AP Chemistry Chapter 18 - The Nucleus: A Chemist's View

18.1 Nuclear Stability and Radioactive Decay

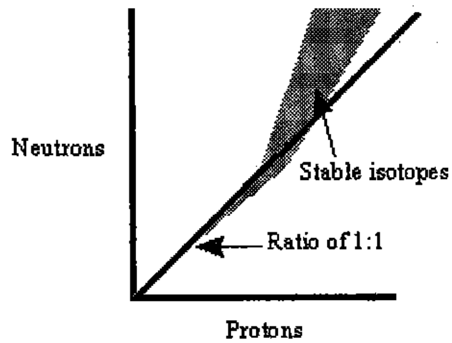
A. Radioactive Decay

1. Decomposition forming a different nucleus and producing one or more particles
   a. Total mass number and atomic number must be conserved in any nuclear change

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n +$$

B. Zone of Stability

1. Of 2000 known nuclides, only 279 are stable with respect to radioactive decay
2. All nuclides with more than 83 protons (bismuth) are unstable
3. Light nuclides are most stable when the neutron/proton ratio is 1
4. Heavier nuclides are most stable when the neutron/proton ratio is greater than 1
5. Magic numbers
   a. Special stability exists when the number of protons or neutrons is: 2, 8, 20, 28, 50, 82, 126



C. Types of Radioactive Decay

1. Alpha Emission
   a. Alpha particle (α) is a helium nucleus ($^{4}_{2}He$), so it has a 2+ charge
   b. Alpha emission is restricted almost entirely to very heavy nuclei

$$^{210}_{84}Po + \rightarrow ^{206}_{82}Pb + ^{4}_{2}He$$

2. Beta Emission
   a. Beta particle (β) is an electron emitted from the nucleus during nuclear decay

$$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}\beta$$

   b. Beta particles are emitted when a neutron is converted into a proton and an electron

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta$$

3. Positron Emission
   a. Positrons are particles that have the same mass as an electron, but a positive charge
   b. Positron emission arises from the conversion of a proton into a neutron and a positron

$$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{+1}\beta \qquad ^{38}_{19}K \rightarrow ^{38}_{18}Ar + ^{0}_{+1}\beta$$

4. Electron Capture
    a. Inner orbital electron is captured by the nucleus of its own atom
    b. Electron combines with a proton and a neutron is formed

$$ {}_{-1}^{0}e + {}_{1}^{1}p \rightarrow {}_{0}^{1}n \qquad {}_{47}^{106}Ag + {}_{-1}^{0}e \rightarrow {}_{46}^{106}Pd $$

5. Gamma Emission
    a. Gamma rays () are high-energy electromagnetic waves emitted from a nucleus as it changes from an excited state to a ground energy state
    b. Gamma rays are produced when nuclear particles undergo transitions in energy levels
    c. Gamma emission usually follows other types of decay that leave the nucleus in an excited state

10^{-12}	10^{-10}	10^{-8}	4 to 7×10^{-7}	10^{-4}	10^{-2}	1	10^{2}	10^{4}
gamma	xrays	UV	visible	IR	micro	Radio waves		
						FM	short	AM

D. Decay Series
   1. In some cases, multiple decays are needed to produce a stable nuclide
      a. Original nuclide is called the "Parent" nuclide
      b. Ensuing decay nuclides are called "daughter" nuclides

18.2 The Kinetics of Radioactive Decay

A. Rate of Decay
   1. The negative of the change in the number of particles per unit of time

$$ Rate = -\frac{\Delta N}{\Delta t} \propto N \qquad Rate = -\frac{\Delta N}{\Delta t} = kN $$

      a. This is a first order rate law, so...

$$ \ln\left(\frac{N}{N_0}\right) = -kt $$

← does it look familiar?

N_0 = original number of nuclides (at t = 0)
N = the number of nuclides remaining at time t

B. Half-Life ($t_{1/2}$)
   1. The time required for the number of nuclides to reach half the original value

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

← again, does it look familiar?

Representative Radioactive Nuclides and Their Half Lives			
Nuclide	*Half-life*	*Nuclide*	*Half-life*
$^{3}_{1}H$	12.32 years	$^{214}_{84}Po$	163.7 μseconds
$^{14}_{6}C$	5715 years	$^{218}_{84}Po$	3.0 minutes
$^{32}_{15}P$	14.28 days	$^{218}_{85}At$	1.6 seconds
$^{40}_{19}K$	1.3 x 10^9 years	$^{238}_{92}U$	4.46 x 10^9 years
$^{60}_{27}Co$	10.47 minutes	$^{239}_{94}Pu$	2.41 x 10^4 years

18.3 Nuclear Transformations

A. Nuclear Transformation
   1. The change of one element into another

B. Methods of Transformation
   1. Particle accelerators overcome the repulsive forces of the target nucleus
      a. Cyclotron
         (1) Particle is accelerated from the inside and takes the spiral path to the target outside
      b. Linear Accelerator
         (1) Particle is accelerated down a linear track

C. Transuranium Elements
   1. Elements beyond Uranium
      93 -112, 114, 116, 118 (as of May, 1999)
      *** notice the absence of odd atomic numbers in the heavy nuclides

18.4 Detection and Uses of Radioactivity

A. Detection
   1. Geiger counter
   2. Scintillation counter

B. Dating by Radioactivity
   1. Decay rate of unstable nuclides can be used to determine age of some objects
   2. Carbon-14 dating (radiocarbon dating)
      a. Carbon-12 is stable
      b. Carbon-14 decays, with a half-life of 5730 years

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta$$

         (1) Living things take in carbon-12 and carbon-14, in a fixed ratio
         (2) When a living thing dies, the amount of carbon-12 does not change, but carbon-14 begins to decrease through decay

18.5 Thermodynamic Stability of the Nucleus

A. Mass Defect

1. The difference between the mass of an atom and the sum of the masses of its protons, neutrons, and electrons

For $^{4}_{2}He$:

2 protons:	(2 x 1.007 276 amu) = 2.014 552 amu
2 neutrons:	(2 x 1.008 665 amu) = 2.017 330 amu
2 electrons:	(2 x 0.000 5486 amu) = 0.001 097 amu
	total combined mass = 4.032 979 amu
	Helium's atomic mass = 4.002 60 amu
	Mass defect = 0.030 38 amu

B. Nuclear Binding Energy

1. The energy released when a nucleus is formed from nucleons
2. The energy required to break apart the nucleus
3. Mass defect is related to nuclear binding energy by the equation:

$$E = mc^2 \qquad \Delta E = \Delta mc^2$$

mcΔt

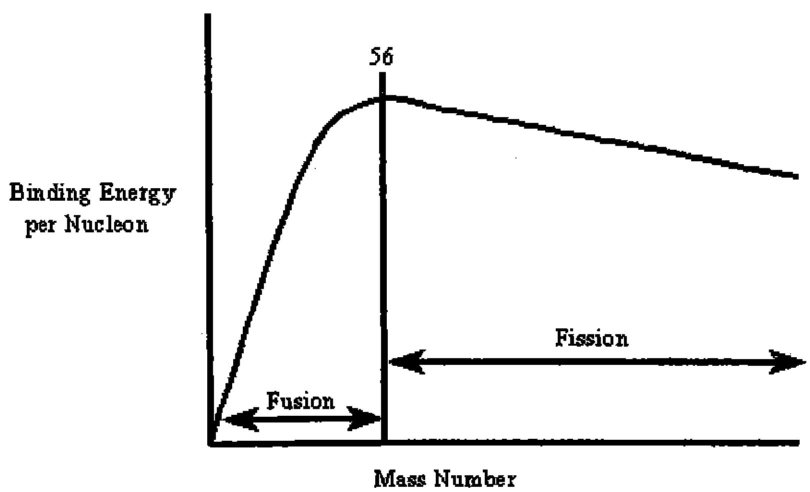
a. (-0.03038 amu)(1.66 x 10^{-27} kg/amu) = -5.04 x 10^{-29} kg

b. ΔE = (-5.04 x 10^{-29} kg)(3.00 x 10^{8} m/s)^2 = -4.54 x 10^{-12} J

c. Binding energy per nucleon = $\frac{4.54 \times 10^{-12}\ J}{4\ nucleons}$ = 1.14 J/nucleon

C. Binding Energy per Nucleon

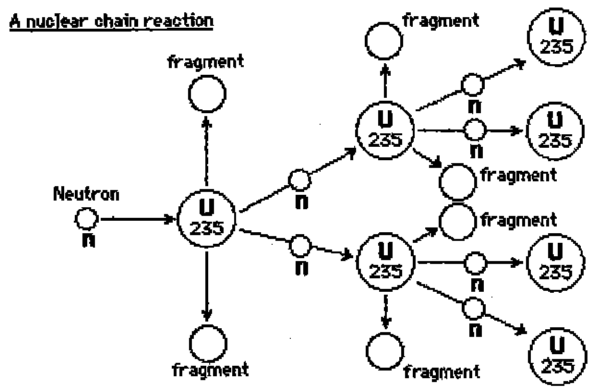
1. The binding energy of the nucleus divided by the number of nucleons it contains
2. High binding energy per nucleon results in greater stability
   a. The most stable nucleus is that of iron-56



18.6 Nuclear Fission and Nuclear Fusion

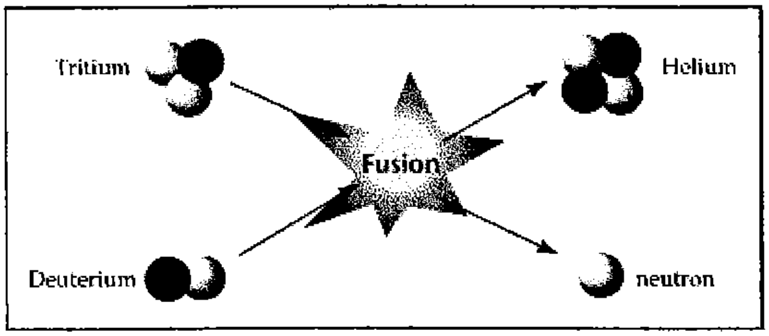
A. Nuclear Fission
   1. Splitting a heavy nucleus into two nuclei with smaller mass numbers
   2. The mass of the products is less than the mass of the reactants. Missing mass is converted to energy

B. Chain Reaction
   1. A reaction in which the material that starts the reaction is also one of the products and can start another reaction



C. Critical Mass
   1. The minimum amount of nuclide that provides the number of neutrons needed to sustain a chain reaction

D. Nuclear Fusion
   1. Combining two light nuclei to form a heavier, more stable nucleus



A. Fusion Reactions
   1. More energetic than fission rxns
   2. Source of energy of the hydrogen bomb
   3. Could produce energy for human use if a way can be found to contain a fusion rxn (magnetic field?)

NUCLEAR DECAY

Name ______________

Predict the products of the following nuclear reactions.

1. ${}^{42}_{19}K \rightarrow {}^{0}_{-1}e + {}^{42}_{20}Ca$

2. ${}^{239}_{94}Pu \rightarrow {}^{4}_{2}He + {}^{235}_{92}U$

3. ${}^{235}_{92}U \rightarrow {}^{4}_{2}He + {}^{231}_{90}Th$

4. ${}^{1}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He$

5. ${}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H$

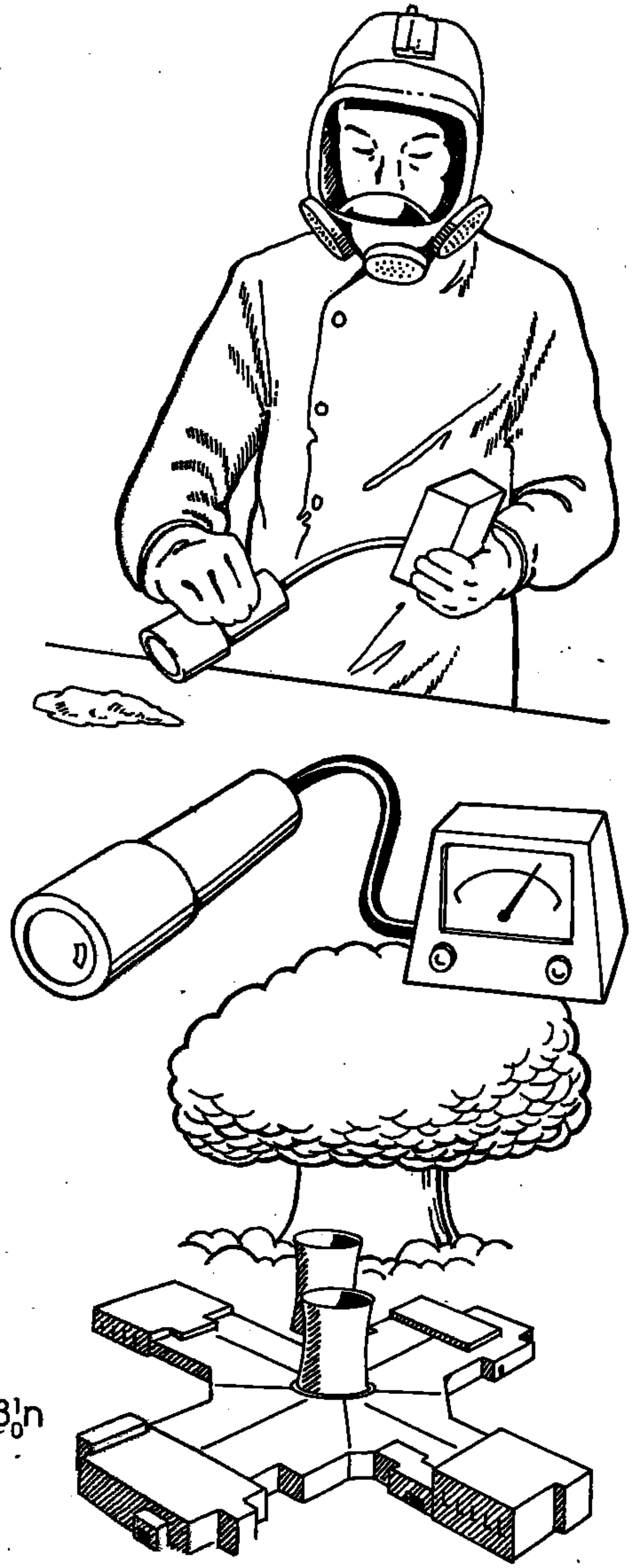
6. ${}^{27}_{13}Al + {}^{4}_{2}He \rightarrow {}^{30}_{15}P + {}^{1}_{0}n$

7. ${}^{9}_{4}Be + {}^{1}_{1}H \rightarrow {}^{6}_{3}Li + {}^{4}_{2}He$

8. ${}^{37}_{19}K \rightarrow {}^{0}_{+1}e + {}^{37}_{18}Ar$

9. ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{142}_{56}Ba + {}^{91}_{36}Kr + 3{}^{1}_{0}n$

10. ${}^{238}_{92}U + {}^{4}_{2}He \rightarrow {}^{241}_{94}Pu + {}^{1}_{0}n$



HALF-LIFE CALCULATIONS

Name ____________________

Half-life is the time required for one-half of a radioactive nuclide to decay (change to another element). It is possible to calculate the amount of a radioactive element that will be left if we know its half-life.

Example: The half-life of Po-214 is 0.001 second. How much of a 10 g sample will be left after 0.003 seconds?

Answer: Calculate the number of half-lives:

$$0.003 \text{ seconds} \times \frac{1 \text{ half-life}}{0.001 \text{ second}} = 3 \text{ half-lives}$$

After 0 half-lives, 10 g are left.
After 1 half-life, 5 g are left.
After 2 half-lives, 2.5 g are left.
After 3 half-lives, 1.25 g are left.

Solve the following problems.

1. The half-life of radon-222 is 3.8 days. How much of a 100 g sample is left after 15.2 days?

   1, 2, 3, 4
   100, 50, 25, 12.5, 6.25
   $\left(\frac{1}{2}\right)^n \times \text{mass}$ ____________

2. Carbon-14 has a half-life of 5,730 years. If a sample contains 70 mg originally, how much is left after 17,190 years?

   70, 35, 17.5, 8.75
   8.75 g

3. How much of a 500 g sample of potassium-42 is left after 62 hours? The half-life of K-42 is 12.4 hours?

   $\frac{62 \text{ hr}}{12.4 \text{ hr/HL}} = 5$ Half Lives
   $\left(\frac{1}{2}\right)^n \times 500$
   $\left(\frac{1}{2}\right)^5 \times 500 =$ 15.625 g

4. The half-life of cobalt-60 is 5.26 years. If 50 g are left after 15.8 years, how many grams were in the original sample?

   $\frac{15.8 \text{ yr}}{5.26 \text{ yr/HL}} = 3$ Half Lives
   $\left(\frac{1}{2}\right)^n \times x = 50$
   $\left(\frac{1}{2}\right)^3 \cdot x = 50$
   $x = 400$ g

5. The half-life of I-131 is 8.07 days. If 25 g are left after 40.35 days, how many grams were in the original sample?

   $\frac{40.35 \text{ days}}{8.07 \text{ days/HL}} = 5$ Half Lives
   $\left(\frac{1}{2}\right)^5 \cdot x = 25$g
   $x = 800$ g

6. If 100 g of Au-198 decays to 6.25 g in 10.8 days, what is the half-life of Au-198?

   4 H.L is 10.8 days
   $\left(\frac{1}{2}\right)^n \cdot 100 = 6.25$, $n = 4$
   1 HL = 2.7 days

HALF-LIFE OF RADIOACTIVE ISOTOPES

Name ______________________

1. How much of a 100.0 g sample of $^{198}_{79}Au$ is left after 8.10 days if its half-life is 2.70 days?

   $\frac{8.10}{2.70} = 3$ H.L $(1/2)^3 \cdot 100 =$

   Answer: 12.5 g

2. A 50.0 g sample of ^{16}N decays to 12.5 g in 14.4 seconds. What is its half-life?

   2 H.L = 14.4 sec, 1 H.L = 7.2 sec 2 Half Lives $(1/2)^n \cdot 50 = 12.5$, $(1/2)^n = 1/4$, $n = 2$

   Answer: 7.2 sec

3. The half-life of ^{42}K is 12.4 hours. How much of a 75$\bar{0}$ g sample is left after 62.0 hours?

   $\frac{62 \text{ Hr}}{12.4 \text{ Hr/HL}} = 5$ Half Lives $(1/2)^5 \times 750 = x$, $x = 23.4$ g

   Answer: 2.34 g

4. What is the half-life of ^{99}Tc if a 50$\bar{0}$ g sample decays to 62.5 g in 639,000 years?

   $\frac{500}{62.5}$ $(1/2)^n \times 500 = 62.5$, $(1/2)^n = 1/8$, $n = 3$; 3 Half Lives = 639,000

   Answer: 1 HL = 213,000 yr

5. The half-life of ^{232}Th is 1.4×10^{10} years. If there are 25.0 g of the sample left after 2.8×10^{10} years, how many grams were in the original sample?

   $\frac{2.8 \times 10^{10} \text{ yr}}{1.4 \times 10^{10} \text{ yr}} = 2$ HL $(1/2)^2 \times X = 25$, $x = 100$ grams

   Answer: 100 grams

6. There are 5.0 g of ^{131}I left after 40.35 days. How many grams were in the original sample if its half-life is 8.07 days?

   $\frac{40.35 \text{ days}}{8.07 \text{ days}} = 5$ H.L. $(1/2)^5 \cdot x = 5$, $x = 160$ g

   Answer: 160 g

Name:

Nuclear Reactions worksheet

Part I - Complete the following reactions

1. $^{210}_{84}Po \longrightarrow {}^{4}_{2}He + \underline{{}^{206}_{82}Pb}$

2. $^{40}_{19}K \longrightarrow {}^{0}_{-1}e + \underline{{}^{40}_{20}Ca}$

3. $^{134}_{55}Cs \longrightarrow {}^{0}_{-1}e + \underline{{}^{134}_{56}Ba}$

4. $^{99}_{42}Mo \longrightarrow {}^{0}_{-1}e + \underline{{}^{99}_{43}Tc}$

5. $^{243}_{94}Pu \longrightarrow {}^{0}_{-1}e + \underline{{}^{243}_{95}Pu}$

6. $^{28}_{13}Al \longrightarrow {}^{28}_{14}Si + \underline{{}^{0}_{-1}e}$

7. $^{225}_{89}Ac \longrightarrow {}^{4}_{2}He + \underline{{}^{221}_{87}Fr}$

Part II - Complete the following Nuclear Bombardment Reactions

8. $^{14}_{7}N + {}^{4}_{2}He \longrightarrow {}^{1}_{1}H + \underline{{}^{17}_{8}O}$

9. $^{9}_{4}Be + {}^{4}_{2}He \longrightarrow {}^{1}_{0}n + \underline{{}^{12}_{6}C}$

10. $^{249}_{98}Cf + {}^{12}_{6}C \longrightarrow 4({}^{1}_{0}n) + \underline{{}^{257}_{104}Rf}$

11. $^{239}_{94}Pu + 2({}^{1}_{0}n) \longrightarrow {}^{241}_{95}Am + \underline{{}^{0}_{-1}e}$

12. $^{254}_{99}Es + \underline{{}^{4}_{2}He \text{ or } \alpha} \longrightarrow {}^{258}_{101}Md$

13. $^{12}_{6}C + \underline{{}^{244}_{96}Cm} \longrightarrow {}^{254}_{102}No + 2({}^{1}_{0}n)$

14. $^{96}_{42}Mo + {}^{2}_{1}H \longrightarrow \underline{{}^{98}_{43}Tc}$

Part III - Answer the following Questions regarding half-life.

15.) A sample of bismuth-210 has a mass of 132 g. It's half life is 5.0 days. What is the mass of bismuth-210 after 20 days?

$\frac{20}{5} = 4$ H.L $\quad (\frac{1}{2})^4 = \frac{1}{16} \times 132 =$ **8.25 g**

16.) A sample of thorium-234 has a mass of 20 g. It's half life is 24.1 days. What is the mass of thorium-234 remaining after 144.6 days?

$\frac{144.6}{24.1} = 6$ H.L $\quad (\frac{1}{2})^6 = \frac{1}{64} \times 20 =$ **.3125 g**

17.) Carbon-14 has a half life of 5,730 years. A scientist discovers a fossil that contains 1/4 the amount of carbon-14 found in living things. About how old is this fossil?

$(\frac{1}{2})^n = \frac{1}{4}$ $\quad n = 2 \quad$ 2 H.L.

$2 \times 5730 = 11{,}460$ yrs

18.) An ancient tool made from bone contains 1/8th the carbon-14 found in living things. About how old is it?

3 HL $\quad 5730 \times 3 = 17{,}190$ yrs

19.) About how old is a fossil that contains 1/16th the amount of Carbon-14 found in living things?

$\frac{1}{16} = (\frac{1}{2})^n \quad n = 4 \quad 5730 \times 4 = 22920$ yrs

Part IV - Fission Reactions.

20.) ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{141}_{56}Ba + {}^{X}_{36}Kr + 3({}^{1}_{0}n)$ X = 92

21.) ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{137}_{52}Te + {}^{X}_{40}Zr + 2({}^{1}_{0}n)$ X = 97

22.) ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{X}_{37}Rb + {}^{137}_{55}Cs + 3({}^{1}_{0}n)$ X = 96

23.) ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{94}_{38}Sr + {}^{140}_{54}Xe + X({}^{1}_{0}n)$ X = 2

24.) ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{82}_{Y}X + {}^{151}_{61}Pm + 3({}^{1}_{0}n)$ X = Ga Y = 31