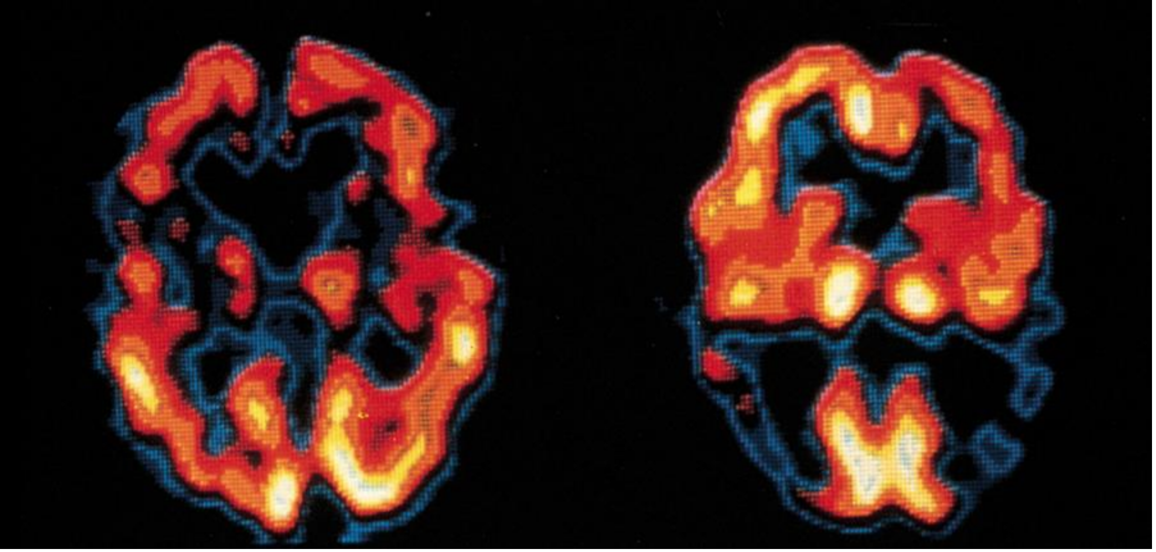
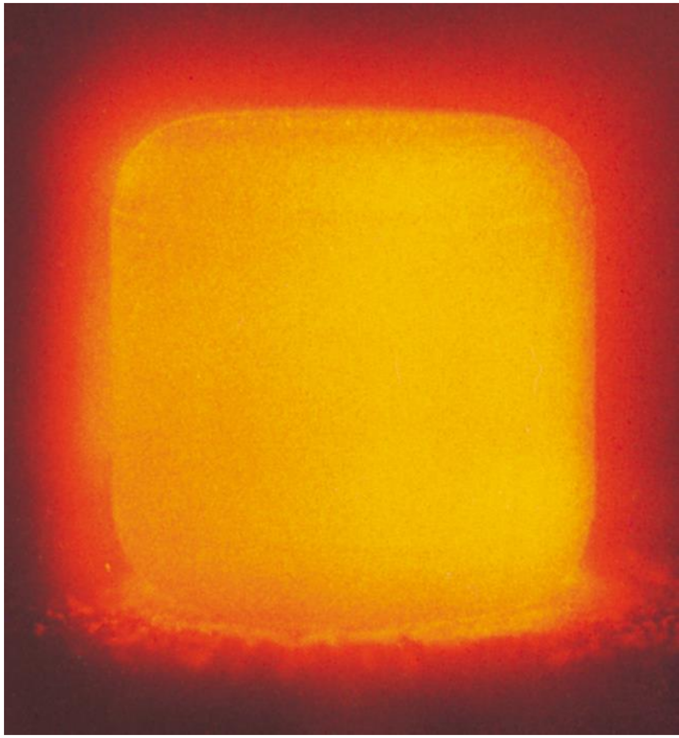




Nuclear Chemistry

Chapter 23

Atomic number (Z) = number of protons in nucleus

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

= atomic number (Z) + number of neutrons

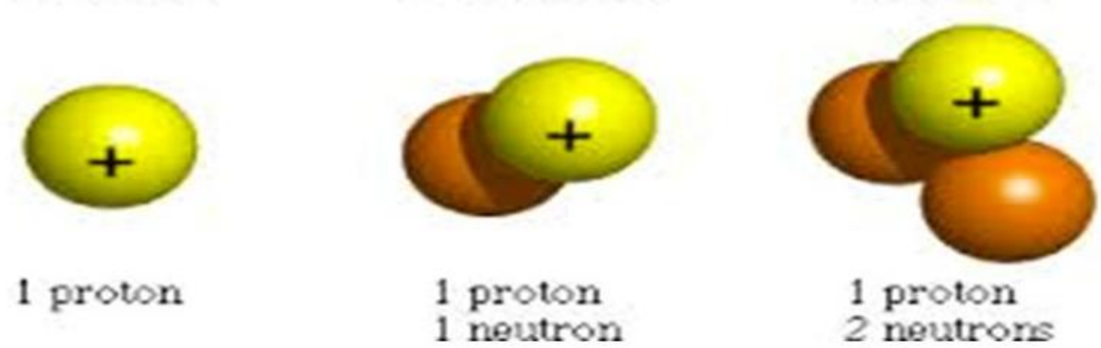
Mass Number → $^{A}_{Z}X$ ← Element Symbol

Atomic Number →

	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

Isotopes: Different forms of the same element, having the same Atomic number (protons) and different mass number (different number of neutrons)

Proton	Deuteron	Tritium
$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$



Stable isotope: Is one that does not emits radiations spontaneously and Not decomposed into another nucleoid.

Radioactive isotope: Is one that emit radiations spontaneously and decompose Into another nucleoid

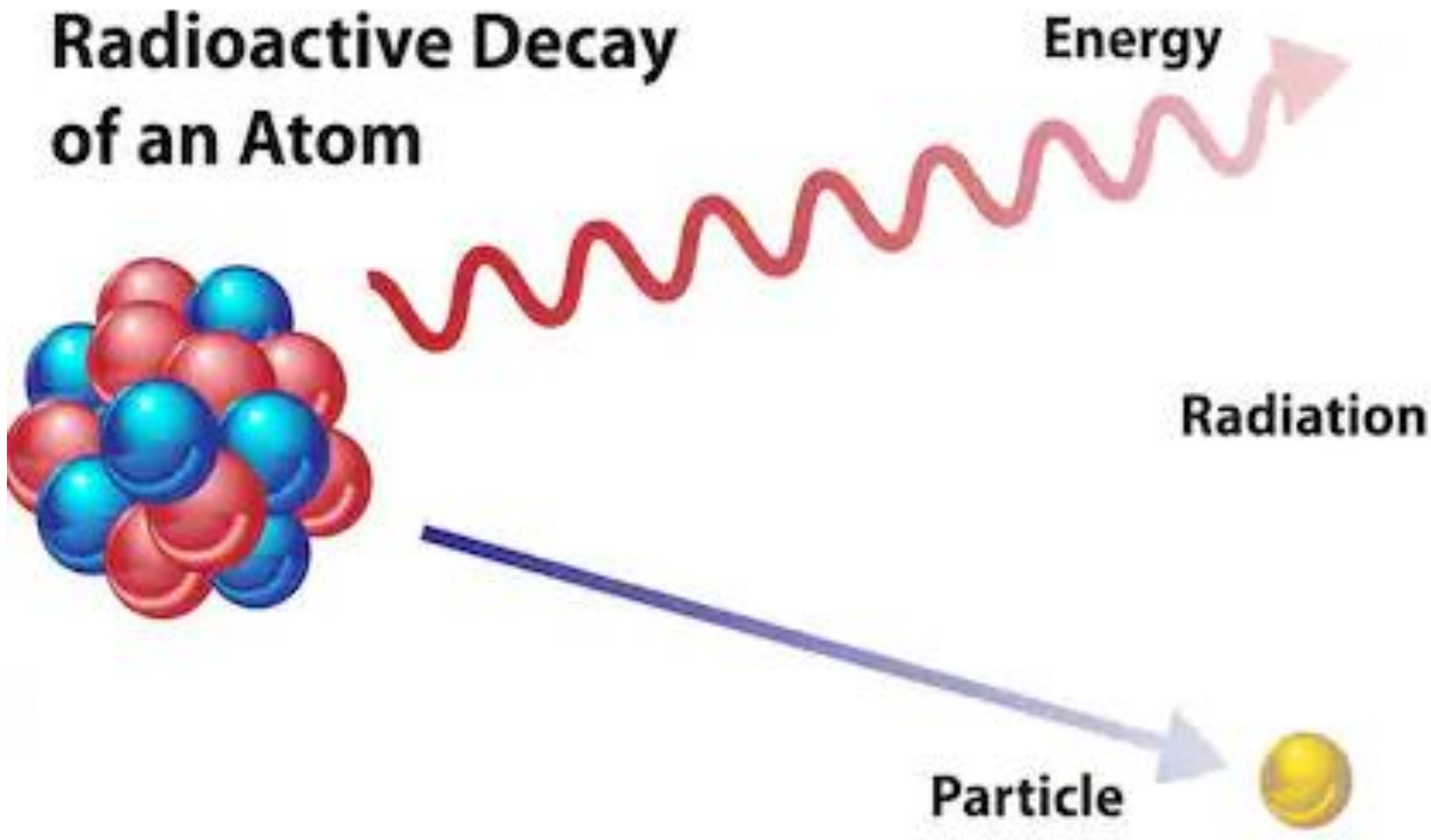
Radioactive and Stable isotopes

Radioactive isotopes

- Radioactive isotope or radioisotope, natural or artificially created isotopes of a chemical element having an unstable nucleus that decays, emitting alpha, beta, or gamma rays until stability is reached.
- The stable end product is a nonradioactive isotope of another element, i.e., radium-226 decays finally to lead-206.

Stable isotopes

- Stable isotopes are chemical isotopes that may or may not be radioactive, but if radioactive, have half lives too long to be measured.
- Only 90 nuclides from the first 40 elements are energetically stable .
- there are 255 known stable nuclides of the 80 elements which have one or more stable isotopes.



Example:

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

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.

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

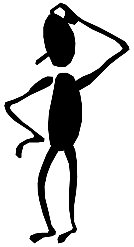
235 + 1 = 138 + 96 + 2x1

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



Example 5.1

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

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

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

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

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

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

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.

Nuclear Stability and Radioactive Decay

Beta decay

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

Decrease # of neutrons by 1

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

Increase # of protons by 1

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

Positron decay

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

Increase # of neutrons by 1

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

Decrease # of protons by 1

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

ν and $\bar{\nu}$ have A = 0 and Z = 0

Nuclear Stability and Radioactive Decay

Electron capture decay

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

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

Increase # of neutrons by 1

Decrease # of protons by 1

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

Alpha decay

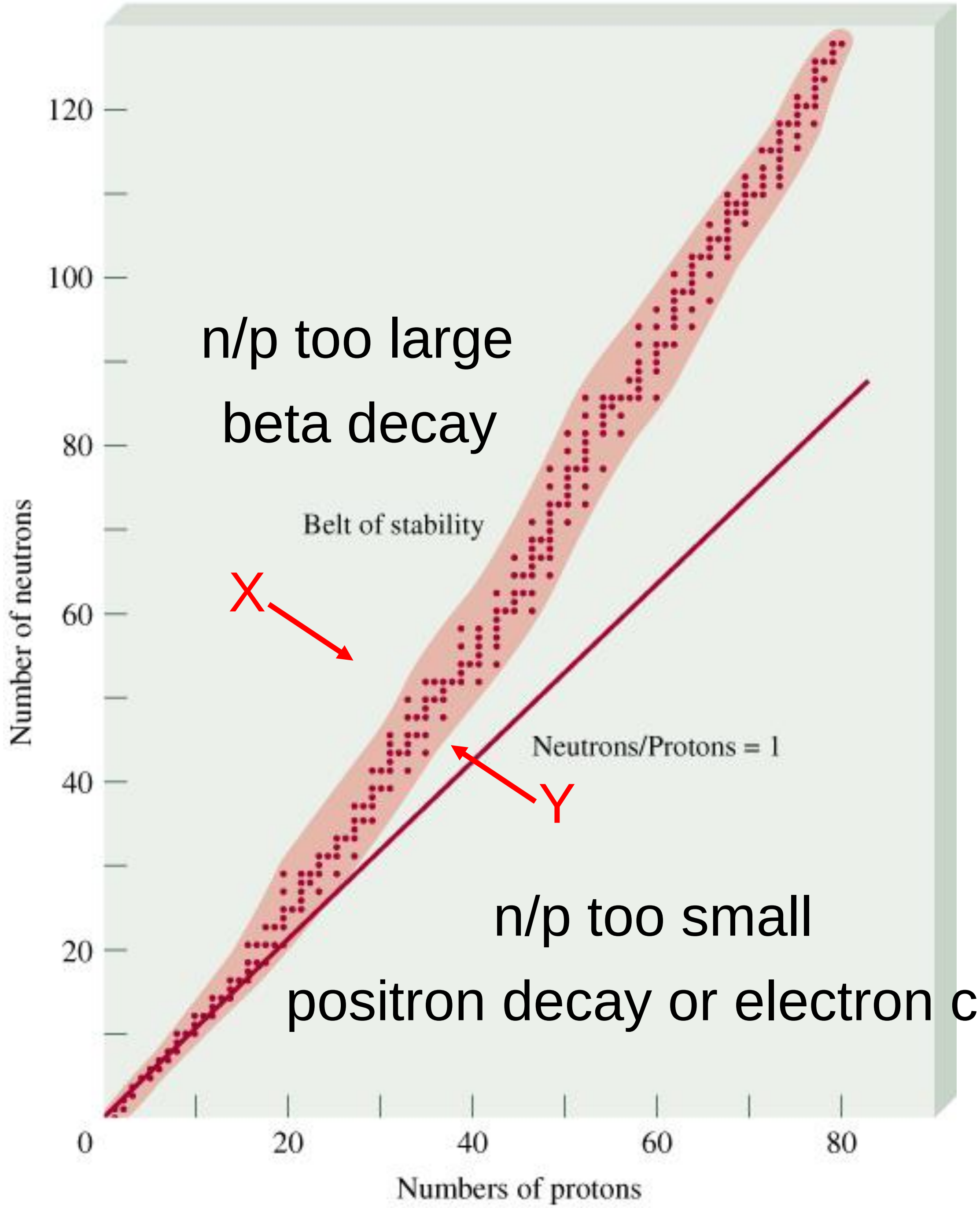
$$^{212}_{84}Po \longrightarrow ^{4}_{2}He + ^{208}_{82}Pb$$

Decrease # of neutrons by 2

Decrease # of protons by 2

Spontaneous fission

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



n/p too large

beta decay

n/p too small

positron decay or electron capture

Nuclear Stability

- 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

Kinetics of Radioactive Decay

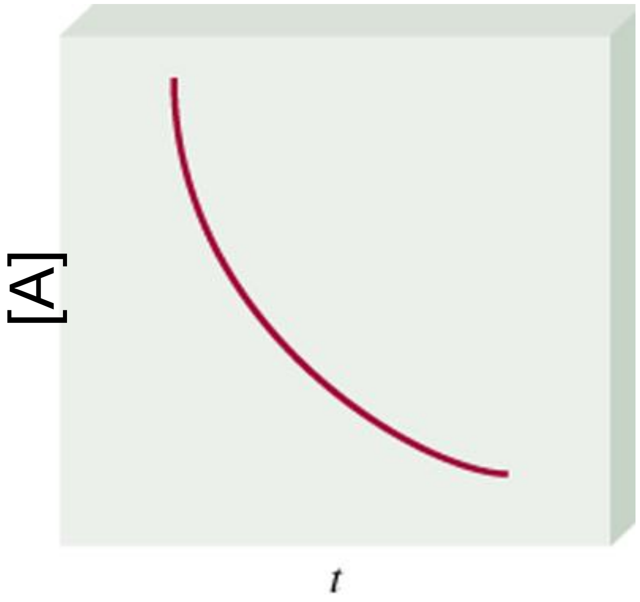
$$A \longrightarrow \text{daughter} \qquad \text{rate} = -\frac{\Delta A}{\Delta t} = kA$$

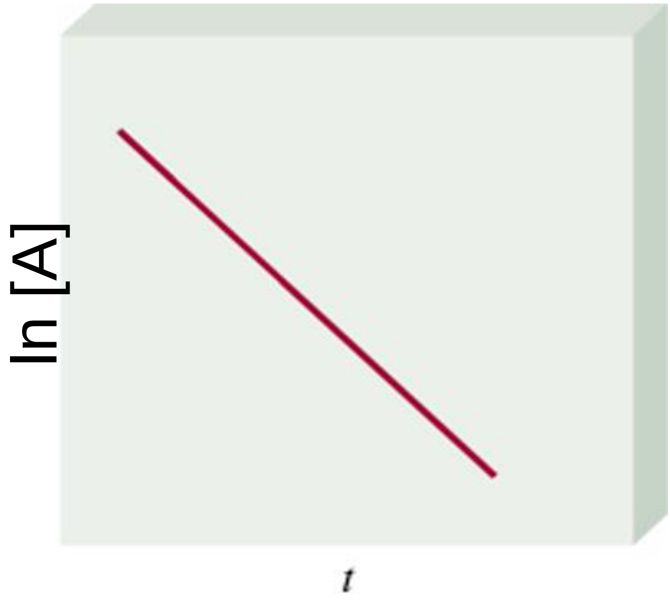
A = the number of atoms at time t

A_0 = the number of atoms at time $t = 0$

k = the decay constant

$$[A] = [A]_0 \exp(-kt) \qquad k = \frac{\ln 2}{t_{1/2}} \qquad \ln[A] = \ln[A]_0 - kt$$





Example 5.2

If 12% of a certain radioisotope decays in 5.2 years, what is the half-life of this isotope?

$\ln A_o/A = k\ t$

12% decays means the remaining is 88%

$\ln 100/88 = k \times 5.2\ y$

$K = 2.8 \times 10^{-4}\ y^{-1}$

$t_{1/2} = 0.693 / 2.8 \times 10^{-4}\ y$

$= 247.5\ y$

Example 5.3 The half-life of ^{90}Sr is 29 years. What fraction of the atoms in sample of ^{90}Sr would remain 175 years later?

a) 0.166 b) 0.125 c) 0.015 d) 0.50

$$k = \ln 2/\, t_{1/2} = 0.693/29 = 0.0239\ y^{-1}$$

$$\ln A_o/A = k\, t$$

$$= 0.0239\ y^{-1} \times 175\ y = 4.18$$

$$A_o/A = e^{4.18} = 65.36$$

$$A = A_o/65.36 = 1/\ 65.36 = 0.015$$

Another solution:

number of periods= total time / $t_{1/2}$

number of periods = 175/29 = 6 periods

$$1 \longrightarrow \frac{1}{2} \longrightarrow \frac{1}{4} \longrightarrow \frac{1}{8} \longrightarrow \frac{1}{16} \longrightarrow \frac{1}{32} \longrightarrow \frac{1}{6}$$

Radiocarbon Dating

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

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

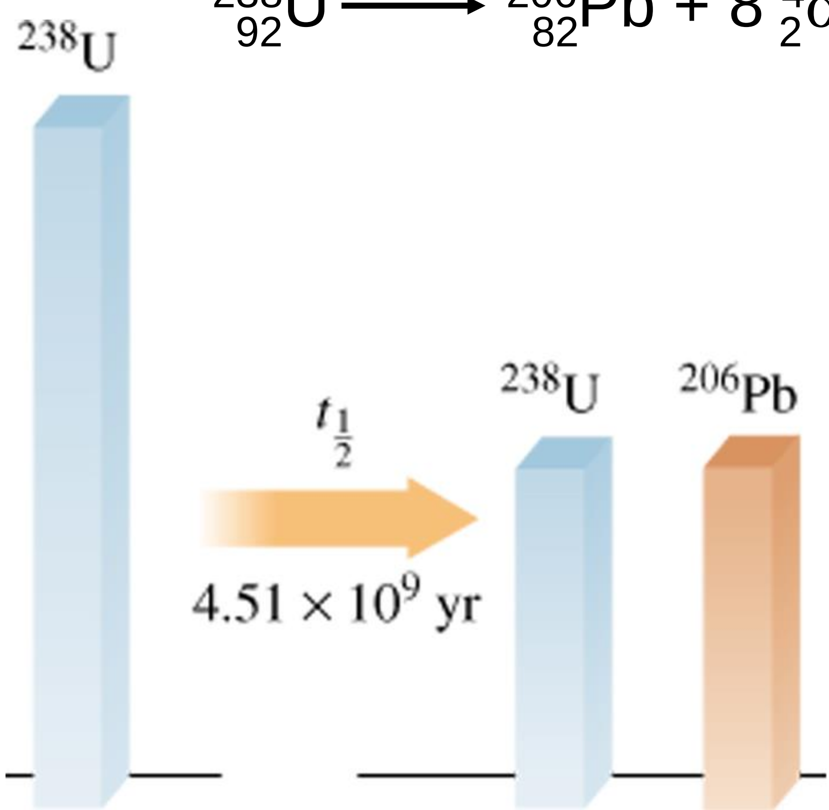
$t_{½}$ = 5730 years

$k = 0.693/5730 = 1.2 \times 10^{-4}\ y^{-1}$

Uranium-238 Dating

$$^{238}_{92}U \longrightarrow ^{206}_{82}Pb + 8\,^{4}_{2}\alpha + 6\,^{0}_{-1}\beta$$

$t_{½} = 4.51 \times 10^{9}$ years



Example 5.4 : The carbon-14 activity of some ancient Peruvian Corn was found to be 10 dpm/g of carbon. If present-day plant Life shows 15 dpm/g, how old is the Peruvian corn? half-life time of carbon-14 is 5730 y.

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

$= 0.693/5730\ y$

$k = 1.2 \times 10\ {-4}\ y^{-1}$

$\ln A_o/A = k\ t$

$\ln 15/10 = 1.2 \times 10^{-4} \times t$

$t = 3352.4\ y$

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

$$BE + {}^{19}_{9}F \longrightarrow 9\,{}^{1}_{1}p + 10\,{}^{1}_{0}n$$

$$E = \Delta mc^2$$

Theoretical mass = 9 x (p mass) + 10 x (n mass) – ^{19}F mass

B.E. (a.m.u) = Th. Mass- actual mass

B.E. (a.m.u) = [9 x 1.007825 + 10 x 1.008665] – 18.9984

BE = 0.1587 amu

1 amu = 1.49 x 10^{-10} J

BE = 2.37 x 10^{-11}J

$$\text{binding energy per nucleon} = \frac{\text{binding energy}}{\text{number of nucleons}}$$

$$= \frac{2.37 \times 10^{-11}\ \text{J}}{19\ \text{nucleons}} = 1.25 \times 10^{-12}\ \text{J}$$

Example 5.6: Find the nuclear binding energy of potassium-40 (atomic mass = 39.9632591 a.m.u) in units of joules per nucleon. [Data: neutron mass = 1.008665 a.m.u; proton mass = 1.007825a.m.u; 1kg = 6.022 x10^{26} a.m.u, c =3x 10^8 m/s]

$^{40}_{19}K$ Protons = 19 ; neutrons = 40-19 = 21

Th. Mass = [19 x 1.007825+ 21 x 1.008665]

Ac. Mass = 39.9632591 a.m.u

B.E. = 40.33064 - 39.9632591

= 0.3673809 a.m.u

B.E. = 0.3673809 a.m.u / 6.022 x10^{23}x1000

= 6.1 x 10^{-24} Kg

B.E. = Δmc^2

B.E. = 6.1 x 10^{-24} x (3 x10^8)^2 Kg.m^2.s^{-2} or (J)

B.E. = 18.3 x10^{-8} J

B.E./nucleon = 18.3 x10^{-8} J/40 = 4.58x10^{-7} J/n

Example: calculate the energy released from the following decay :

$$^{192}_{72}Pt \longrightarrow {}^{4}_{2}He + {}^{188}_{76}Os$$

If you know : Atomic mass of Pt = 191.9614 amu , Os= 187.956, He= 4.0026 a.m.u

Δm= 191.9614 – (187.965 +4.0026)

= 2.8 x 10^{-3} a.m.u

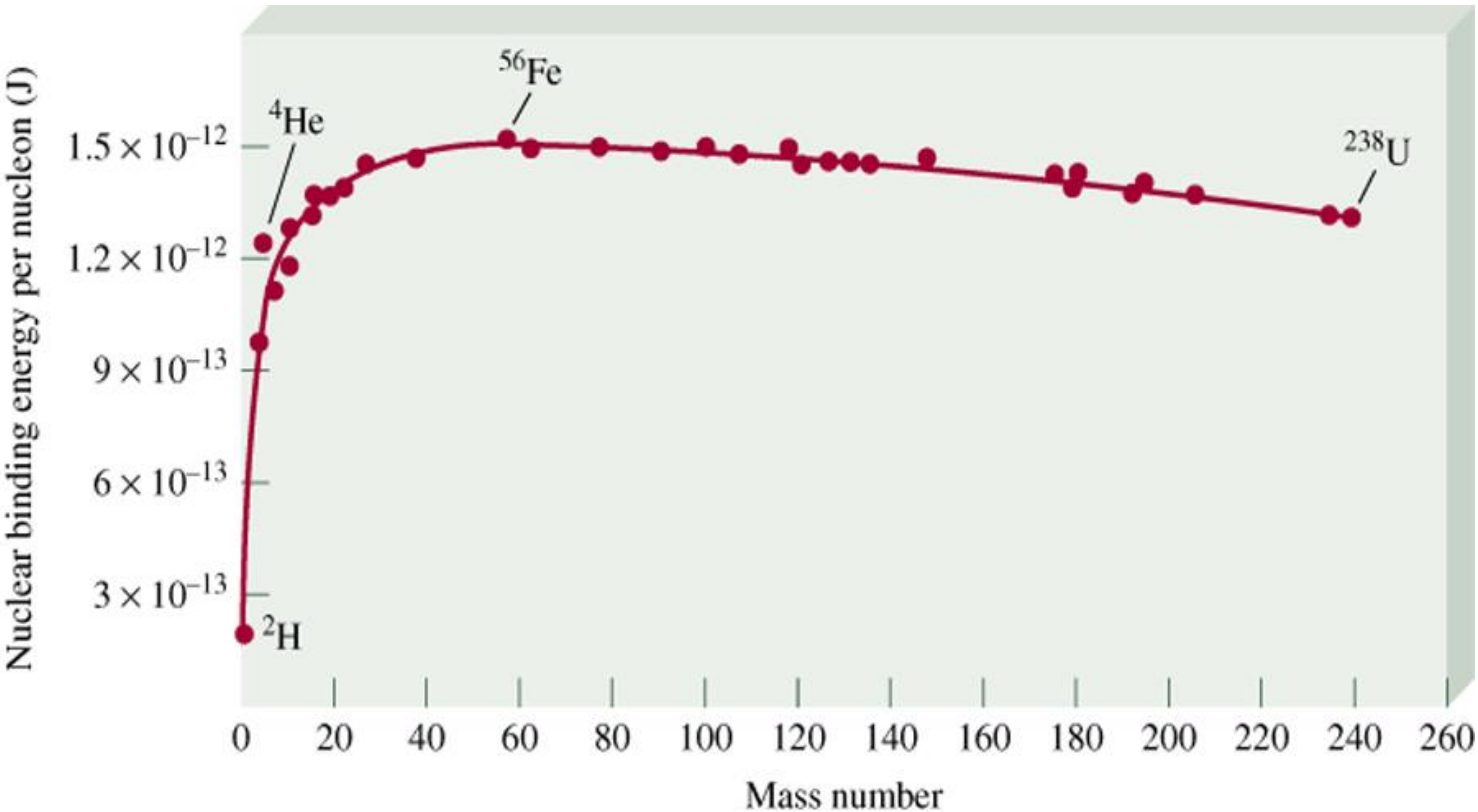
1 a.m.u = 931.5 Mev

2.8 x 10^{-3} a.m.u = ? Mev

= 2.8 x 10^{-3} x 931.5

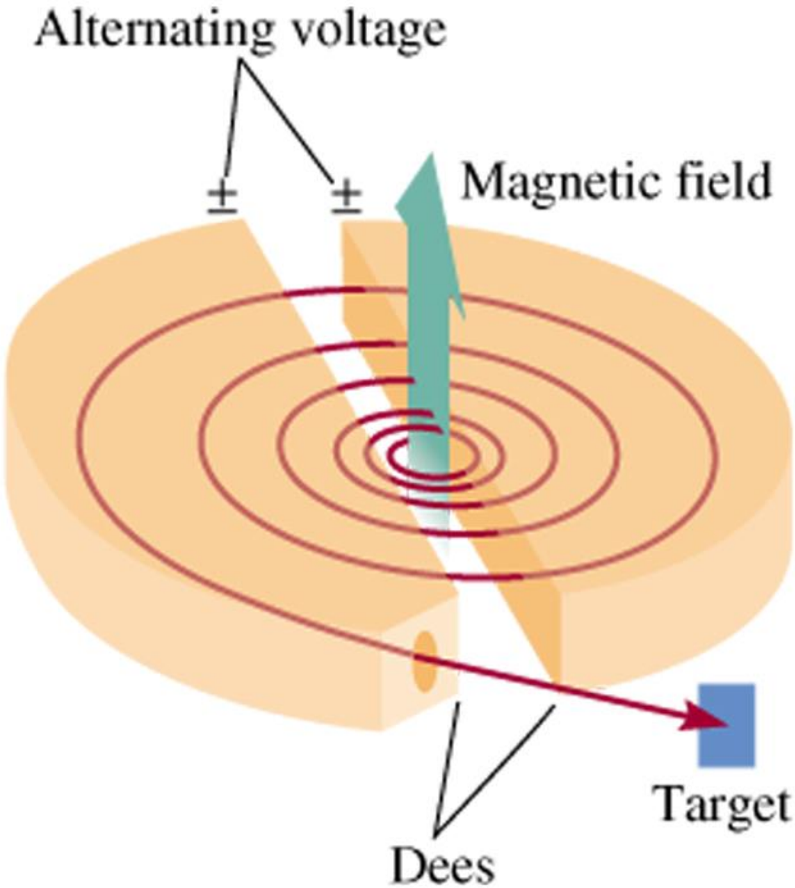
= 2.608 Mev

Nuclear binding energy per nucleon vs Mass number



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

Nuclear Transmutation



Cyclotron Particle Accelerator

$$^{14}_{7}N + ^{4}_{2}\alpha \longrightarrow ^{17}_{8}O + ^{1}_{1}p$$

$$^{27}_{13}Al + ^{4}_{2}\alpha \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

$$^{14}_{7}N + ^{1}_{1}p \longrightarrow ^{11}_{6}C + ^{4}_{2}\alpha$$

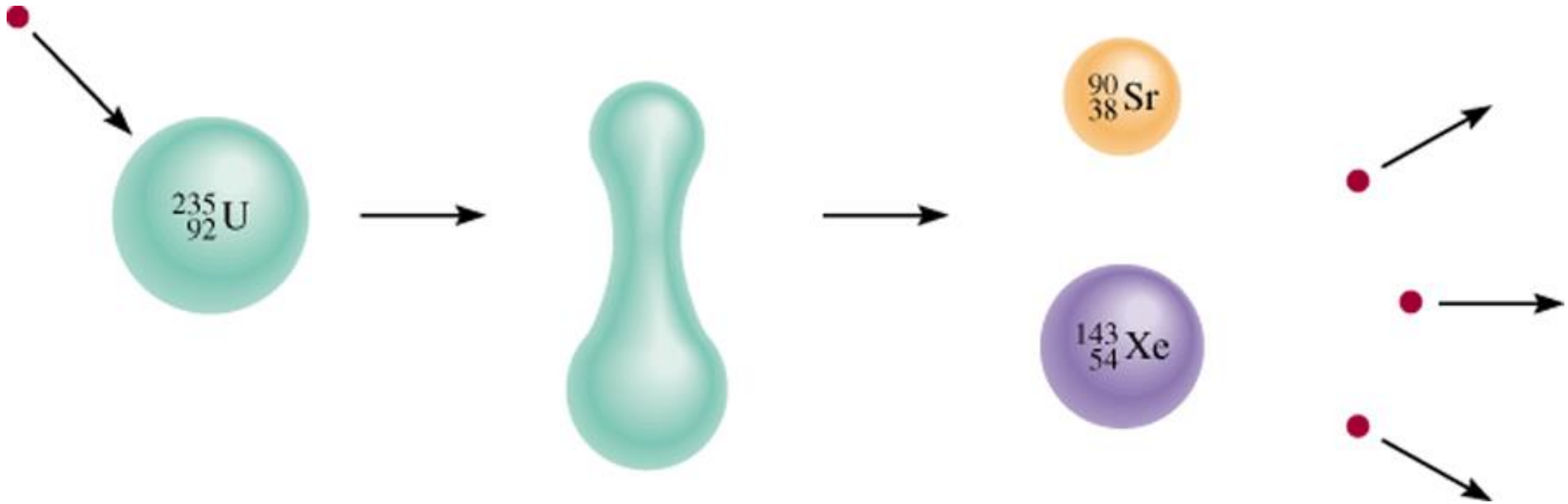
Nuclear Transmutation

TABLE 23.4

The Transuranium Elements

Atomic Number	Name	Symbol	Preparation
93	Neptunium	Np	$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{93}Np + ^{0}_{-1}\beta$
94	Plutonium	Pu	$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$
95	Americium	Am	$^{239}_{94}Pu + ^{1}_{0}n \longrightarrow ^{240}_{95}Am + ^{0}_{-1}\beta$
96	Curium	Cm	$^{239}_{94}Pu + ^{4}_{2}\alpha \longrightarrow ^{242}_{96}Cm + ^{1}_{0}n$
97	Berkelium	Bk	$^{241}_{95}Am + ^{4}_{2}\alpha \longrightarrow ^{243}_{97}Bk + 2^{1}_{0}n$
98	Californium	Cf	$^{242}_{96}Cm + ^{4}_{2}\alpha \longrightarrow ^{245}_{98}Cf + ^{1}_{0}n$
99	Einsteinium	Es	$^{238}_{92}U + 15^{1}_{0}n \longrightarrow ^{253}_{99}Es + 7^{0}_{-1}\beta$
100	Fermium	Fm	$^{238}_{92}U + 17^{1}_{0}n \longrightarrow ^{255}_{100}Fm + 8^{0}_{-1}\beta$
101	Mendelevium	Md	$^{253}_{99}Es + ^{4}_{2}\alpha \longrightarrow ^{256}_{101}Md + ^{1}_{0}n$
102	Nobelium	No	$^{246}_{96}Cm + ^{12}_{6}C \longrightarrow ^{254}_{102}No + 4^{1}_{0}n$
103	Lawrencium	Lr	$^{252}_{98}Cf + ^{10}_{5}B \longrightarrow ^{257}_{103}Lr + 5^{1}_{0}n$
104	Rutherfordium	Rf	$^{249}_{98}Cf + ^{12}_{6}C \longrightarrow ^{257}_{104}Rf + 4^{1}_{0}n$
105	Dubnium	Db	$^{249}_{98}Cf + ^{15}_{7}N \longrightarrow ^{260}_{105}Db + 4^{1}_{0}n$
106	Seaborgium	Sg	$^{249}_{98}Cf + ^{18}_{8}O \longrightarrow ^{263}_{106}Sg + 4^{1}_{0}n$
107	Bohrium	Bh	$^{209}_{83}Bi + ^{54}_{24}Cr \longrightarrow ^{262}_{107}Bh + ^{1}_{0}n$
108	Hassium	Hs	$^{208}_{82}Pb + ^{58}_{26}Fe \longrightarrow ^{265}_{108}Hs + ^{1}_{0}n$
109	Meitnerium	Mt	$^{209}_{83}Bi + ^{58}_{26}Fe \longrightarrow ^{266}_{109}Mt + ^{1}_{0}n$

Nuclear Fission



$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{90}_{38}Sr + ^{143}_{54}Xe + 3^{1}_{0}n + \text{Energy}$$

Energy = [mass ^{235}U + mass n – (mass ^{90}Sr + mass ^{143}Xe + 3 x mass n)] x c^2

Energy = 3.3×10^{-11} J per ^{235}U

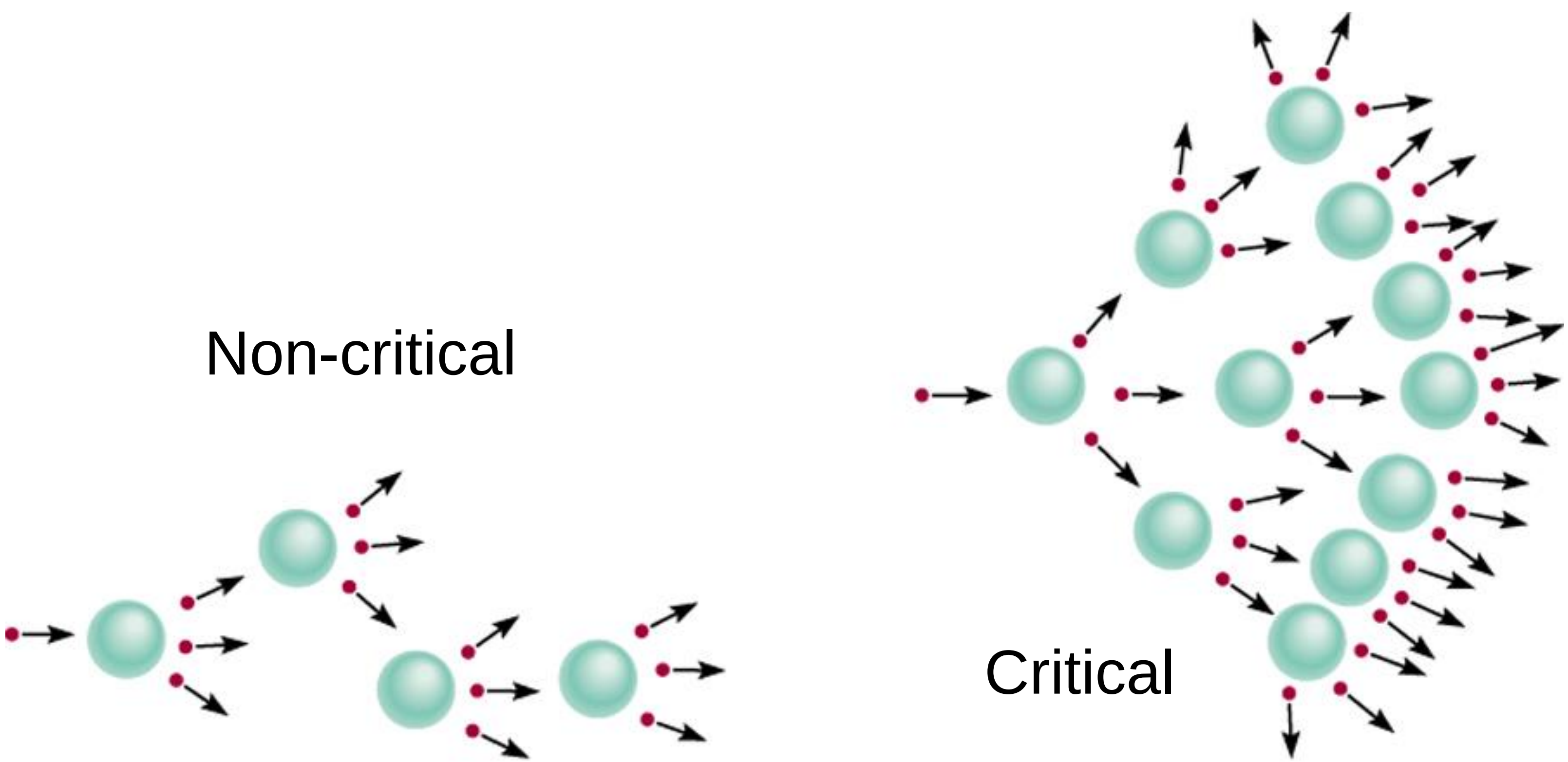
= 2.0×10^{13} J per mole ^{235}U

Combustion of 1 ton of coal = 5×10^{7} J

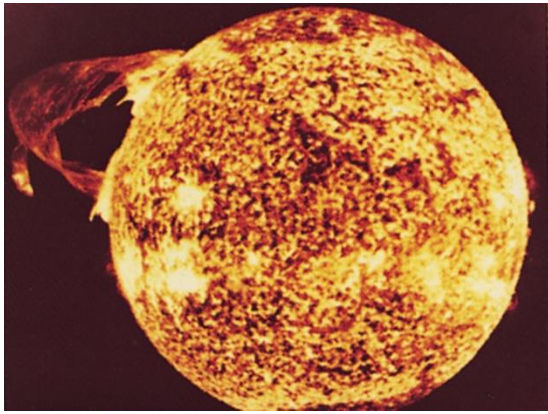
Nuclear Fission

Nuclear chain reaction is a self-sustaining sequence of nuclear fission reactions.

The minimum mass of fissionable material required to generate a self-sustaining nuclear chain reaction is the ***critical mass***.



Nuclear Fusion



Fusion Reaction	Energy Released
${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{1}H + {}^{1}_{1}H$	6.3×10^{-13} J
${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$	2.8×10^{-12} J
${}^{6}_{3}Li + {}^{2}_{1}H \longrightarrow 2\ {}^{4}_{2}He$	3.6×10^{-12} J

Tokamak magnetic plasma confinement