Nuclear Chemistry

Chapter 23

- **Nuclear Chemistry**

deals with the study of properties, composition and changes in the nuclei of an atom.

23.1 Nuclear Reactions

Nuclear transmutation - bombardment of nuclei by neutrons, protons or other nuclei

Radioactive decay - spontaneous loss of particles from a nucleus

Atomic number (Z) = number of protons in nucleus

Mass number (A) = number of protons + number of neutrons

= atomic number (Z) + number of neutrons

Isotopes- Atoms of the same element having the same atomic number but different atomic mass.

The isotopes of the given series are

Isotopes: have the same number of p^+ and different numbers of n^0.

$^{238}_{92}U$ and $^{234}_{92}U$

$^{234}_{90}Th$ and $^{230}_{90}Th$

$^{214}_{83}Bi$ and $^{210}_{83}Bi$

Mass Number → A

Atomic Number → Z

$^{A}_{Z}X$ ← Element Symbol

	proton	neutron	electron	positron	α particle
	$^{1}_{1}p$ or $^{1}_{1}H$	$^{1}_{0}n$	$^{0}_{-1}e$ or $^{0}_{-1}\beta$	$^{0}_{+1}e$ or $^{0}_{+1}\beta$	$^{4}_{2}He$ or $^{4}_{2}\alpha$
A	1	1	0	0	4
Z	1	0	-1	+1	2

Balancing Nuclear Equations

1. Conserve mass number (A).

The sum of protons plus neutrons in the products must equal the sum of protons plus neutrons in the reactants.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n$$

$$235 + 1 = 138 + 96 + 2x1$$

2. Conserve atomic number (Z) or nuclear charge.

The sum of nuclear charges in the products must equal the sum of nuclear charges in the reactants.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n$$

$$92 + 0 = 55 + 37 + 2x0$$

^{212}Po decays by alpha emission. Write the balanced nuclear equation for the decay of ^{212}Po.

alpha particle - ${}^{4}_{2}\mathrm{He}$ or ${}^{4}_{2}\alpha$

$$ {}^{212}_{84}\mathrm{Po} \longrightarrow {}^{4}_{2}\mathrm{He} + \boxed{{}^{A}_{Z}\mathrm{X}}\ ? $$

$212 = 4 + A$ $\qquad$ $A = 208$

$84 = 2 + Z$ $\qquad$ $Z = 82$

$$ {}^{212}_{84}\mathrm{Po} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{208}_{82}\mathrm{Pb} $$

EXAMPLE 23.1

Balance the following nuclear equations (that is, identify the product X):

(a) ${}^{212}_{84}\text{Po} \longrightarrow {}^{208}_{82}\text{Pb} + \text{X}$

(b) ${}^{137}_{55}\text{Cs} \longrightarrow {}^{137}_{56}\text{Ba} + \text{X}$

Answer (a) The mass number and atomic number are 212 and 84, respectively, on the left-hand side and 208 and 82, respectively, on the right-hand side. Thus, X must have a mass number of 4 and an atomic number of 2, which means that it is an α particle. The balanced equation is

$${}^{212}_{84}\text{Po} \longrightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\alpha$$

(b) In this case the mass number is the same on both sides of the equation, but the atomic number of the product is 1 more than that of the reactant. The only way this change can come about is to have a neutron in the Cs nucleus transformed into a proton and an electron; that is, ${}^{1}_{0}\text{n} \longrightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta$ (note that this process does not alter the mass number). Thus, the balanced equation is

$${}^{137}_{55}\text{Cs} \longrightarrow {}^{137}_{56}\text{Ba} + {}^{0}_{-1}\beta$$

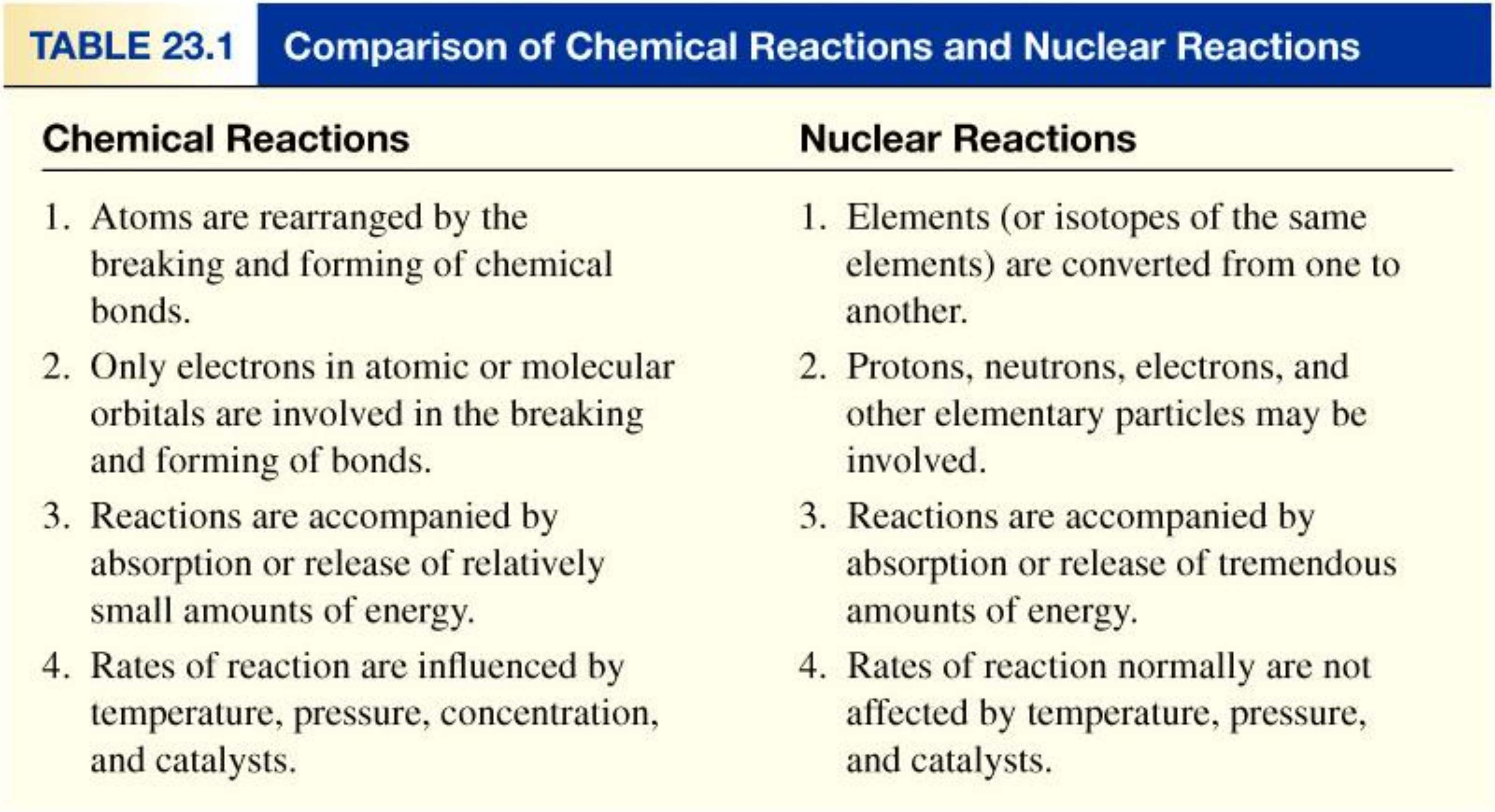


TABLE 23.1 Comparison of Chemical Reactions and Nuclear Reactions

Chemical Reactions	Nuclear Reactions
1. Atoms are rearranged by the breaking and forming of chemical bonds.	1. Elements (or isotopes of the same elements) are converted from one to another.
2. Only electrons in atomic or molecular orbitals are involved in the breaking and forming of bonds.	2. Protons, neutrons, electrons, and other elementary particles may be involved.
3. Reactions are accompanied by absorption or release of relatively small amounts of energy.	3. Reactions are accompanied by absorption or release of tremendous amounts of energy.
4. Rates of reaction are influenced by temperature, pressure, concentration, and catalysts.	4. Rates of reaction normally are not affected by temperature, pressure, and catalysts.

23.2 Nuclear Stability

A. General facts and rules

- Certain numbers of neutrons and protons are ***extra*** stable
  - n or p = 2, 8, 20, 50, 82 and 126
  - Like extra stable numbers of electrons in noble gases (e^- = 2, 10, 18, 36, 54 and 86)
- Nuclei with even numbers of both protons and neutrons are more stable than those with odd numbers of neutron and protons
- All isotopes of the elements with atomic numbers higher than 83 are radioactive
- All isotopes of Tc and Pm are radioactive

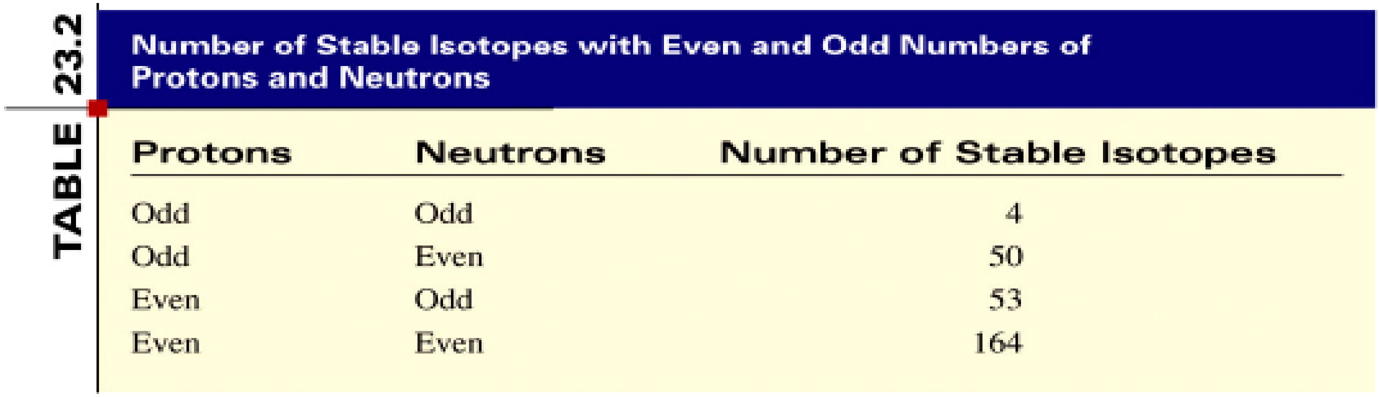
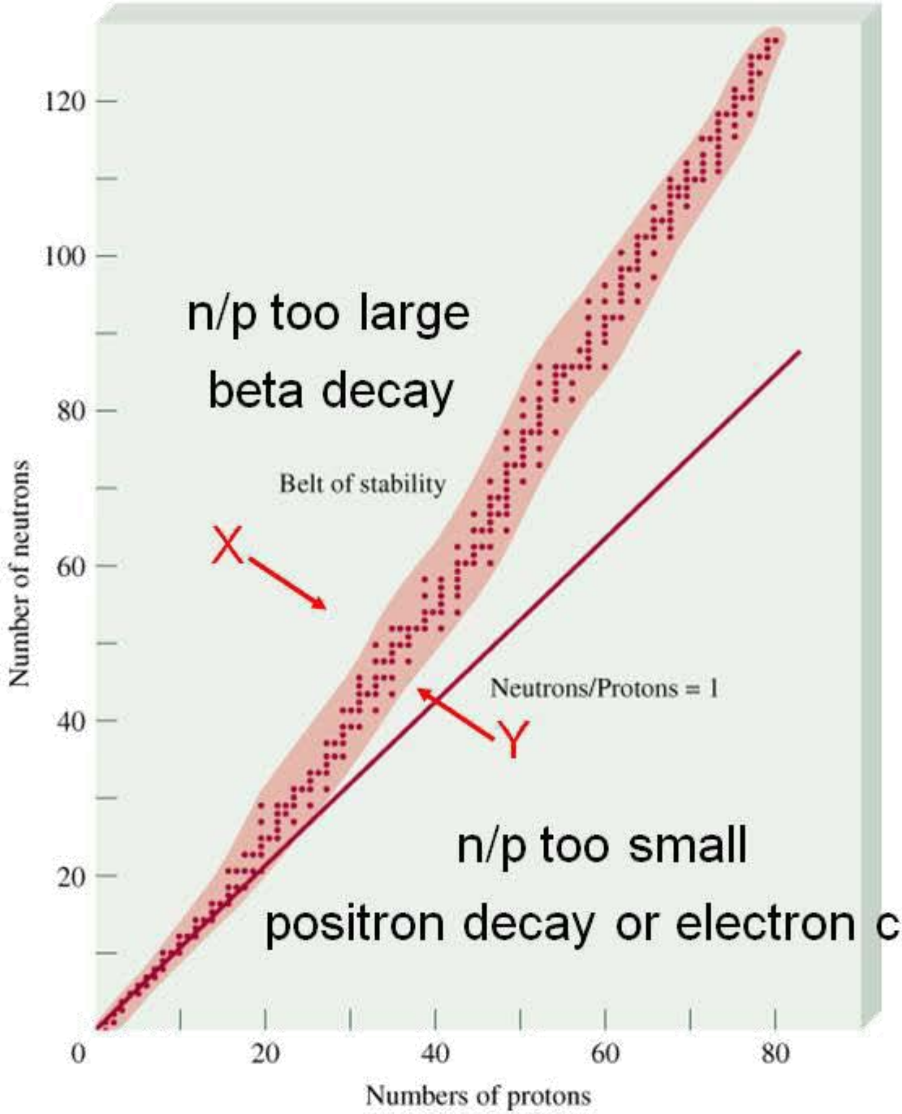


TABLE 23.2 **Number of Stable Isotopes with Even and Odd Numbers of Protons and Neutrons**

Protons	Neutrons	Number of Stable Isotopes
Odd	Odd	4
Odd	Even	50
Even	Odd	53
Even	Even	164

belt of stability (Figure 23.1) nuclei outside are radioactive



n/p too large

beta decay

n/p too small

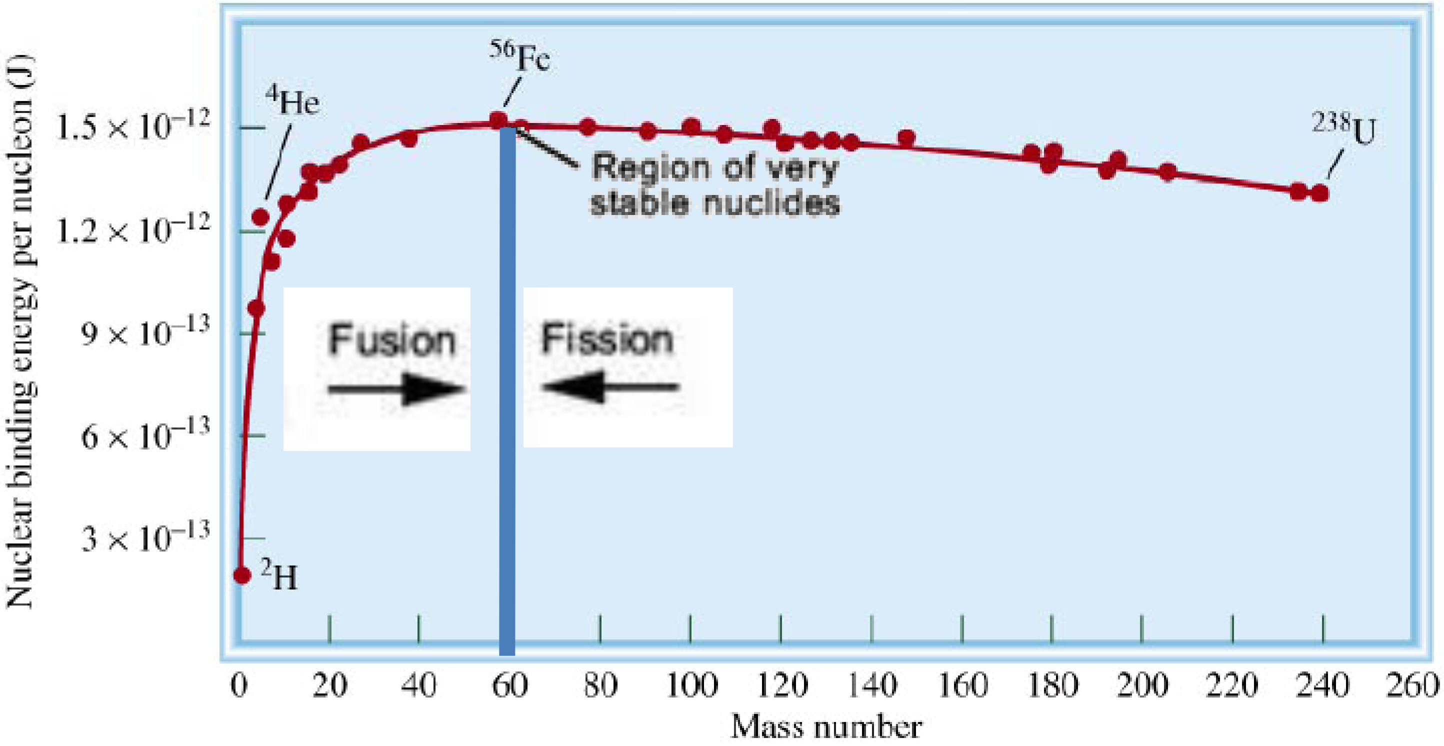
positron decay or electron capture

B. Nuclear Binding Energy

Nuclear binding energy (BE) is the energy required to break up a nucleus into its component protons and neutrons.

- $E = mc^2$
    - m = mass
    - c = speed of light (3 x 10^8 m/s)
    - E = energy

Nuclear binding energy per nucleon vs Mass number



$$\frac{\text{nuclear binding energy}}{\text{nucleon}} \uparrow \qquad \text{nuclear stability} \uparrow$$

23.3 Natural Radioactivity

Types of decay

Beta decay

"daughter"

"parent" $^{14}_{6}\text{C} \longrightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$

$^{40}_{19}\text{K} \longrightarrow {}^{40}_{20}\text{Ca} + {}^{0}_{-1}\beta$

Decrease # of neutrons by 1

Increase # of protons by 1

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

Positron decay

$^{11}_{6}\text{C} \longrightarrow {}^{11}_{5}\text{B} + {}^{0}_{+1}\beta$

$^{38}_{19}\text{K} \longrightarrow {}^{38}_{18}\text{Ar} + {}^{0}_{+1}\beta$

Increase # of neutrons by 1

Decrease # of protons by 1

$$^{1}_{1}\text{p} \longrightarrow {}^{1}_{0}\text{n} + {}^{0}_{+1}\beta$$

Electron capture decay

$${}^{37}_{18}\text{Ar} + {}^{0}_{-1}\text{e} \longrightarrow {}^{37}_{17}\text{Cl}$$

$${}^{55}_{26}\text{Fe} + {}^{0}_{-1}\text{e} \longrightarrow {}^{55}_{25}\text{Mn}$$

Increase # of neutrons by 1

Decrease # of protons by 1

$${}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e} \longrightarrow {}^{1}_{0}\text{n}$$

Alpha decay

$${}^{212}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + {}^{208}_{82}\text{Pb}$$

Decrease # of neutrons by 2

Decrease # of protons by 2

Spontaneous fission

$${}^{252}_{98}\text{Cf} \longrightarrow 2\,{}^{125}_{49}\text{In} + 2\,{}^{1}_{0}\text{n}$$

Examples:

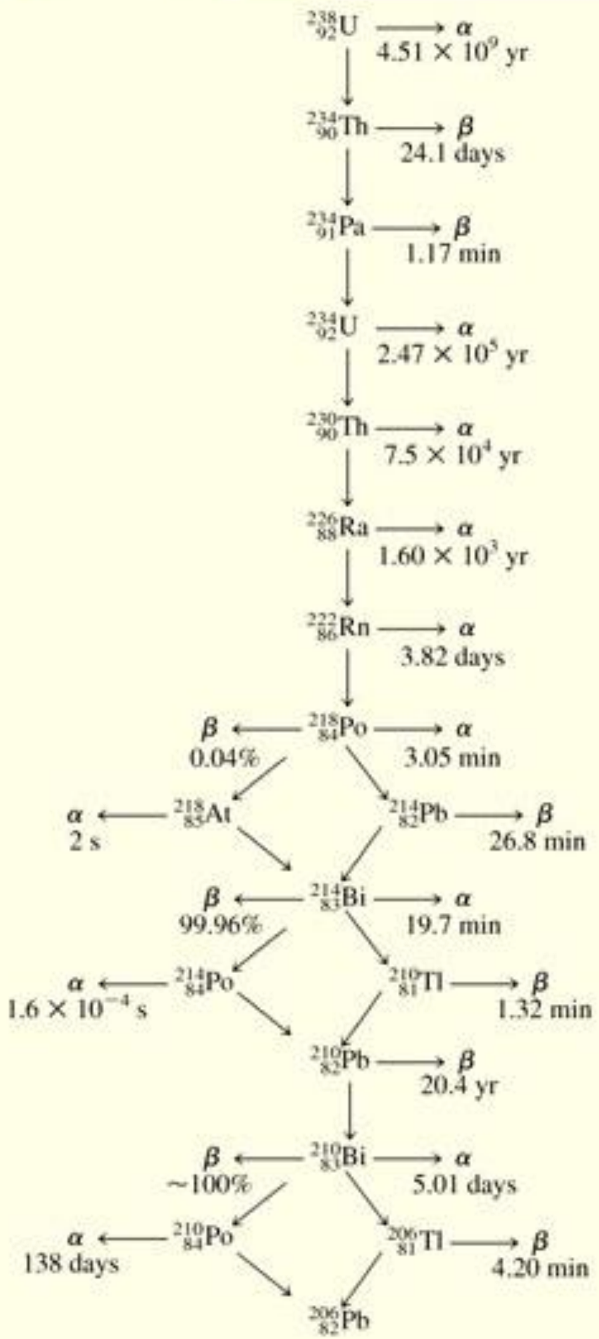
1. When a radioisotope emits alpha (α) particle, the mass number of radioactive Atom is;

a) stays the same
b) increases by one
c) decreases by four.
d) increases by two.

2. The formation of $^{14}{}_{7}N$ from $^{14}{}_{6}C$ is obeyed

a) α decay
b) β decay
c) positron decay
d) e- capture

TABLE 23.3 The Uranium Decay Series*



Kinetics of Radioactive Decay

$$N \longrightarrow \text{daughter}$$

$$\text{rate} = -\frac{\Delta N}{\Delta t} \qquad \text{rate} = \lambda N$$

$$-\frac{\Delta N}{\Delta t} = \lambda N$$

$$N = N_0\exp(-\lambda t) \qquad \ln N = \ln N_0 - \lambda t$$

N = the number of atoms at time t

N_0 = the number of atoms at time $t = 0$

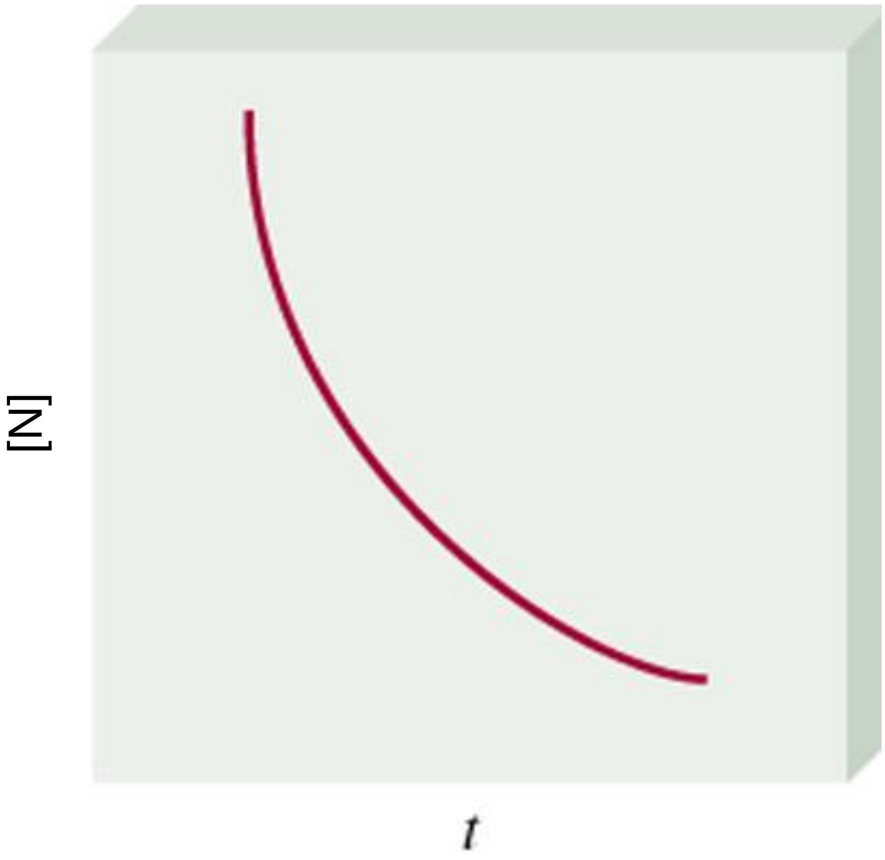
λ is the decay constant

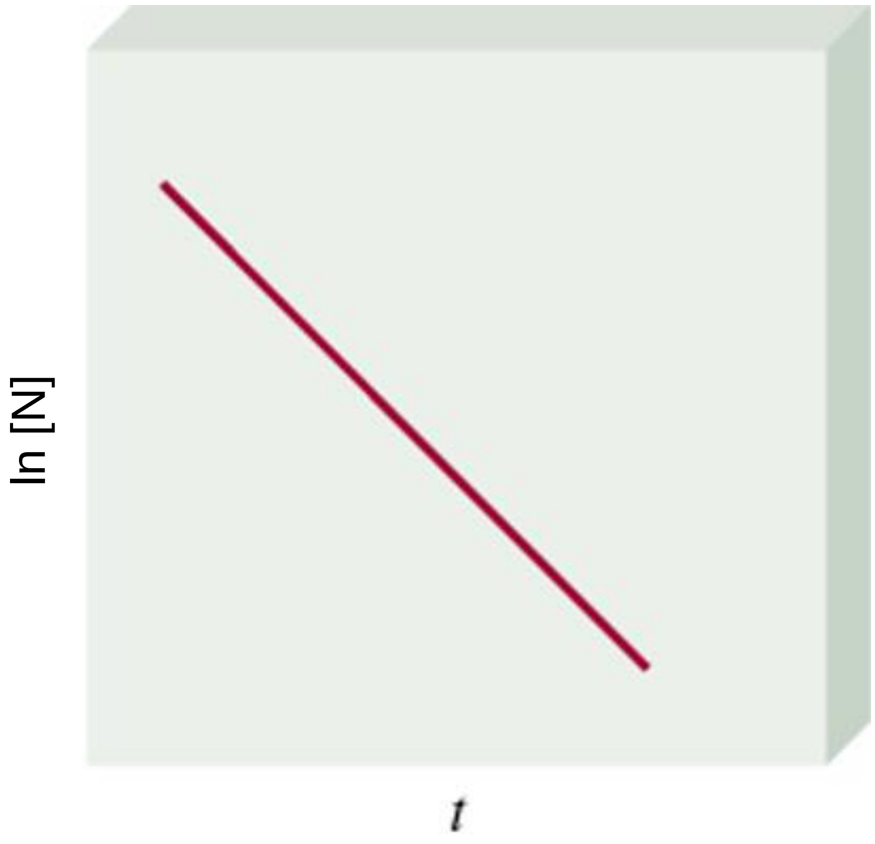
$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Kinetics of Radioactive Decay

$[N] = [N]_0 \exp(-\lambda t)$

$\ln[N] = \ln[N]_0 - \lambda t$





Examples:

The radioactive decay of ^{206}TI to ^{206}Pb has a half-life of 4.2 min. starting with 5.00 x 10^{22} atoms of ^{206}TI, calculate the number of such atoms left after 42.0 min?

A radioactive substance undergoes decays as initial mass = 500 g and mass = 389 g at 1.0 day. Calculate the half life of the reaction.

a) 10 days b) 2.77 days
c) 7.22 days d) 5.55 days

Radioactive Dating

The half live of radioactive isotopes have been used as “atomic clocks” to determine the age of certain objective.

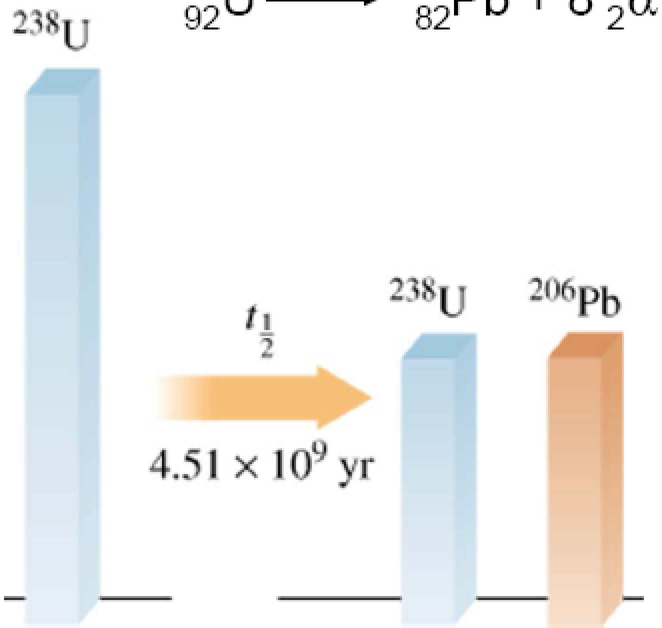
Radiocarbon Dating

$${}^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$$

$${}^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta + \bar{\nu} \qquad t_{1/2} = 5730 \text{ years}$$

Uranium-238 Dating

$${}^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\,{}^{4}_{2}\alpha + 6\,{}^{0}_{-1}\beta \qquad t_{1/2} = 4.51 \times 10^{9} \text{ years}$$



23.4 Nuclear Transmutations

- bombardment of nuclei in particle accelerator - may form new isotopes
- **nucleosynthesis**

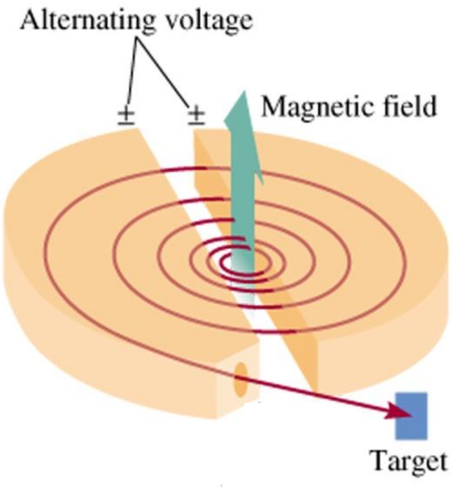
$$^{10}_{5}B + ^{4}_{2}He \text{ ----> } ^{13}_{7}N + ^{1}_{0}n$$

$$^{27}_{13}Al + ^{4}_{2}He \text{ ----> } ^{30}_{15}P + ^{1}_{0}n$$

$$^{10}_{5}B(\alpha, n)^{13}_{7}N$$

$$^{27}_{13}Al(\alpha,n)^{30}_{15}P$$

shorthand notation



Cyclotron Particle Accelerator

Schematic diagram of cyclotron particle accelerator.

The particle (an ion) to be accelerated starts at the center and is forced to move in a spiral path through the influence of electric and magnetic filed until emerges at high velocity .

EXAMPLE 23.3

Write the balanced equation for the nuclear reaction $^{56}_{26}\mathrm{Fe}(\mathrm{d},\alpha)^{54}_{25}\mathrm{Mn}$, where d represents the deuterium nucleus (that is, $^{2}_{1}\mathrm{H}$).

Answer The abbreviation tells us that when iron-56 is bombarded with a deuterium nucleus, it produces the manganese-54 nucleus plus an α particle, $^{4}_{2}\mathrm{He}$. Thus, the equation for this reaction is

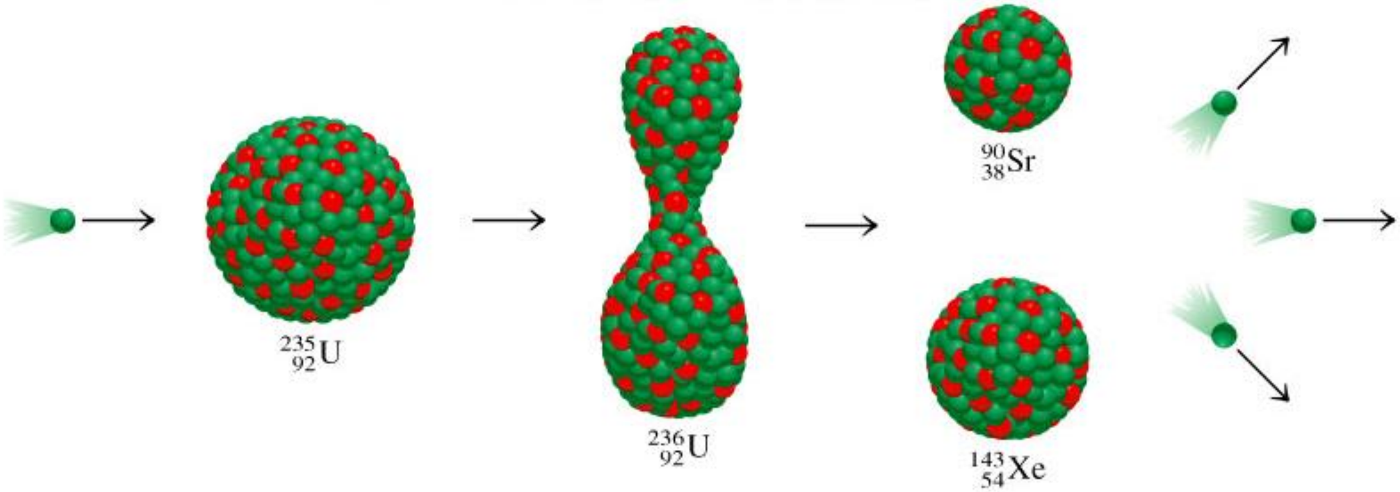
$$^{56}_{26}\mathrm{Fe} + ^{2}_{1}\mathrm{H} \longrightarrow ^{4}_{2}\alpha + ^{54}_{25}\mathrm{Mn}$$

23.5 Nuclear Fission

- process in which heavy nuclei are split into smaller nuclei and neutrons

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow [^{236}_{92}\text{U}] \longrightarrow {}^{90}_{38}\text{Sr} + {}^{143}_{54}\text{Xe} + 3\,{}^{1}_{0}\text{n} + \text{ENERGY}$$

- **chain reaction** - self-sustaining sequence of nuclear fission reactions
- **critical mass** - minimum amount of fissionable material needed for chain reaction



23.6 Nuclear Fusion

The type of reaction that occurs in the sun, is the combination of two light nuclei to form one heavy nucleus. Because fusion reactions take place only at very high temperatures, they are often called thermonuclear reactions.

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} $$

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} $$

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{1}\mathrm{H} + {}^{\ 0}_{+1}\beta $$

$$^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \text{energy}$$