Name ________________________ **Honors Chemistry** ____/____/____

Nuclear Chemistry

The properties of the nucleus are not of primary importance to chemists. For the most part, the nucleus can be regarded as a collection of nucleons (neutrons and protons). The number of protons in a particular nucleus is called the atomic number (Z) and the sum of neutrons and protons is the mass number (A). Atoms that have identical atomic numbers but different mass number values are called isotopes. The term nuclide is a unique atom, represented by the symbol: ${}^{A}_{Z}X$.

Types of Radioactive Decay

- Some important observations about radioactive decay.
  - All nuclides with 84 or more protons are unstable with respect to radioactive decay.
  - **Light nuclide are stable when Z equals (A - Z), that is when the neutron/proton ratio is 1.**
  - In all cases of nuclear decay the mass number and atomic number both conserve mass.
- An alpha particle or **α particle** is a helium nucleus. (${}^{4}_{2}\mathrm{He}$). **Alpha particle production is a very common mode of decay for heavy radioactive nuclides.**
  - Alpha particles have a mass of 4 amu, are positively charged and are the most easily stopped of the three particles (a sheet of paper will stop them). It is the least dangerous.
  - Uranium–238 decays by alpha particle production: ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$
- Beta particle or **β-particle** production is the most common decay process in which the mass number of the decaying nucleus remains constant.
  - Beta particles are high speed electrons (${}^{0}_{-1}\mathrm{e}$), with a mass of 0.00055 amu, a negative charge and can be stopped by a sheet of aluminum. They are more penetrating and more dangerous than alpha particles.
  - Thorium-234 decomposes by losing a beta particle: ${}^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$
  - The beta particle is assigned the mass number 0, since its mass is tiny compared with that of a proton or neutron.
  - **Beta particle production changes neutrons into protons.**
- A **gamma ray**, or **γ ray**, refers to a high energy photon.
  - Gamma rays have no mass or charge, and are the most penetrating (several cm's of lead are needed to stop them). They can cause severe damage.
  - Frequently, gamma ray production accompanies nuclear decays, such as in the alpha particle decay of uranium-238: ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{0}\gamma$
  - The emission of gamma rays is one way a nucleus with excess energy (in an excited nuclear state) can relax to its ground state. You will not be expected to predict gamma ray production.
- **Positron production occurs for nuclides whose neutron/proton ratios are too small).**
  - The positron is a particle with the same mass as the electron but opposite charge (${}^{0}_{1}\mathrm{e}$).
  - Positron production occurs in sodium-22: ${}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{1}\mathrm{e}$
  - **In positron production a proton is changed to a neutron.**
  - The positron is the antiparticle of the electron.

Summary:

Type of Decay	Example	Why?
Alpha	${}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$	Occurs in heavier nuclides.
Beta	${}^{227}_{89}\mathrm{Ac} \rightarrow {}^{227}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e}$	The most common nuclear decay. A neutron changes to a proton.
Gamma	Excited nucleus → Ground State Nucleus + ${}^{0}_{0}\gamma$	To release excess energy. Accompanies other types of decay
Positron Production	${}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\mathrm{e}$	Occurs when n/p^{+} ratio is less than 1. A proton becomes a neutron.

Half-Life

- The half-life ($t_{½}$) of a radioactive sample is defined as the time required for the nuclides to reach half the original value.
- Example: The half-life of molybdenum-99 is 67.0 hours. How much of a 100.-mg sample is left after 335 h?

  335 ÷ 67 = 5 half lives

  To determine how much will be left after 5 half-lives, it is easy to sketch a graph.

  100 > 50 > 25 > 12.5 > 6.25 > **3.125**

  1 ½ life 2 ½ lives 3 ½ lives 4 ½ lives 5 ½ lives
- The formula used to calcite half-life is: **$A=Ai(½)^{t/H}$ (memorize this formula)**

  Where: A = the amount you have on hand, Ai = the original amount, t = time or age of the sample H = Half life

  Example: Calculate the amount of mass left after 2.0 minutes of 200.0 grams of X is left to decay. The sample has a half-life of 45.0 seconds.

  $A=Ai(0.50)^{t/H}$

  2.0 minutes x 60 seconds/minutes = 120 seconds

  $A= 200.0(0.50)^{[120/45.0]}$

  A= 31.50 grams
- The half -lives of radioactive nuclides vary over a tremendous range. For example, $^{144}_{60}\text{Nd}$ has a half –life of 5×10^{15} years, while $^{214}_{84}\text{Po}$ has a half-life of 2×10^{-4} second.

Nuclear Transformations

- **Nuclear transformation** involves changing one element into another.
- In 1919 Lord Rutherford discovered that by bombarding $^{14}_{7}\text{N}$ with alpha particles, the nuclide $^{17}_{8}\text{O}$ could be produced. $^{14}_{7}\text{N} + ^{4}_{2}\text{He} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$
- Particle accelerators are devices used to give particles very high velocities. Because of the electrostatic repulsion between the target nucleus and a positive ion, accelerators are needed when positive ions are used as bombarding particles. The particle, accelerated to a very high velocity, can overcome the repulsion and penetrate the target nucleus, thus effecting the transformation. One type of particle accelerator is the **cyclotron**.
- By using neutron and positive-ion bombardment, scientists have been able to extend the periodic table. Since 1940, the elements with atomic numbers 93-118, called the **transuranium elements** have been synthesized.

Detection and Uses of Radioactivity

- The most common instrument used to measure radioactivity levels is the **Geiger counter**. The probe of the Geiger counter is filled with argon gas, which can be ionized by a rapidly moving particle:

  $$\text{Ar} \xrightarrow{high-energy-particle} \text{Ar}^{+}(g) + e^{-}$$

  Argon gas does not normally conduct a current when an electrical potential is applied. However, the formation of ions and electrons produced by the passage of high-energy particles allows a momentary current to flow. Electronic devices detect this current flow, and the number of these events are counted.

Dating by Radioactivity

- A method that has been very important for dating ancient articles made from wood or cloth is **radiocarbon dating**, or **carbon-14 dating**.
- Radiocarbon dating is based on the radioactivity of the nuclide $^{14}_{6}\text{C}$, which decays via β-particle production:

  $$^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + ^{0}_{-1}\text{e}$$
- Carbon-14 dating can be used to date wood and cloth artifacts because the $^{14}_{6}\text{C}$, along with the other carbon isotopes in the atmosphere, reacts with oxygen to form carbon dioxide. A living plant consumes carbon dioxide in the photosynthesis process and incorporates the carbon, including $^{14}_{6}\text{C}$ into its molecules. As

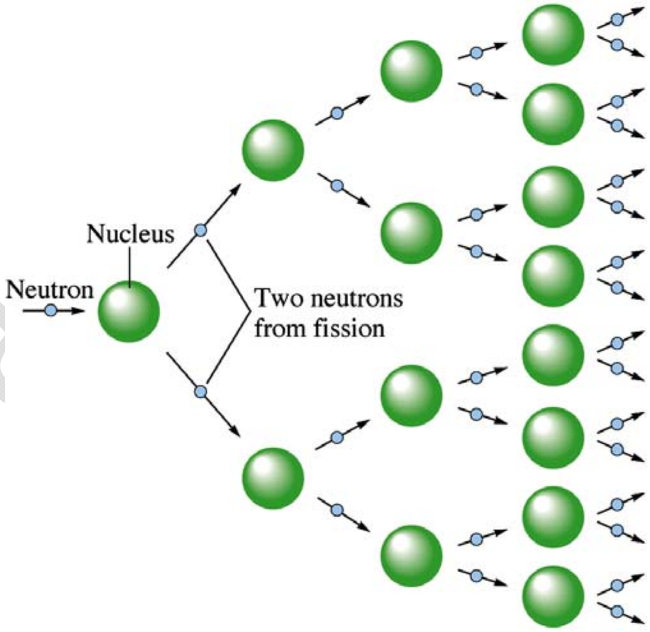
long as the plant lives, the $^{14}_{6}C/^{12}_{6}C$ ratio in its molecules remains the same as in the atmosphere because of the continuous uptake of carbon. However as soon as a tree or plant is cut, the $^{14}_{6}C/^{12}_{6}C$ ratio begins to decrease because of the radioactive decay of $^{14}_{6}C$ ($^{12}_{6}C$ is stable). The half-life of $^{14}_{6}C$ is 5730 years. Items with a $^{14}_{6}C/^{12}_{6}C$ ratio half of what is found in currently living trees is approximately 5730 years old.

- One drawback of radiocarbon dating is that a fairly large piece of the object (from a half to several grams) must be burned to form carbon dioxide, which is then analyzed for radioactivity.
- Another method, using a mass spectrometer, allows for a very accurate determination of the $^{14}_{6}C/^{12}_{6}C$ ratio and only requires about 10^{-3} g.

Nuclear Fission and Nuclear Fusion

- Combining of two light nuclei to form a heavier, more stable nucleus is called **fusion**.
- Splitting a heavy nucleus into two nuclei with smaller mass numbers is called **fission**.
- Because of the bonding energies involved in holding the nucleus together, both these processes involve energy changes more than a million times larger than those associated with chemical reactions.

Nuclear Fission



- The fission of $^{238}_{92}U$ produces about 26 million times more energy than the combustion of methane.

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{52}Te + ^{97}_{40}Zr + 2\,^{1}_{0}n$$

- In addition to the product nuclides, neutrons are also produced in the fission reactions of $^{238}_{92}U$. This makes it possible to have a self-sustaining fission process - **a chain reaction**.
- For the fission process to be self-sustaining, at least one neutron from each fission event must go on to split another nucleus.
- If on average, **less than one** neutron causes another fission event, the process dies out and the reaction is said to be **subcritical**.
- If **exactly one** neutron from each fission event causes another fission event, the process sustains itself at the same level and is said to be **critical**.
- If **more than one** neutron from each fission event causes another fission event, the process rapidly escalates and the heat buildup causes a violent explosion. This situation is described as **supercritical**.
- To achieve the critical state, a certain mass of fissionable material, called the **critical mass**, is needed.

Homework:

1. Define nucleon.

2. What is an alpha particle?

3. Which nuclides usually experience alpha decay?

4. What is a beta particle?

5. What transformation happens in beta particle production?

6. What is a gamma ray?

7. What transformation occurs in positron production?

8. Write balanced equations for each of the following processes.
    - ${}^{11}_{6}\mathrm{C}$ produces a positron
    - ${}^{214}_{83}\mathrm{Bi}$ produces a beta particle
    - ${}^{237}_{93}\mathrm{Np}$ produces an alpha particle
    - ${}^{245}_{96}\mathrm{Cm}$ produces a beta particle
    - ${}^{238}_{92}\mathrm{U}$ produces an alpha particle
    - ${}^{214}_{84}\mathrm{Po}$ produces two alpha particles and two beta particles.
    - ${}^{251}_{98}\mathrm{Cf} \rightarrow 2\,{}^{1}_{0}\mathrm{n} + {}^{131}_{54}\mathrm{Xe} +$ ___________ (fill in the missing information)
    - ${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} +$ ___________ (fill in the missing information)
    - ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{141}_{55}\mathrm{Cs} + 3\,{}^{1}_{0}\mathrm{n} +$ ___________ (fill in the missing information)

9. Radioactive iodine-131 has a half-life of eight days. The amount of a 200.0 gram sample left after 32 days would be:

10. Iodine-131 is a radioactive isotope with a half-life of 8 days. How many grams of a 64 g sample of iodine-131 will remain at the end of 24 days?

11. Actinium-225 has a ½ life of 10 days. How many grams of a 2.00 gram sample will remain at the end of 60 days?

12. The half-life of ^{55}Cr is about 2.0 hours. The delivery of a sample of this isotope from the reactor to a certain laboratory requires 12 hours. About what mass of such material should be shipped in order that 1.0 mg of ^{55}Cr is delivered to the laboratory?

13. Silver-111 has a half-life of 7.45 days. If you have 400.0 grams now, how much will remain after 30.0 days?

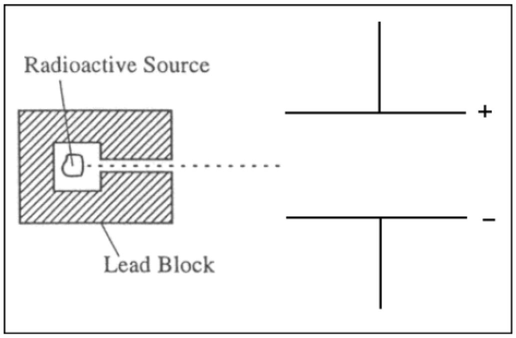
14. Sodium-24 has a half-life of 15.00 hours. If you have 32.40 grams now, how much will remain after 5.00 hours?

15. Tungsten-181 has a half-life of 121.2 days. If you have 2013 grams now, how much will remain after 365 days?

16. Strontium-90 has a half-life of 29.12 years. If you have 2.00 micrograms now, how much will remain after 83.16 years?

17. Answer each of the following questions regarding radioactivity.
(a) Write the nuclear equation for decay of Plutonium-234 by alpha emission.

(b) Describe how alpha, beta, and gamma rays each behave when they pass through an electric field. Use the diagram below to illustrate your answer.



(c) Why is it not possible to eliminate the hazard of nuclear waste by the process of incineration?