Name ________________________________ **Section** ______________

Nuclear Chemistry

I. Radioactive Isotopes and Nuclear Equations

Atoms are composed of three main subatomic particles: protons, neutrons and electrons. Protons and neutrons are found in the nucleus of an atom. The total number of protons and neutrons determines an atom's mass. The number of protons defines the element.

Some nuclei are unstable, so they naturally decompose (or "decay") over time, spontaneously emitting particles and/or energy. Such emissions are called **radioactivity** (or radioactive decay) and the unstable atoms are referred to as **radioactive isotopes** or **radioactive nuclides**. Different isotopes are identified by their element name (or chemical symbol) followed by their mass number. For example, uranium-235 (U-235) and uranium-238 (U-238) are two different isotopes of the element uranium.

Some nuclides can also be induced to decay by bombardment of high-energy particles (e.g. neutrons, electrons, and other nuclei). These kinds of nuclear changes are called **nuclear transmutation**.

Both radioactive decay and nuclear transmutation are examples of **nuclear reactions**.

Atomic Notation (Nuclear Symbol): gives the mass number and atomic number for a specific isotope or particle.

$$\text{mass number} = A,\ \text{atomic number} = Z:\quad {}^{A}_{Z}E \quad E = \text{Element symbol}$$

atomic number: number of protons (p^+) = number of electrons (e^-) in a neutral atom.

mass number: whole number sum of protons (p^+) and neutrons (n) in an atom's nucleus. Different isotopes of an element will have different mass numbers.

Atomic notation for some common particles: proton = ${}^{1}_{1}\text{H}$ neutron = ${}^{1}_{0}\text{n}$ electron = ${}^{0}_{-1}\text{e}$

Complete the following table: (1 pt each = 4 pts)

Isotope	Mass Number	# of Protons	# of Neutrons	# of Electrons
${}^{239}\text{Pu}$				

Modes of Decay

There are five different ways in which naturally occurring radioactive nuclei decay. For emission reactions, often called decay reactions, the nuclear particle is a product. In the capture reaction, the nuclear particle is a reactant. A reactant isotope is called the parent nuclide, while a product isotope is called the daughter nuclide.

alpha (α) emission (or decay): a helium nucleus, ${}^{4}_{2}\alpha$ or ${}^{4}_{2}\text{He}$, is emitted. In alpha decay reactions, the mass number decreases by four and the atomic number decreases by two for the daughter.

$$^{238}_{92}\text{U} \rightarrow {}^{4}_{2}\alpha + {}^{234}_{90}\text{Th}$$

beta (β) emission (or decay): an electron, ${}^{0}_{-1}\beta$ or ${}^{0}_{-1}\text{e}^-$, is emitted when a neutron inside the nucleus decays to produce a proton and an electron. In this case, the parent and daughter have the same mass number but the atomic number increases by 1 for the daughter nuclide.

$$^{234}_{90}\text{Th} \rightarrow {}^{0}_{-1}\beta + {}^{234}_{91}\text{Pa}$$

gamma (γ) emission (or decay): high energy photons or gamma rays, ${}^{0}_{0}\gamma$, are emitted. This often accompanies the emission of alpha and beta particles as a way to release energy.

$$^{99m}_{43}\text{Tc} \longrightarrow {}^{99}_{43}\text{Tc} + {}^{0}_{0}\gamma$$

positron (${}^{0}_{1}$e) emission (or decay): a positron, ${}^{0}_{1}$e, is emitted when a proton inside an atom decays to produce a neutron and a positron. In this type of radioactive decay, the parent and daughter have the same mass but the atomic number decreases by 1 for the daughter nuclide.

$$^{22}_{11}\text{Na} \longrightarrow {}^{0}_{1}\text{e} + {}^{22}_{10}\text{Ne}$$

electron capture: an electron in the 1s orbital "falls" into the nucleus, which fuses with a proton to form a neutron.

$$^{82}_{37}\text{Rb} + {}^{0}_{-1}\text{e} \longrightarrow {}^{82}_{36}\text{Kr}$$

A nuclear reaction can also be forced to occur by bombarding a radioactive isotope with another particle. This process of causing radioactivity is called nuclear transmutation. Nuclear transmutations can result in α–, β–, and γ-emissions as well as the production of protons, neutrons, and other isotopes:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

Balancing Nuclear Equations

This differs from balancing general chemical equations because instead of balancing elements (or atoms) present, **mass numbers** (protons + neutrons) **and atomic numbers are balanced**.

For example: $^{222}_{86}\text{Rn} \longrightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\alpha$

parent nuclide daughter nuclide

where the mass numbers are equal to 222, and the atomic numbers are equal to 86.

Exercise 1: Identify the missing nuclide in each to complete the following nuclear equations: (2 pts each)

a. What nuclide is formed when curium-242 is struck by an alpha particle?

$^{242}_{96}\text{Cm} + {}^{4}_{2}\alpha \rightarrow {}^{1}_{0}\text{n} +$ __________

b. Identify the nuclide created when uranium-238 is bombarded by a neutron:

$^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{0}_{-1}\beta +$ _________

c. Identify the missing particle in the following transmutation reaction:

_______ $+ {}^{15}_{7}\text{N} \rightarrow {}^{260}_{105}\text{Db} + 4\,{}^{1}_{0}\text{n}$

Exercise 2: Write complete nuclear equations for the following processes: (3 pts each)

a. Gallium-73 undergoes alpha decay.

b. Tin-121 decays by beta emission.

c. Osmium-188 is **the daughter nuclide** when a radioactive nuclide undergoes alpha decay.

________ → ________ + ________

d. A parent nuclide decays by beta emission to produce Xenon-131 as **the daughter nuclide**.

________ → ________ + ________

II. Half-Life and Radioactive Decay Problems

Table 1.Half-lives for U-238 Decay Series

Nuclide	Type of radiation	Half life ($t_{1/2}$)
uranium-238	α	4.47 billion years
thorium-234	β	24.1 days
protactinium-234m	β	1.17 minutes
uranium -234	α	245000 years
thorium -230	α	8000 years
radium-226	α	1600 years
radon-222	α	3.823 days
polonium-218	α	3.05 minutes
lead-214	β	26.8 minutes
bismuth-214	β	19.7 minutes
polonium -214	α	0.000164 seconds
lead-210	β	22.3 years
bismuth-210	β	5.01 days
polonium -210	α	138.4 days
lead-206	none	none

Radioactive decay is a first-order rate process; thus, radioactive processes obey the first- order integrated rate law:

$$\ln\left(\frac{A_t}{A_0}\right) = -kt$$

where A_0 = initial activity or amount of substance; A_t = activity or amount of substance after a certain time; k = rate constant; and t = time.

All radioactive nuclides also have a characteristic half-life , $t_{1/2}$, which is the time required for half the amount of a radioactive sample to decay. For first-order reactions, the half-life is related to the rate constant, k, by the following equation:

$$t_{1/2} = \frac{0.693}{k}$$

Table 1 (above) indicates the half-lives and decay processes for all the radionuclides in the decay series for Uranium-238. Use the information in the table and the equations above to answer the following questions:

1. 1. a. What is the half-life for radium-226? (1 pt) _______

b. How many half-lives have passed for radium-226 after 9,600 years? (2 pts) _____ half-lives (HL)

c. How much of a 885 mg sample of radium-226 would remain after 9,600 years? (2 pts)

d. What is the value of the rate constant, k, for radium-226? Include units for k! (2 pts)

e. How much of a 422 mg sample of radium-226 would remain after 3,800 years? (4 pts)

f. How much time would it take for 755 mg of radium-226 to decay to 167 mg? (4 pts)

2. How many hours does it take for a sample of lead-214 to decay to 4.15 % of its initial value? (See table 1 on page 3 for the half-life.) (5 pts)

III. Applications of Radioactive Isotopes

The half-lives of different radioactive nuclides range from fractions of a second to billions of years. Examples of parent-daughter pairs, their decay processes, half-lives, and applications are listed below.

Table 2: Half-lives, Types of Decay and Applications of Radioactive Isotopes

Parent/Daughter	Decay Process	Half-life	Application
Strontium-90 / Yttrium-90	ß emission	28.8 years	Industrial applications and treatment for eye and skin diseases
Iodine-123 / Tellerium-123	e^- capture and γ emission	13 hours	Thyroid imaging
Iodine-131 / Xenon-131	ß emission	8 days	Thyroid treatment
Technetium-99m (excited) / Technetium-99	γ emission	6 hours	Bone scans
Phosphorus-32 / Sulfur-32	ß emission	14.28 days	Leukemia Therapy; tracers DNA sequencing
Americium-241 / Neptunium-237	ß and γ emissions	432 years	Smoke detectors
Plutonium-239 / Uranium-235	α and γ emissions	24,400 years	Nuclear reactors
Uranium-235 / Pb-207	series of α and γ emissions	713 million years	
Potassium-40 /Argon-40	electron capture	1.25 billion years	Archeological Dating
Carbon-14 / Nitrogen-14	β emission	5730 years	
Rubidium-87 / Strontium-87	β emission	50 billion years	
Uranium-238 / Lead-206	series of α and β emissions	4.50 billion years	

Uses for Radioactive Isotopes

Smoke detectors contain Americium-241, an artificially produced radioactive isotope that emits alpha particles and low energy gamma rays.

1. The half-life for Americium-241 is ________________. [Use Table 2] (1 pt)
2. How many half-lives have passed after 100 years for a sample of Americium-241? _________ HL (use three significant figures) (2 pts)
3. Use the information from questions 1 and 2 to calculate what percentage of the Americium-241 remains after 100 years. Use three significant figures for the percentage and show your work! (2 pts)

_______%

4. A smoke detector requires about 0.3 micrograms of Americium-241 to work properly. If the smoke detector originally contains 0.5 microgram of Americium-241, does it contain enough radioactive material to function properly after 100 years? Explain your answer. (3 pts)