phase.)

(b) $\Delta H^\circ_{\text{rxn}} = 2801.3$ kJ/mol. For 7.0×10^{14} kg of glucose, $\Delta H^\circ = 1.1 \times 10^{19}$ kJ (approximate annual amount of solar energy for the production of glucose in plants on Earth).

81. $V_{\text{ethane}} = 4.10$ L

(12.6: Phase Changes pg. 421−423)

61. At the boiling point, energy input is used to break the intermolecular forces (London-dispersion, dipole-dipole, and/or hydrogen bonding) between molecules. The energy is not used to make the molecules any faster. Hence, temperature remains constant during boiling.

69. 1 mole of steam to 1 mole of water at 100°C would transfer more energy than freezing 1 mole of water to 1 mole of ice at 0°C. This is because for water, $\Delta H^\circ_{\text{vap}} = -40.65$ kJ/mol gives off more energy than $\Delta H^\circ_{\text{fus}} = -6.01$ kJ/mol

71. $q_{\text{total}} = 2.67 \times 10^3$ kJ

Chapter 21: Nuclear Chemistry (pg. 734 to 736)

1. Ordinary chemical reactions involve electrons in the valence energy level of the atoms. Nuclear reactions deal with changes of nucleons (neutrons and protons) in the nucleus of an atom.

2. All the atomic numbers (bottom numbers of the notation) on either side has to be equalled. All the mass numbers (top numbers of the notation) on either side has to be equalled.

3. There is no difference between $^{0}_{-1}e$ and $^{0}_{-1}\beta$. Both mean an electron or beta particle.

4. An electron is a fundamental particle of an atom. It has a charge of −1 and a mass of 9.11×10^{-31} kg (about 1800 times lighter than a proton). A positron is antimatter of an electron. It has the same mass as an electron, but it has a +1 charge.

5. **(a)** $^{23}_{11}\text{Na}$ **(b)** $^{1}_{1}\text{H}$ or $^{1}_{1}p$ **(c)** $^{56}_{26}\text{Fe}$ **(d)** $^{1}_{0}n$ **(e)** $^{0}_{-1}e$

7. Generally, nuclei that have an even number of protons and an even number of protons are the most stable.

8. The belt of stability is a region of a graph (that of number of neutrons versus the number of protons of all isotopes) where the nuclei are considered stable.

11. $E = mc^2$ is really $\Delta E_{\text{bind}} = -\Delta mc^2$. It states that the mass defect (the difference in mass resulting from when the nucleons binding together compared to when they exist individually) can be converted to pure energy responsible for the nuclear force needed to hold the nucleus together.

12. Since heavier nuclei will naturally have more nucleons, they will have a bigger binding energy overall. By comparing binding energy per nucleon for different isotopes, we can see which isotope is more stable despite their different mass number. The more binding energy each nucleon in an isotope has, the more stable is its nuclei. The most stable nucleus in the periodic table is iron-56.

14. **(a)** Lithium-9 should be less stable. The neutron-to-proton ratio is too high. For small atoms, the *n*/*p* ratio will be close to 1:1.

(b) Sodium-25 is less stable. Its neutron to proton ratio is probably too high.

(c) Scandium-48 is less stable because of odd numbers of protons and neutrons. We would not expect calcium-48 to be stable even though it has a magic number of protons. Its *n*/*p* ratio is too high.

16. **(a)** Neon-17 should be radioactive. It falls below the belt of stability (low *n*/*p* ratio).
(b) Calcium-45 should be radioactive. It falls above the belt of stability (high *n*/*p* ratio).
(c) All technetium isotopes are radioactive.
(d) Mercury-195 should be radioactive. Mercury-196 has an even number of both neutrons and protons.
(e) All curium isotopes are unstable.

19. **(a)** 6.30×10^{-12} J/nucleus and 9.00×10^{-13} J/nucleon
(b) 4.92×10^{-11} J/nucleus and 1.41×10^{-12} J/nucleon

21. Nuclear decay usually occurs with heavier nuclei where the *n*/*p* ratios are not ideal. If the *n*/*p* ratio is smaller then the belt of stability, then the nuclei will likely go through beta decay. If the *n*/*p* ratio is larger then the belt of stability, then the nuclei will likely go through a positron emission or an electron capture. Very large nuclei will likely undergo alpha decay to lower its overall size.

23. **(a)** ${}^{232}_{90}\text{Th} \xrightarrow{\alpha} {}^{228}_{88}\text{Ra} \xrightarrow{\beta} {}^{228}_{89}\text{Ac} \xrightarrow{\beta} {}^{228}_{90}\text{Th}$
(b) ${}^{235}_{92}\text{U} \xrightarrow{\alpha} {}^{231}_{90}\text{Th} \xrightarrow{\beta} {}^{231}_{91}\text{Pa} \xrightarrow{\alpha} {}^{227}_{89}\text{Ac}$
(c) ${}^{237}_{93}\text{Np} \xrightarrow{\alpha} {}^{233}_{91}\text{Pa} \xrightarrow{\beta} {}^{233}_{92}\text{U} \xrightarrow{\alpha} {}^{229}_{90}\text{Th}$

25. 4.89×10^{19} atoms

29. 65.2 years

33. In the shorthand notation for nuclear reactions, the first symbol inside the parentheses is the "bombarding" particle (reactant) and the second symbol is the "ejected" particle (product).
(a) ${}^{15}_{7}\text{N} + {}^{1}_{1}p$ (or ${}^{1}_{1}\text{H}$) $\rightarrow {}^{12}_{6}\text{C} + {}^{4}_{2}\alpha$ X is ${}^{15}_{7}\text{N}$
(b) ${}^{27}_{13}\text{Al} + {}^{2}_{1}d$ (or ${}^{2}_{1}\text{H}$) $\rightarrow {}^{25}_{12}\text{Mg} + {}^{4}_{2}\alpha$ X is ${}^{25}_{12}\text{Mg}$
(c) ${}^{55}_{25}\text{Mn} + {}^{1}_{0}n \rightarrow {}^{56}_{25}\text{Mn} + {}^{0}_{0}\gamma$ X is ${}^{56}_{25}\text{Mn}$

35. ${}^{209}_{83}\text{Bi} + {}^{4}_{2}\text{He} \rightarrow {}^{213}_{85}\text{At} \rightarrow {}^{212}_{85}\text{At} + {}^{1}_{0}n \rightarrow {}^{211}_{85}\text{At} + {}^{1}_{0}n$

38. Any isotopes higher have a higher mass number and atomic number than iron-56 can undergo fission.

40. A control rod is a device that can be lowered to absorb neutrons generated in a nuclear fission. When it is raised, the same fission reaction can take place in a nuclear reactor. A moderator is a material surrounding the fuel rods that also absorbs neutrons. However, it cannot be raised up and down like a control rod.

41. A light-water reactor uses U-235 as fuel because regular water moderator used is a good neutron absorber. A heavy-water reactor uses U-238 as fuel because deuterium (heavy) water is used as moderator and it does not absorbed neutron as well as regular water. A breeder reactor converts some of the unused uranium fuel into plutonium which serves as an alternate fuel for the fission reaction.

44. Iron-56 is an isotope that has the highest binding energy per nucleon in its nucleus. Elements heavier than Fe-56 undergo fission because they have break up into smaller pieces to be liked Fe-56. Elements lighter than Fe-56 undergo fusion because they have to combine to become bigger piece to be liked Fe-56.

45. A hydrogen bomb first initiate by setting off a fission bomb. This will generate enough heat to set off the fusion material in the bomb.

46. A fusion reactor does not produce radioactive wastes that have long half-lives. However, fusion reaction requires extremely high temperature to initialize the reaction. This presents various technical difficulties such as generating the hot plasma using higher power lasers and having to contain it in a safe manner.

55. **(a)** ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{140}_{56}\text{Ba} + {}^{93}_{36}\text{Kr} + 3\,{}^{1}_{0}n$ **(b)** ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{144}_{55}\text{Cs} + {}^{90}_{37}\text{Rb} + 2\,{}^{1}_{0}n$
(c) ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{87}_{35}\text{Br} + {}^{146}_{57}\text{La} + 3\,{}^{1}_{0}n$ **(d)** ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{160}_{62}\text{Sm} + {}^{72}_{30}\text{Zn} + 4\,{}^{1}_{0}n$

67. Percent of C-14 left = 0.24%

85. 53.0 g of Zn