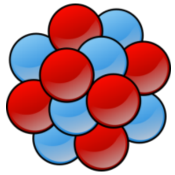
Composition of a nucleus :



Nucleus consists of protons and neutrons

Protons are positively charged (q = 1.6 x 10^{-19} C)

Neutrons are electrically neutral

Mass of proton is almost equal (but slightly less) than that of a neutron.

m_{proton} = 1.6726 x 10^{-27} kg or 1.0072 amu (938.27 MeV)

m_{neutron} = 1.6749 x 10^{-27} kg or 1.0086 amu (939.56 MeV)

1 amu is a unit of mass in nuclear physics. It is the mass of 1/12$^{\text{th}}$ of a C-12 atom

1 amu = 1.6605 x 10^{-27} kg (931.494 ≈ 931.5 MeV)

Discovery of neutron

Bombarding beryllium nuclei with alpha-particles resulted in emission of neutral radiation. This neutral radiation was found to knock out protons from light nuclei such as helium, carbon and nitrogen.

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

It was assumed that the neutral radiation was that of photons (the only neutral radiation known at that time). Applying the laws of conservation of energy and momentum it was proved that the neutral radiation could not be photons as the energy of such photons would have to be much higher than the initial energy i.e. from the bombardment of beryllium nuclei with α-particles.

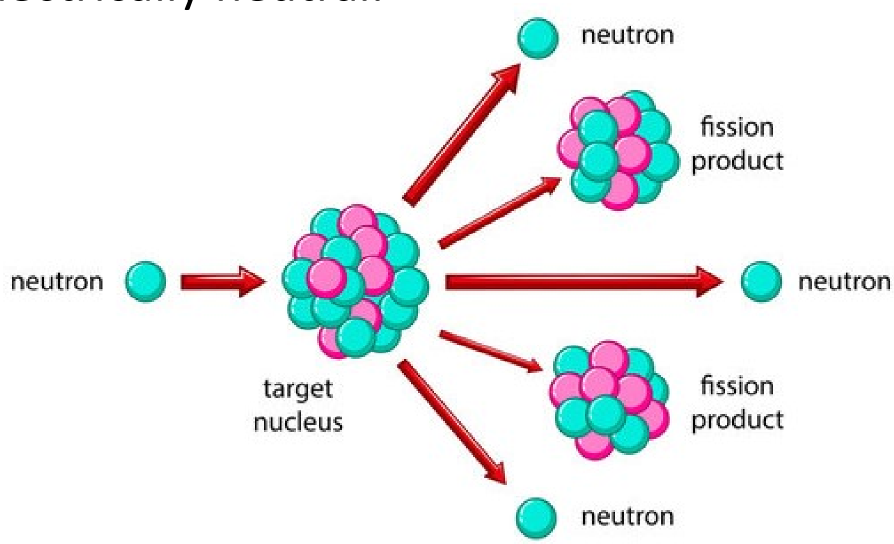
James Chadwick assumed that the neutral radiation consists of a new type of neutral particles called neutrons. Applying the laws of conservation of energy and momentum, he was able to determine the mass of new particle 'as very nearly the same as mass of proton'.

Chadwick was awarded the 1935 Nobel Prize in Physics for his discovery of the neutron.

A free neutron is unstable. It decays into a proton, an electron and a antineutrino. It has a mean life of about 1000s. A neutron is stable inside the nucleus

Properties of neutron $^{1}_{0}n$

- Mass of neutron is nearly equal to that of proton
- Mass of neutron 1.6749×10^{-27} kg or 1.0086 amu
- Energy equivalent of neutron is 939.56 MeV
- A free neutron is unstable. It decays into a proton, an electron and a antineutrino. It has a mean life of about 1000s.
- Neutron is stable inside the nucleus.
- Neutron does not cause ionization as it is electrically neutral.
- Neutrons are best projectiles for initiating nuclear reactions because they are not repelled by the positive charge of the nucleus. They can enter the nucleus and thus cause instability in the nucleus leading to nuclear reaction



Notation of a nucleus and types of nuclei

A : Mass number (number of protons + neutrons)

Z : Atomic number (number of protons)

Representation of a nucleus

Mass number

Symbol of nucleus

$$^{A}_{Z}X$$

Atomic number

Isotopes : Nuclei with same number of protons

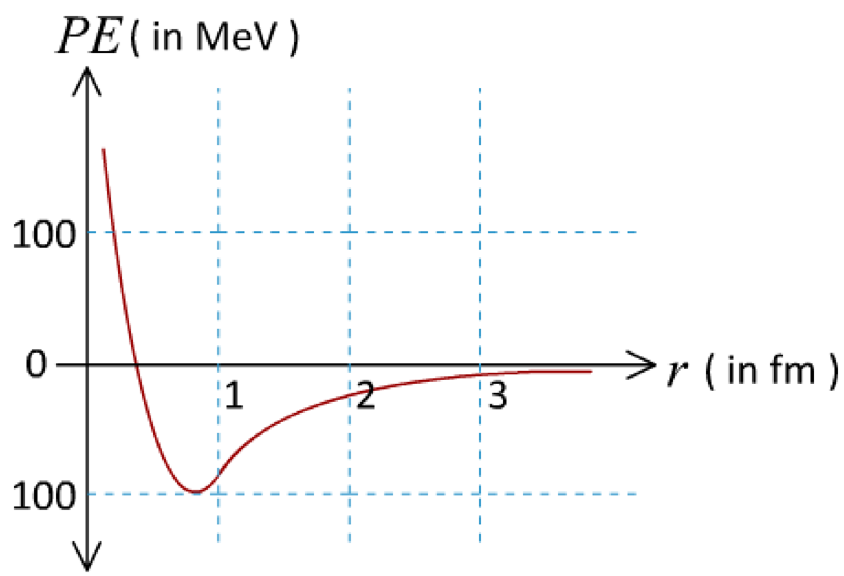
Isotones : Nuclei with same number of neutrons

Isobars : Nuclei with same number of nucleons

Isomers : Different excited states of a nucleus

Nuclear forces :

- Nuclear forces are the forces that bind the nucleus.
- They are short range forces with a range of about a fermi i.e. 10^{-15} m
- They are the strongest forces in nature. They are stronger than electrostatic repulsive forces between protons at such small distances.
- Nuclear forces are saturated forces i.e. nuclear force falls rapidly to zero for distances beyond a few fermi. This results in constant binding energy per nucleon.
- Nuclear forces are charge independent and spin dependent



At a distance of 0.8fm PE is minimum. This implies that for distance less than 0.8fm nuclear forces are repulsive and for distances more than 0.8fm, nuclear forces are attractive.

Nuclear radius, volume and density

Nuclear radius is given by

$\boxed{R = R_o A^{1/3}}$ where $R_o = 1.2$ fm

Volume of a nucleus

Assuming nucleus to be spherical in shape, volume is given by

$$V = \frac{4}{3}\pi\left(R_o A^{1/3}\right)^3$$

$$\boxed{V = \frac{4}{3}\pi R_o^{\,3} A}$$

Volume of a nucleus is directly proportional to its mass number (A)

Density of a nucleus

$$\rho = \frac{M}{V}$$

$$\rho = \frac{A\, m_{\text{amu}}}{4/3\, \pi R_o^{\,3} A}$$

$$\boxed{\rho = \frac{3\, m_{\text{amu}}}{4\,\pi R_o^{\,3}}}$$

From the above relation it is observed that density of nucleus is same for any nucleus (i.e. independent of mass number)

Nuclear density is much higher than the density of the material as mass of the nucleus is confined to a very small region i.e in a sphere of radius of the order of fermi.

Mass defect and binding energy :

Mass defect is the difference of sum of masses of nucleons and mass of the nucleus.

$$\Delta m = \left[Z \times m_{\text{p}} + (A - Z) \times m_{\text{n}} \right] - M_{\text{nucleus}}$$

$$\Delta m = \left[Z \times m_{\text{H}} + (A - Z) \times m_{\text{n}} \right] - M_{\text{atom}}$$

Z = number of protons

m_{p} = mass of each proton

M_{nucleus} = Mass of nucleus

M_{atom} = Mass of atom

$(A - Z)$ = number of neutrons

m_{n} = mass of each neutron

m_{H} = mass of a hydrogen atom

Binding energy is the energy released in formation of nucleus. Using Einstein's mass energy equivalence,

$$BE = \Delta m c^2$$

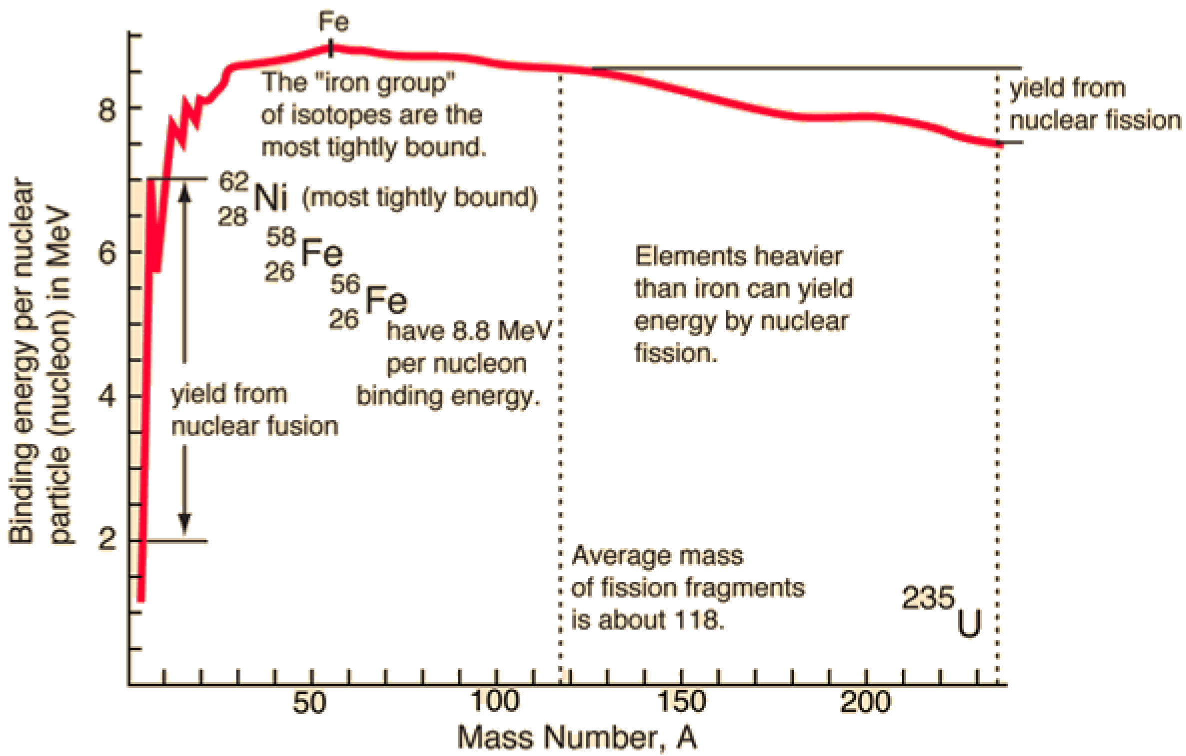
If mass defect is given in amu then BE is given by $BE = \Delta m \times$ 931.5MeV

Packing fraction :

Packing fraction is defined as binding energy per nucleon.

$$\text{packing fraction} = \frac{BE}{A}$$

Higher packing fraction implies greater stability.



- Very heavy nuclei may undergo fission to form relatively light nuclei
- Very light nuclei may undergo fusion to form relatively heavy nuclei
- Nuclei such as Fe of moderate mass number have the largest stability
- Presence of spikes indicate the possibility of shell like structure in arrangement of nucleons

Neutron proton ratio and radioactivity

Nuclear forces are of limited range as a result of which each nucleon interacts strongly only with its nearest neighbors. With increase in mass number, the distance between nucleons increases. Coulomb repulsion between protons, which acts over a longer range, results in high repulsion. Therefore heavy nuclei are unstable and exhibit natural radioactivity.

Activity (A) :

It is defined as the number of nuclei decaying (or disintegrating) per unit time.

$$\boxed{A = \frac{\mathrm{d}N}{\mathrm{d}t}}$$

- SI unit of activity is becquerel (Bq) defined as one decay per second.
- 1 curie (Ci) : It is a non-SI unit of activity and it is defined as 3.7×10^{10} disintegrations per second

Activity of a sample is directly proportional to the number of un-decayed nuclei at that instant of time

$$\boxed{\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N}$$

Negative sign indicates decreasing number of un-decayed nuclei.

λ is called decay constant.

SI unit of λ is s^{-1}

Radioactive decay law :

Consider a sample having N_o number of initial undecayed nuclei. After a time interval t net N be the number of undecayed nuclei. Activity of the sample at that instant of time is

$$\frac{dN}{dt} = -\lambda N$$

$$\frac{dN}{N} = -\lambda\, dt$$

Integrating the above equation

$$\int_{N_o}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

$$[\ln N]_{N_o}^{N} = -\lambda t$$

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

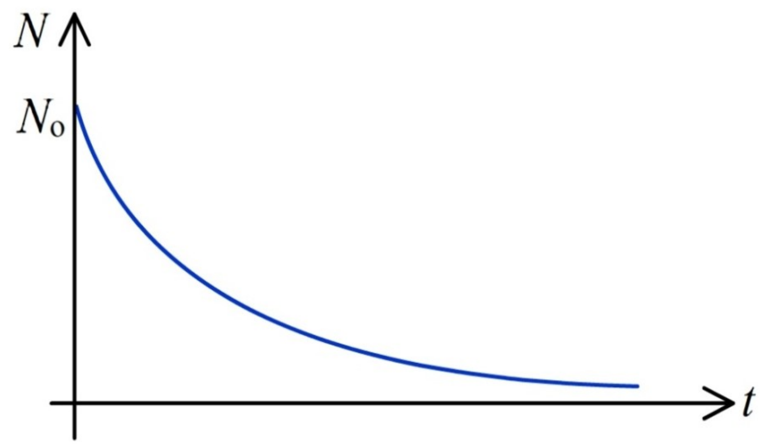
$$\ln \frac{N}{N_o} = -\lambda t$$

$$\ln \frac{N}{N_o} = -\lambda t$$

Taking antilog we get

$$\frac{N}{N_o} = e^{-\lambda t}$$

$$\boxed{N = N_o\, e^{-\lambda t}}$$



Half life ($T_{1/2}$):

Time taken for half the nuclei in a sample to decay is called half life

Using the radioactive decay law we get

$$N = N_o e^{-\lambda t}$$

Considering that half of the nuclei remain undecayed in a time $T_{1/2}$

$$\frac{N_o}{2} = N_o e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

$$2 = e^{\lambda T_{1/2}}$$

Taking log on both sides we get

$$\ln 2 = \lambda T_{1/2}$$

$$\boxed{T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}}$$

In each time interval equal to $T_{1/2}$ the number of un-decayed nuclei decreases to half the previous level. If time interval (t) is an integral multiple (n) of half lives, then the number of un-decayed nuclei is given by

$$\boxed{\frac{N_o}{2^n}}$$ where $t = n \times T_{1/2}$

Mean life (τ)

Average life time of all the nuclei in a sample is defined as the average of the life times of all nuclei in the sample.

$$\boxed{\tau = \frac{1}{\lambda}}$$

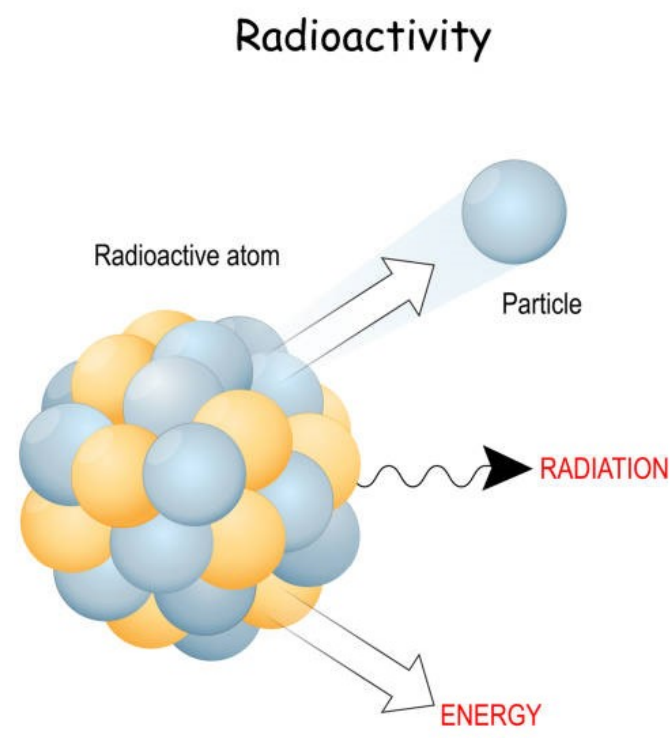
Relation between $T_{1/2}$ and τ

$$\boxed{T_{1/2} = 0.693 \times \tau}$$

Note : All nuclear decays are statistical and random in nature.
$T_{1/2}$ and τ cannot be attributed to a single nucleus.

Different kinds of nuclear decay

Isotopes of nuclei and some heavy nuclei may be unstable. Such unstable nuclei attain stability by emission of particles of different types. These emissions are accompanied by release of energy and the nucleus is said to undergo radioactive decay or disintegration.

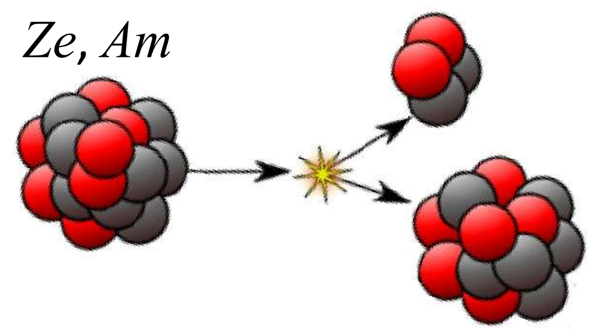


- Alpha decay (α)
- Beta decay (β)
- Gamma decay (γ)
- Positron emission
- Neutron emission

The nuclei emitting the particle is called the *parent nucleus*. The nucleus formed after the decay is called *daughter nucleus*.

Alpha decay (α)

Alpha particle is doubly ionized He nuclei



Charge of α particle : $2e$

Mass of α particle : 4 amu

General equation

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He}$$

Example

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

- With emission of beta particle atomic number of nucleus decreases by 2 and mass number of nucleus decreases by 4
- α - particles are effected by $\boldsymbol{E}$ and $\boldsymbol{B}$
- α - particles cause ionization of gases
- α - particles have least penetration power
- α - particles effect photographic plates

Beta decay (β)

Charge of β particle : $\pm e$ Mass of β particle : m_e

The two types of beta decay are β^- decay and β^+ decay

$\text{n} \rightarrow \text{p} + \text{e}^- + \bar{\nu}$ β^- decay is involves conversion of neutron to proton

$\text{p} \rightarrow \text{n} + \text{e}^+ + \nu$ β^+ decay is involves conversion of proton to neutron

- In both types of beta decay, mass number of nucleus remains constant where as its atomic number changes by 1.
- β^- decay is accompanied by emission of an antineutrino
- β^+ decay is accompanied by emission of a neutrino

General equation

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A}_{Z\pm1}X + {}^{\pm}\beta + \nu \text{ (or } \bar{\nu} \text{)}}$$

Examples

$${}^{32}_{15}\text{P} \rightarrow {}^{32}_{16}\text{S} + \text{e}^- + \bar{\nu}$$

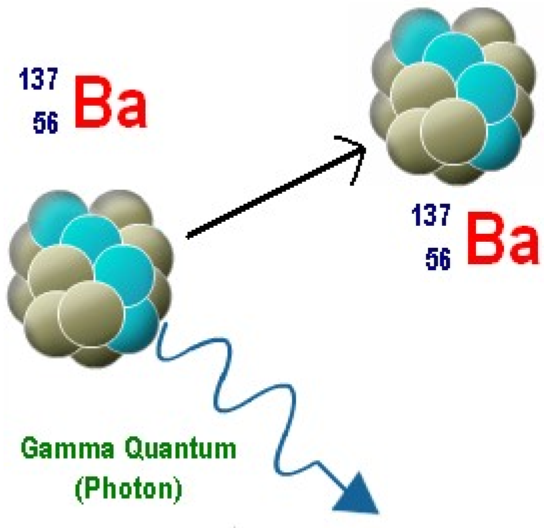
$${}^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + \text{e}^+ + \nu$$

Beta decay (β)

- All β particles emitted do not have the same energy because β decay is accompanied by emission of an antineutrino which carries of a part of momentum and energy released in the process.
- Neutrinos are neutral particles with very small (possibly, even zero) mass compared to electrons. They have only weak interaction with other particles and therefore very difficult to detect.
- A free neutron decays to proton. Decay of proton to neutron is possible only inside the nucleus, since proton has smaller mass than neutron.

Gamma decay (γ)

Gamma rays are $e.m.$ rays of very high frequency.



- Gamma rays are emitted during de-excitation of nuclei from higher excited state to lower excited state or ground state.
- With emission of γ rays, atomic number and mass number remain constant.
- γ rays are not effected by $\boldsymbol{E}$ and $\boldsymbol{B}$
- γ rays cannot cause direct ionization of gases
- γ rays have very high greater penetration power
- Energy of gamma rays is of the order of MeV