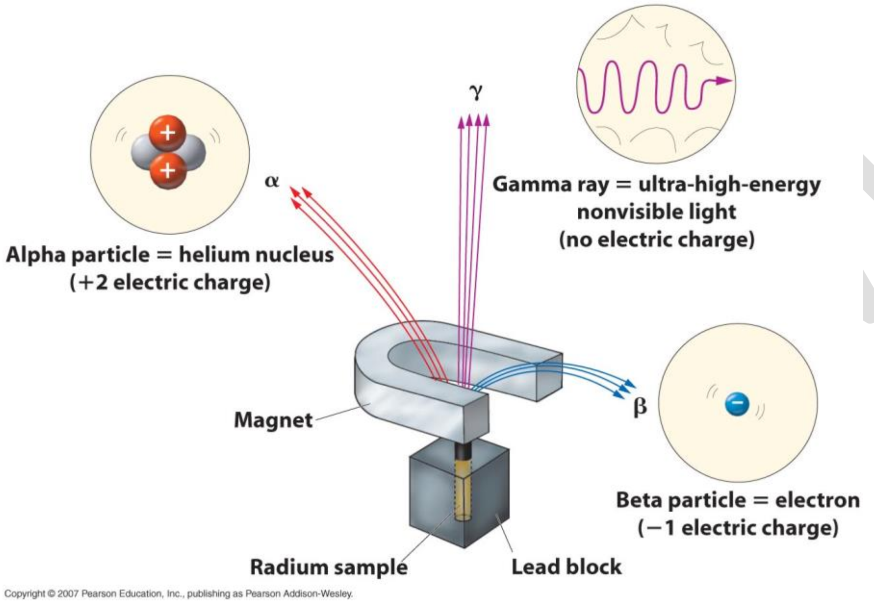
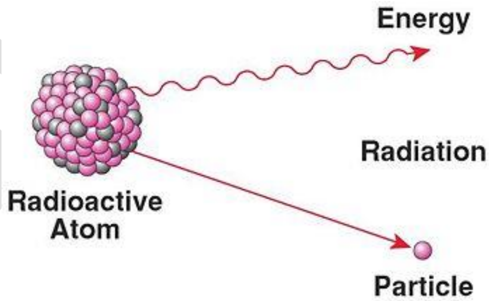
# Nuclear Chemistry

## History

- Henri Becquerel, 1896 with his associates Marie and Pierre Curie accidentally observed radioactivity of uranium salts that were fogging photographic film.
- M. Curie discovered radioactivity, the spontaneous disintegration of some elements into smaller pieces (1898 discovered the elements polonium and radium).
- Marie Curie a pioneer of Radioactivity, received Noble prize in Physics (1903) with H. Becquerel and her husband, P. Curie, and Nobel Prize in Chemistry (1911).




- E. Rutherford (1903) established that radioactive elements emit three types of radiations designated by alpha (α), beta (β) and gamma (γ) rays.
- Radioactive Decay is the spontaneous disintegration of a nucleus into a slightly lighter nucleus, accompanied by emission of particles, electromagnetic radiation, or both




## α -particle Emission

- α decay is a process in which an unstable nucleus transforms itself into a new nucleus by emitting an alpha particle ( a helium nucleus with charge +2, $^{4}_{2}He$).
- On α decay, the present nucleus is transformed into a daughter nucleus with mass number smaller by 4 and atomic number smaller by 2 units
- α decay is not much penetrating but exhibits very high ionizing power.
- α decay is most common in elements with an atomic number greater than 83. Examples of nuclei that undergo α decay are Th-230 and U-238.

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$
$$^{236}_{92}U \rightarrow ^{96}_{39}Y + ^{136}_{53}I + 4\,^{1}_{0}n$$

**β-particle Emission**

- β decay is the process of spontaneous emission of an electron or positron from nucleus.
- β particle emission is due to the result of decay of neutron into proton and electron.
- β emission increases the atomic number by one by adding one proton (simultaneously one neutron is also lost to make mass of the daughter and parent isotope similar).
- β decay is more penetrating than the alpha decay because the particles are smaller but less penetrating than gamma decay.
- β decay is most common in elements with a high neutron to proton ratio.
- The nuclear symbol representing an electron (β particle) is ${}^{0}_{-1}\beta$ or ${}^{0}_{-1}e$.

$${}^{131}_{53}I \rightarrow {}^{132}_{54}Xe + {}^{0}_{-1}e$$

**γ-particle emission**

- γ rays are electromagnetic waves (no mass and no charge) that release electromagnetic energy.
- The process of emission of a γ ray photon during the radioactive disintegration of a nucleus is called γ decay and on γ decay the mass number and the atomic number of the daughter nucleus remain unchanged and no new element is formed.
- After an alpha or beta decay the daughter nucleus is usually left in the excited state. It attains the ground state by single or successive transition by emitting one photons. A high energy γ ray is given off when the parent isotope falls into a lower energy state.
- γ radiation is the most penetrating of all and γ radiation is simply a loss of energy by the nucleus (de-excitation).
- In the alpha decay of U-238, two γ rays of different energies are emitted in addition to the α particle.

**Neutrino**

- It is a subatomic particle with very low mass (around electron) and no electrical charge.
- Neutrinos travel at almost the speed of light and many quadrillions of them penetrate your body every second.
- Due to its low mass and no charge, it interacts only slightly with atoms and can penetrate several light years of densely packed matter before interacting with an atom. For this reason, they are very difficult to detect.

**Positron**

- Positron is a particle that is emitted from the nucleus when a proton is converted into a neutron. Positron has the same mass as but opposite charge than an electron

$${}^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{1}e$$

**Electron Capture (K-Capture)**

- During this process, one of the protons in the atom's nucleus pulls an orbiting electron and neutralizes both the electron and itself.
- This causes the atom to decay and become a different element with the same atomic mass.

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

**Antineutrino**

- Antineutrinos are the antiparticles of neutrinos. The antineutrino is an elementary subatomic particle with infinitesimal mass and with no electric charge.

| Name | Symbol(s) | Representation | Description |
|---|---|---|---|
| Alpha particle | $^{4}_{2}He$ or $^{4}_{2}\alpha$ |  | (High-energy) helium nuclei consisting of two protons and two neutrons |
| Beta particle | $^{0}_{-1}e$ or $^{0}_{-1}\beta$ |  | (High-energy) electrons |
| Positron | $^{0}_{+1}e$ or $^{0}_{+1}\beta$ |  | Particles with the same mass as an electron but with 1 unit of positive charge |
| Proton | $^{1}_{1}H$ or $^{1}_{1}p$ |  | Nuclei of hydrogen atoms |
| Neutron | $^{1}_{0}n$ |  | Particles with a mass approximately equal to that of a proton but with no charge |
| Gamma ray | $\gamma$ |  $\gamma$ | Very high-energy electromagnetic radiation |

**Structure of nucleus**

- The nucleus is positively charged and consists of protons and neutrons, which are bound together by very strong short-range forces.
- The particles which make up the nucleus are collectively called as nucleons (p+n).
- The radius of a nucleus is incredibly small, around $10^{-15}$ m (1 fm).
- Most of the mass of an atom is concentrated in the nucleus and hence density is very high, approximately 2.4 x $10^{14}$ $gcm^{-3}$.
- The number of protons is the atomic number (Z) and the number of protons and neutrons together is effectively the mass number of the atom (A). For example, $^{228}{}_{88}Ra$ (88 = atomic number = number of protons = number of electrons and 228 = total number of protons and neutrons).

**Nuclear size**

- An approximate idea about the size of the nucleus was obtained from the scattering of α-particles.
- The approximate radius of a nucleus is estimated to be around 5 x $10^{-15}$ fm.
- Scattering of fast neutrons gives more reliable information on the radius R of a nucleus as the distance from the nuclear centre within which nuclear forces act.
- This is given by the empirical relation $R = R_oA^{1/3}$ , $R_o$ is a constant equal to 1.4 fm and A is the mass number of the nucleus.

**Density of nucleus**

The radius of a nucleus is proportional to $A^{1/3}$

- Volume of the nucleus is given by 4/3 $\pi R^3$
- Correlating the above two, nucleus volumes are proportional to nuclear masses and hence all nuclei should have approximately the same density.
- Since, almost the entire mass of the atom is located inside the small nucleus, the density of the nucleus would be very high (around $10^{11}$ kg/cc)

**Q. Calculate the density of the Al nucleus if its radius is 5 fm.**

**Physical properties of proton and neutron**

- . J. Thomson discovered a negatively charged particle called the electron.

- Rutherford proposed that these electrons orbit a positive nucleus. In a subsequent experiment he found that there is a smaller positively charged particles in the nucleus called proton. (Goldstein also contributed).
- There is a third subatomic particle known as neutron (J. Chadwick, 1932).
- A neutron has about the same diameter as a proton.
- Together with neuron they make up virtually all the mass of an atom.
- Mass of neutron is slightly more than the mass of proton, but they are both much more massive than electron (approx. 2000 times)
- Protons and neutrons are bound together because of the strong nuclear forces.

| Particle | Charge | Relative charge | Mass | Relative mass | Location |
|---|---|---|---|---|---|
| Electron | $-1.6 \times 10^{-19}$ C | -1 | $9.050 \times 10^{-28}$ g | 0 | Orbital |
| Proton | $1.6 \times 10^{-19}$ C | +1 | $1.672 \times 10^{-24}$ g | 1 amu | Nucleus |
| Neutron | neutral | 0 | $1.674 \times 10^{-24}$ g | 1 amu | Nucleus |

**Isotopes of elements**

- The nuclei of an element which only differ in the number of neutrons keeping the number of protons same are termed as isotopes. Consequently, mass number differs.
  Isotopes of hydrogen(Z=1): ${}^{1}_{1}H_{0}$, ${}^{2}_{1}H_{1}$, ${}^{3}_{1}H_{2}$
  Isotopes of chlorine(Z=17): ${}^{35}_{17}Cl_{18}$, ${}^{36}_{17}Cl_{19}$, ${}^{36}_{17}Cl_{20}$
  Isotopes of uranium(Z=92): ${}^{233}_{92}U_{141}$, ${}^{235}_{92}U_{143}$, ${}^{238}_{92}U_{146}$
- The isotopes are chemically indistinguishable because of their same atomic number, but their radioactive properties and other physical properties which depend on atomic mass are different.
- There are two main types of isotopes

**Stable isotopes**

- Stable isotopes have a stable proton-neutron combination and do not display any sign of decay (Deuterium, Carbon-13, Oxygen-18 etc).
- They do not produce radiation or its associated health risks.

**Radioactive isotopes**

- Radioactive isotopes have an unstable combination of protons and neutrons.
- These isotopes decay, emitting radiation that includes alpha, beta and gamma rays.
- These isotopes are classified according to their creation process: cosmogenic, anthropogenic and radiogenic. For example, Carbon-14, Tritium, Cobalt-60 etc.
- The radioactive isotope carbon-14 is used in radiocarbon dating.

**Benefits**

- Isotopes are used in nuclear weapons and energy, bone imaging, radiation therapy to treat cancer, radiocarbon dating etc.

**Discovery of isotopes**

- Evidence in favour of existence of isotopes emerged from two independent lines of research, the first being the study of radioactivity.
- The ores of radioactive elements U and Th had been found to contain small quantities of several radioactive substances such as ionium and mesothelium respectively.

- Ionium when mixed with thorium, could no longer be retrieved by chemical means alone. Similarly, mesothelium was shown to be chemically indistinguishable from radium. It concluded that ionium and mesothelium were not new elements after all, but rather new forms of old ones.
- Generalizing these English chemist F. Soddy in 1910 suggested that "elements of different atomic weights may possess identical chemical properties."
- H. N. McCoy and W. H. Ross later conclusively showed the method of isolating the radioactive isotope of uranium.
- J. J. Thomson and F. W. Aston, conducted many experiments to show that substances when ionized, had species that were much heavier than the main content.
- In 1931, H. Urey and G. M. Murphy discovered the effect of isotopes on atomic mass.

**Significance**

Substances occupying the same position in the periodic table and having the same chemical properties have differences because of their isotopic components. One significant difference is the mode of radioactive decay of similar elements occupying same place in the periodic table.

**Atomic weights and isotopes**

- The atomic weight of an element depends on the number of isotopes and their relative abundances. Presently, the atomic weight is expressed in atomic mass unit (amu) in C-12 scale, amu is exactly $1/12^{th}$ of the mass of a C-12 atom.

  1amu $=1.6603 \times 10^{-24}$ g
- Considering the isotope atomic weight is given by

  Atomic weight (amu)= $\sum(xiMi)/\sum x\ i$ where $\sum x\ i = 100$

  $x_i \rightarrow$percentage of abundance of the i $^{th}$ isotope having mass $M_i$ in amu.

  $M_i = 1.007581Z + 1.00898N$ (neglecting the mass defect and mass of electron)

  Z and N are no. of protons and neutrons in the i $^{th}$ isotope respectively.

  $m_p$= 1.007581 amu, $m_n$ = 1.00898 amu

  $M_i$ can be regarded as mass number for simplicity i.e.

  $M_i = A_i = Z+N$ ($A_i$ gives the mass number of the i $^{th}$ isotope)

  Thus, atomic weight= $\sum xiAi/\sum x$ i
- Abundance for the two isotopes of Cl, $^{35}$Cl and $^{37}$Cl are 75.4% and 24.6% respectively

  Therefore, atomic weight of chlorine = (75.4x35+24.6x37)/100 amu = 35.492 amu

**Note:** Atomic mass unit (amu) is also referred to as Dalton. 1 amu = 1 Dalton.

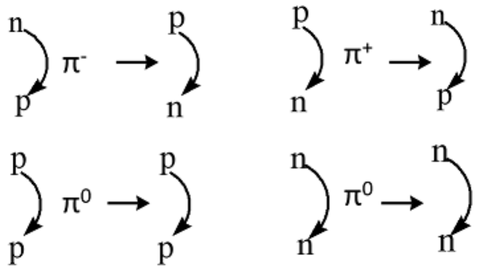
**Nuclear isomerism:**

- Pairs of nuclei with same atomic and mass numbers but different radioactive properties are known as nuclear isomers and the phenomenon is called nuclear isomerism.
- Bombardment of $^{79}$Br by slow neutrons produces $^{80}$Br. The $^{80}$Br undergoes β-decay with two half-lives viz. 4.5 hrs and 18 minutes respectively.
- These are attributed to two isomeric states of $^{80}$Br. The same nuclide produced by other means also shows this isomerism.

**Forces in the nucleus**

- Protons have a positive charge. A nucleus with two or more protons will experience electrostatic repulsion.
- In a stable nucleus, the attractive forces are greater than the repulsive forces.

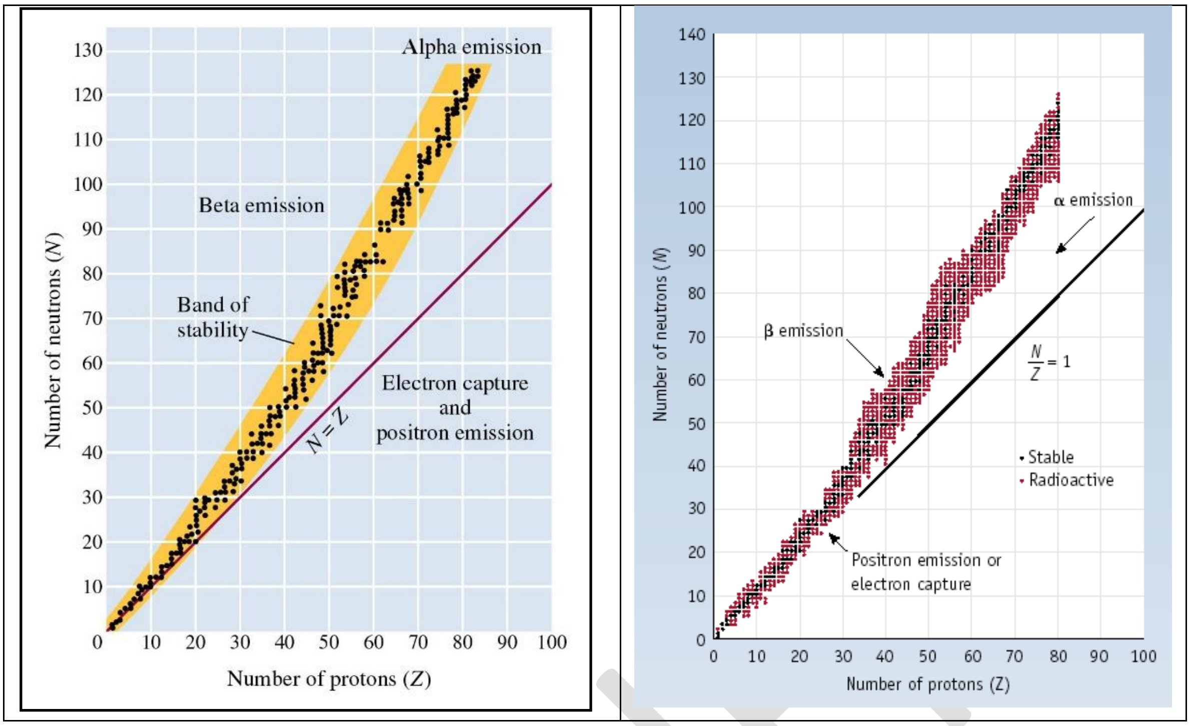
- In unstable nucleus the repulsive forces exceed the attractive forces and spontaneous fission occurs.
- The attractive forces in the nucleus cannot be electrostatic because there are no oppositely charged particles and the forces only act over a very short range (2-3 fm).
- The attractive force does not depend on the charge as the attractive force binds protons to protons, protons to neutrons and neutrons to neutrons.
- Two nuclear particles is proposed to be held together by sharing a particles.
- The particle exchanged is called a π meson. It may be positive ($\pi^+$), negative ($\pi^-$) and neutral $\pi^0$.
- Exchange of $\pi^-$ or $\pi^+$ mesons accounts for the binding energy between neutrons and protons. The transfer of a charge converts a neutron to a proton or vice-versa.
- The resultant attractive forces are indicated below




- A $\pi^0$ meson is exchanged between two protons or between two neutrons.
- The attractive forces between p-n, n-n, and p-p are probably similar in strength.
- Different types of mesons have similar mass. The mass of a $\pi^0$ meson is 264 times than that of an electron and that of both $\pi^+$ and $\pi^-$ mesons are 273 times that of electron.
- All mesons are very unstable outside the nucleus.
- Number of charged particles in a nucleus remains constant. But meson transfer is continuous.
- The transformation of neutrons into protons and vice-versa are first order reaction.
- In a stable nucleus, these two changes are in equilibrium.

**Nuclear Stability**

- Depends on the neutron to proton ratio. Generally, a nucleus with neutron:proton ratio 1 is stable.
- For atoms with Z < 20, equal number of protons and neutrons makes the nucleus stable.
- For atoms with Z > 20, more neutrons than protons make the nucleus stable. As the nucleus gets larger, greater number of neutrons are required for stabilization.
- An unstable nucleus undergoes decay, nature of decay depends on the cause of instability.
- The shaded region in the figure shows what nuclides would be stable, the so-called belt of stability.




- Nuclei above this belt have too many neutrons. They tend to decay by emitting beta particles.
- Nuclei below the belt have too many protons. They tend to become more stable by positron emission or electron capture.
- Nuclei with atomic number > 83 are radioactive. These nuclei tend to decay by emitting alpha particles.
- Large radioactive nuclei cannot stabilize by undergoing only one nuclear transformation. They undergo a series of decays until they form a stable nuclide (often a nuclide of lead) (Radioactive Series).
- Nuclei with an even number of protons and neutrons tend to be more stable than nuclides that have odd numbers of these nucleons.

**Radioactivity**

- The phenomena of radioactivity were discovered by Henri Becquerel in 1896.
- Radioactivity is the phenomenon of spontaneous emission of radiation form a radioactive nucleus to form one or more nuclei with the release of energy. This is also known as natural radioactivity.
- The emitted radiations are alpha (α), beta (β) and gamma (γ) radiation. These radiations are active as they affect photographic plates and interact with electric and magnetic fields.
- Radioactivity may also be observed in some artificially obtained isotopes.
- Becquerel (Bq) is the SI unit of radioactivity. 1 Bq = 1 disintegration per second.
- Curie (Ci) has been used to measure radioactivity. This is defined as the quantity of a radioactive material which has a decay rate of $3.7 \times 10^{10}$ disintegration per second.
- that will have 37,000,000,000 transformations in one second. $3.7 \times 10^{10}$ Bq
- $3.7 \times 10^{10}$ Bq = 1 curie.

**Types of Radioactive Decay**

- There are **six common types** of radioactive decay.
- **Alpha emission**: Emission of a He-nucleus or alpha particle from the nucleus.

$$^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He$$

- **Beta emission**: Emission of a high-speed electron or β particle from the nucleus when a neutron is converted to a proton, electron, and neutrino. Neutrino is emitted in almost all nuclear transformation. Decreases N/P ratio.

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

- **Positron emission**: Emission of a positron from an unstable nucleus. This is equivalent to the conversion of a proton to a neutron and antineutrino. Increases N/P ratio.

$$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{1}e$$
$$^{95}_{43}Tc \rightarrow ^{95}_{42}Mo + ^{0}_{1}e$$

- **Orbital or K-electron capture**: The nucleus may capture an orbital electron and thus convert a proton a neutron with the emission of a neutrino. Increases N/P ratio.

$$^{1}_{1}p + ^{0}_{-1}e \rightarrow ^{1}_{0}n$$
$$^{40}_{19}K + ^{0}_{-1}e \rightarrow ^{40}_{18}N$$

- **Neutron emission:** Neutron emission reduces the N/P ratio. This form of decay is very rare and only occurs in highly energetic nucleus.

$$^{87}_{36}Kr \rightarrow ^{86}_{36}Kr + ^{1}_{0}n$$

- **Gamma emission**: Emission from an excited nucleus of a gamma photon, corresponding to radiation with a wavelength of about $10^{-12}$ m. In many cases, radioactive decay produces a product nuclide in a metastable excited state.

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

- **Proton emission:** Except for nuclei in a very high energy state, proton emission is unlikely as the energy need to remove a proton is about 8MeV.
- Nuclides to the left of the band have more neutrons than that needed for a stable nucleus. These nuclides tend to decay by beta emission because it reduces the neutron-to-proton ratio.
- Nuclides to the right of the band of stability have a neutron-to-proton ratio smaller than that needed for a stable nucleus. These nuclides tend to decay by positron emission or electron capture because it increases the neutron to proton ratio.

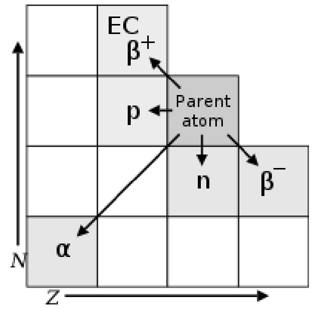
**Theory of radioactive disintegration**

- Rutherford and Soddy (1903) put forwarder the theory of radioactive disintegration.
- The theory is based on radioactive decay of different elements and quantitative correlation of rate of decay with the number of radioactive substances.
- According to this theory,
  -the atoms of a radioactive element are inherently unstable.
  -they disintegrate spontaneously and form atoms of new element which is different from its parent nucleus.
  -the new element formed may, in turn, be again radioactive and disintegrate further until atoms of stable element is formed.
- The disintegration theory has been proved to be successful in establishing the rate expression for radioactive decay process.

**Radioactive (group) displacement law**

- Emission of an α-particle produces an element which is four mass units lighter and the atomic number decreases by two. The daughter element is therefore two places to the left of the parent in the periodic table.

- When a β-particle is emitted the mass number remains the same. However, the atomic number increases by one and the new element is one place to the right of the parent in the period.




**Rate of radioactive disintegration**

- The rate of disintegration at any instant is proportional to the number of active nuclei present at that instant.
- If N is the number of active nuclei present at any instant and dN atoms disintegrate with time dt then the rate of disintegration is –dN/dt, negative indicates that N decreases with time. Therefore, according to law of rate of radioactive disintegration we have,

$$-\frac{dN}{dt} \propto N \quad (-sign\ is\ for\ disintegration)$$

$$\frac{dN}{dt} = -\lambda N - - - - - - - - (i)$$

$$where\ \lambda\ is\ decay\ constant$$

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

$$integrating$$

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

$$log_e N = -\lambda t + c - - - - - - (ii)$$

$$if\ t = 0\ and\ N = N_o$$

$$log_e N_o = c$$

$$now\ eqn\ ii\ becomes$$

$$log_e N = -\lambda t + log_e N_o$$

$$log_e N - log_e N_o = -\lambda t$$

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

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

or $\lambda = (2.303/t) \log (N_o/N)$

- The rate law indicates that a radioelement will take infinite time to decay completely (characteristics of a first order reaction).

**Half-life ($t_{1/2}$)**

- The half-life is the time required for a radioactive nucleus to decay to half of its initial amount.
- After one half-life there is 1/2 of original sample left.
- After two half-lives, there will be 1/2 of the 1/2 = 1/4 the original sample.

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

$$if\ N = \frac{N_o}{2}\ and\ t = t_{\frac{1}{2}}$$

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

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

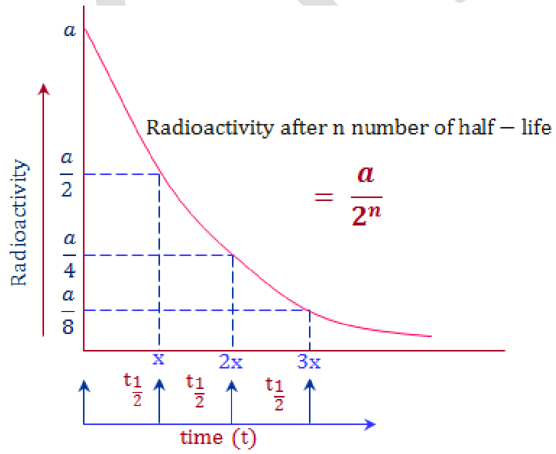
$$2 = e^{\lambda t_{\frac{1}{2}}}$$

$$log_e 2 = \lambda\ t_{\frac{1}{2}}$$

$$0.693 = \lambda\ t_{\frac{1}{2}}$$

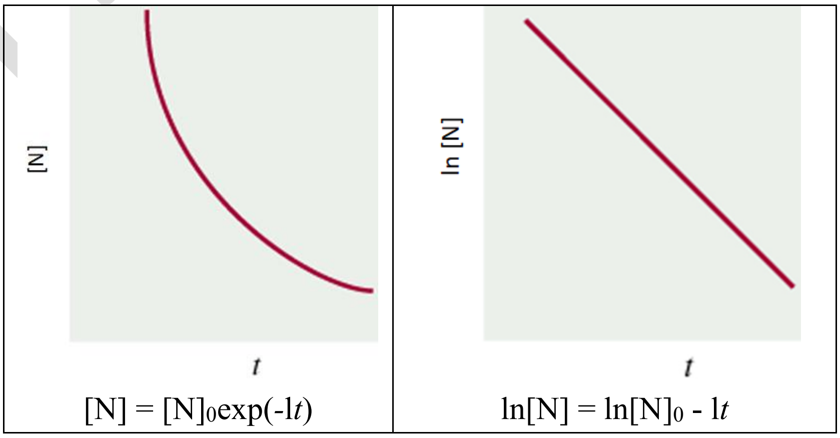
$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

- The half-life period is independent of amount of radioactive element present initially.
- This is true for any fractional life period. The fraction of radioactive elements becomes $1/2^n$ of the initial amount.




**Average life ($t_{av}$):** Time required for a decay of 36.8% of its original amount, $t_{av} = 1.44\ t_{1/2}$

**Kinetics of Radioactive Decay**



**Decay of parent and daughter nuclides: Radioactive equilibrium**

- When a radioactive nuclide A decays into another active nuclide B, the relative amounts of the parent (A) and daughter (B) at any time is determined by the relative magnitudes of the individual decay constants A and B.
  $-dN_A/dt = \lambda_A N_A = N_{oA}\exp(-\lambda_A t)$ and $dN_B/dt = \lambda_A N_A - \lambda_B N_B$
- If the parent is short lived than the daughter ($\lambda_A > \lambda_B$), the rate of growth of the daughter (rate of decay of the parent) is faster than its own disintegration rate. Rate of disintegration of the daughter and parent is different. There cannot be any equilibrium between the parent and the daughter.
- The daughter has a higher decay constant than the parent ($\lambda_A < \lambda_B$). Such radionuclides will reach a steady state after a certain time depending upon the magnitudes of $\lambda_A$ and $\lambda_B$.

**Transient equilibrium:** The relative amount of the daughter remains unchanged with time but the total activity (parent and daughter) slowly decreases. $N_B/N_A = \lambda_A/(\lambda_B - \lambda_A)$

**Secular equilibrium:** Permanent equilibrium is attained when the decay constant of the parent is negligibly small in comparison to decay constant of the daughter ($\lambda_A << \lambda_B$). $N_B/N_A = \lambda_A/\lambda_B$.

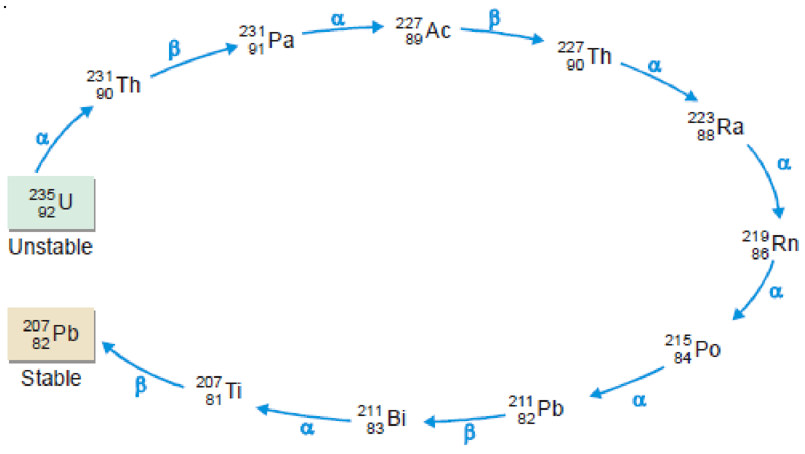
- The parent and the daughter have equal decay constant ($\lambda_A = \lambda_B$). The daughter first reaches a maximum at a time equal to the mean life of B ($1/\lambda_B$) and then decays. Such reactions are very rare.

**Radioactive disintegration series**

- The heavy radioactive elements may be grouped into four decay series. The common radioactive elements Th, U and Ac occur naturally and belong to three different series and named after them.
- They decay by a series of α and β emissions and finally with isotopes of Pb.
- **Thorium series:** It begins with $^{232}_{90}Th$ and ends with $^{208}_{82}Pb$. The mass numbers of the members in the series are given by 4n (n is an integer). So, this is called 4n series.
- **Uranium series:** It begins with $^{238}_{92}U$ and ends with $^{206}_{82}Pb$. The mass numbers of the members in the series are given by 4n + 2 (n is an integer). So, this is called 4n+2 series.
- **Actinium series:** It begins with $^{235}_{92}U$ and ends with $^{207}_{82}Pb$. The mass numbers of the members in the series are given by 4n + 3 (n is an integer). So, this is called 4n+3 series.
- **Neptunium series:** Consists of artificially prepared radionuclides. It begins with $^{214}_{94}Pu$ and ends with $^{209}_{83}Bi$. The mass numbers of the members in the series are given by 4n + 1 (n is an integer). So, this is called 4n+1 series.

THE URANIUM DISINTEGRATION SERIES

| NUCLIDE | PARTICLE PRODUCED | HALF-LIFE |
|---|---|---|
| Uranium-238 ( $^{238}_{92}U$ ) | α | $4.51 \times 10^9$ years |
| Thorium - 234 ( $^{234}_{90}Th$ ) | β | 24.1 days |
| Protactinium-234 ( $^{234}_{91}Pa$ ) | β | 6.75 hours |
| Uranium-234 ( $^{234}_{92}U$ ) | α | $2.48 \times 10^5$ years |
| Thorium-230 ( $^{230}_{90}Th$ ) | α | $8.0 \times 10^4$ years |
| Radium-226 ( $^{226}_{88}Ra$ ) | α | $1.62 \times 10^3$ years |
| Radon-222 ( $^{222}_{86}Rn$ ) | α | 3.82 days |
| Polonium-218 ( $^{218}_{84}Po$ ) | α | 3.1 minutes |
| Lead-214 ( $^{214}_{82}Pb$ ) | β | 26.8 minutes |
| Bismuth-214 ( $^{214}_{83}Bi$ ) | β | 19.7 minutes |
| Polonium-214 ( $^{214}_{84}Po$ ) | α | $1.6 \times 10^{-4}$ second |
| Lead-210 ( $^{210}_{82}Pb$ ) | β | 20.4 years |
| Bismuth-210 ( $^{210}_{83}Bi$ ) | β | 5.0 days |
| Polonium-210 ( $^{210}_{84}Po$ ) | α | 138.4 days |
| Lead-206 ( $^{206}_{82}Pb$ ) | — | Stable |




THE ACTINIUM SERIES

## Magic numbers

- Nuclei containing some specific number of protons and neutrons are exceptionally stable. These numbers are 2, 8, 20, 28, 50, 82 and 126. these numbers are known as magic numbers. (Haxel et al., (1949) now known as shell number).
- Elements having the largest number of isotopes contain 20 and 50 protons or 20, 50 and 82 neutrons ($_{50}Sn$ – 10 isotopes, $_{20}Ca$ – 6 isotopes).
- Nuclides with magic number of protons or neutrons or both are more abundant in nature. $^{40}_{20}Ca$, $^{88}_{38}Sr$, $^{89}_{39}Y$, $^{138}_{56}Ba$, $^{139}_{57}La$, $^{140}_{58}Ce$ are some examples.
- The nuclides $^{17}_{8}O$, $^{87}_{36}Kr$ and $^{137}_{54}Xe$ have one neutron in excess of magic number and possess unusual neutron emitting property.
- Nuclides with magic number of neutrons are reluctant to increase neutron content.
- The naturally occurring radioactive series end in $^{298}_{82}Pb$ (most stable isotope) that contains 82 protons and 126 neutrons.
- The energy of an emitted α-particle is exceedingly high when the decay product belongs to magic number family.
- The magic numbers correspond to closed shells of nucleons and accordingly nuclei with these numbers of nucleons are stable, just like elements with closed shell of extranuclear electrons – shell model.

**Mass defect and binding energy**

- A nucleus in an atom consists of protons and neutrons, together known as nucleons.
- The difference between the mass of a nucleus and the sum of the masses of the nucleons of which it is composed is called the mass defect.
- The mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.
- Mass defect ($\Delta m$) = Combined mass of nucleons - mass of nucleus
- This difference in mass occurs as a nucleus is more stable than it isolated components.
- The lost mass is converted into energy to form the nucleus. Consequently, when isolated nucleons assemble into a stable nucleus, energy is released.
- Thus, the amount of energy released when a nucleus forms from its component nucleons is called binding energy.
- This energy is equal to the lost mass while forming a nucleus, also known as mass defect.
- Similarly, if a nucleus is to be broken down into its constituent components, the energy applied will be equal to binding energy.
- The binding energy is given by, $E = \Delta mc^2$
- Let us consider an example of $^{4}_{2}He$

Mass number (A) = 4, atomic number (Z) = 2,

Number of protons=2, Number of neutrons= A-Z = 4-2 = 2

Expected mass = mass of proton x 2 + mass of neutron x 2

= 1.00727647 x 2 amu + 1.00866490 x 2 amu

= (2.0145528+2.0173298) amu

= 4.0318826 amu

But actual mass = 4.00150608 amu

Mass defect, $\Delta m$ = 4.0318826 amu - 4.00150608 amu = 0.0303766 amu

- This mass defect is released as energy when the nucleus is formed.

  1 amu= $1.6726219\times10^{-27}$kg.

  $\Delta m$ = 0.0303766 amu = $1.6726219 \times 10^{-27}$ x 0.0303766 kg = $0.058085\text{x}10^{-27}$ kg

Therefore, binding energy, $E = \Delta mc^2 = 0.058085 \times 10^{-27}$ kg x $(2.99792 \times 10^8 \text{ m/s})^2 = 0.528915 \times 10^{-11}$ J

- Nuclear binding energy is generally expressed in MeV.
- Nuclear binding energy or, $B = \Delta m \times 931$ MeV, where $\Delta m$ is mass defect.
- Not all nuclei are stable. The relative stability is obtained by comparing the binding energy per nucleon ($\overline{B}$), which is obtained by dividing the nuclear binding energy (B), by the mass number (A) of the nucleus.
- $\overline{B}$ gives a good indication for the stability of the concerned nuclides.
- It is always positive whether the nucleus is stable or not.
- It indicates that during the construction of the nucleus, some mass is always annihilated to bind the nucleons within the nucleus.
- The variation of $\overline{B}$ with the mass number (A) is shown by the binding energy curve.

**Heavy hydrogen or Deuterium ($^2$H):**

Atomic mass of $^2$H = 2.0141 amu.

Mass defect, $\Delta m$ = (1.0076 + 1.0089 – 2.0141) amu = $2.4 \times 10^{-3}$ amu.

Hence B = $2.4 \times 10^{-3}$ amu x 931 MeV = 2.23 MeV

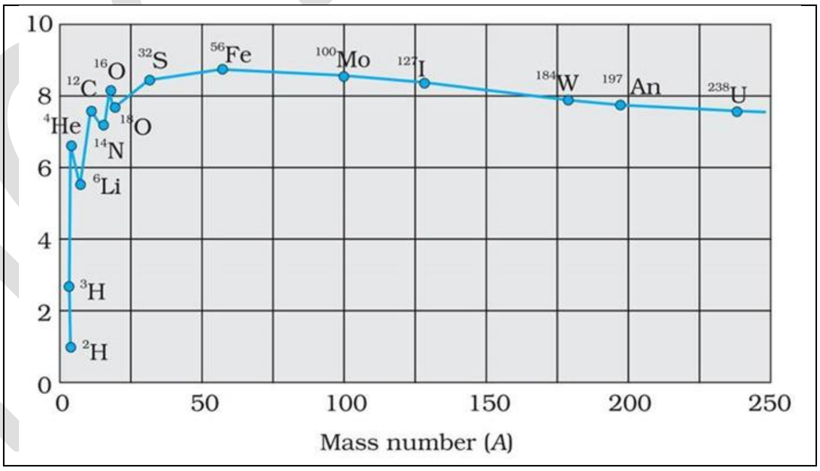
Therefore, $\overline{B}$ = B/2 = 1.12 MeV per nucleon.

**Characteristics of Nuclear Binding Energy Curve**

**Light nuclides (A<30):** The maxima for $\bar{B}$ vary periodically for A with integral multiples of 4. These nuclides are ($^4$He, $^{12}$C, $^{16}$O, $^{20}$Ne, $^{24}$Mg, $^{28}$Si) very much stable. Exception $^8$Be ($^8\text{Be} \rightarrow 2\,^4\text{He}$).

**Medium nuclides (A = 30-90):** There is a rise of $\bar{B}$ from 8.0MeV (for A = 16) to 8.30MeV (for A = 28-32) and then it remains almost constant upto A ≈ 90. The region of transition metals, at around A = 50-60 lies at the center of the plateau. The range (A = 30-90) gives the largest zone of most stability.

**Heavy nuclides (A > 90):** After zirconium (A = 91), $\bar{B}$ falls down gradually from ~8.7 MeV at A ≈ 210. Up to A ≈ 210, the nuclides are stable but after this limit, the nuclides become very unstable. $^{209}$Bi is the heaviest nuclide known to be stable.




**Packing fraction**

- Mass defect is defined as the difference between isotopic mass and mass number.
- Aston introduced the term packing fraction for each nuclide to compare their mass excess.
- It is defined as

  Packing fraction (f) = [Mass defect/mass number] x $10^4$

  = [(Isotopic mass – mass number)/mass number] x $10^4$

  The $10^4$ factor is used to obtain figures which are easy to plot.

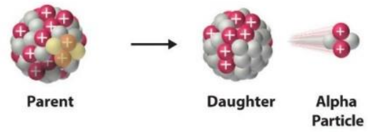
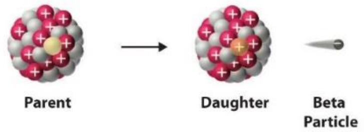
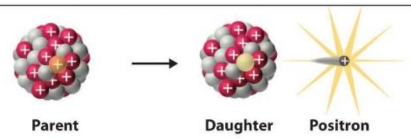
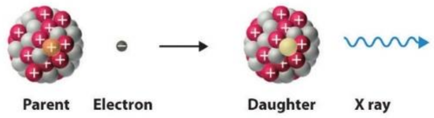
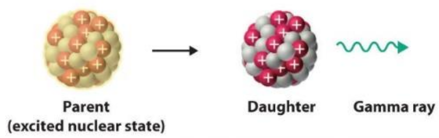
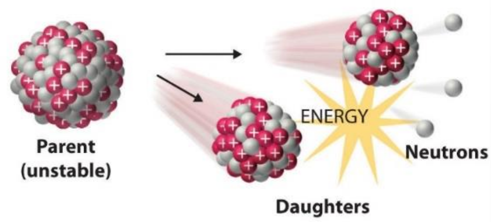
- The packing fraction does not have any precise theoretical significance, but it gives an indication about the stability of a nucleus.
- A negative packing fraction indicates that the nucleus is stable while positive packing fraction indicates that the nucleus is unstable (or less stable).
- Negative f means a negative mass defect, the extent of which is converted to the energy of formation of that nucleus and thereby indicating its stability.

**Nuclear Reactions**

- Nuclear reaction involves the changes in number of protons, neutrons, or electrons in a single atom. This is also called a transmutation reaction.
- Temperature and pressure have no role to play in a nuclear reaction.
- It always follows first order kinetics. Nuclear bombardment reactions are often referred to by an **abbreviated notation.**

| | |
|---|---|
| ${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$ | ${}^{14}_{7}N\ (\alpha, p){}^{17}_{8}O$ |

- In nuclear equations the total of the atomic number and the total of the mass number must be equal on both sides of the equation.
- Nuclear reactions can be classified according to the projectiles viz. charged particle reaction and neutral particle reactions.
- In both the categories the projectiles may be captured (projectile capture reaction) with the emission of $\gamma$ rays or one or more particles (projectile capture particle emission reaction)

| Decay Type | Radiation Emitted | Generic Equation | Model |
|---|---|---|---|
| Alpha decay | ${}^{4}_{2}\alpha$ | ${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$ |   |
| Beta decay | ${}^{0}_{-1}\beta$ | ${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta$ |   |
| Positron emission | ${}^{0}_{+1}\beta$ | ${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}X' + {}^{0}_{+1}\beta$ |   |
| Electron capture | X rays | ${}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}X' + \text{X ray}$ |   |
| Gamma emission | ${}^{0}_{0}\gamma$ | ${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$ |   |
| Spontaneous fission | Neutrons | ${}^{A+B+C}_{Z+Y}X \longrightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n$ |   |

**Charged particle reactions**

- It can be carried out by accelerated protons, deuterons or α-particles.
- Depending upon the nature of the emitted particle, we have different types of reactions.

| Projectile | Reaction Type |
|---|---|
| Proton | $(p, n)$, $(p, \alpha)$, $(p, \gamma)$, $(p, d)$ |
| Deuteron | $(d, p)$, $(d, n)$, $(d, \alpha)$, $(d, \gamma)$ |
| Alpha particles | $(\alpha, n)$, $(\alpha, p)$. |

**Example:**

| | | | |
|---|---|---|---|
| $p, n$: | ${}^{23}_{11}Na + {}^{1}_{1}H = {}^{23}_{12}Mg + {}^{1}_{0}n$ | |
| $p, \alpha$: | ${}^{7}_{3}Li + {}^{1}_{1}H = {}^{4}_{2}He + {}^{4}_{2}He$ | ... (1) |
| $p, \gamma$: | ${}^{27}_{13}Al + {}^{1}_{1}H = {}^{28}_{14}Si + \gamma$ | |
| $p, d$: | ${}^{9}_{4}Be + {}^{1}_{1}H = {}^{8}_{4}Be + {}^{2}_{1}H$ | |
| $d, p$: | ${}^{27}_{13}Al + {}^{2}_{1}H = {}^{28}_{13}Al + {}^{1}_{1}H$ | |
| $d, n$: | ${}^{27}_{13}Al + {}^{2}_{1}H = {}^{28}_{14}Si + {}^{1}_{0}n$ | |
| $d, \alpha$: | ${}^{6}_{3}Li + {}^{2}_{1}H = {}^{4}_{2}He + {}^{4}_{2}He$ | ... (2) |
| $d, \gamma$: | ${}^{63}_{29}Cu + {}^{2}_{1}H = {}^{65}_{30}Zn + \gamma$ | |
| $\alpha, n$: | ${}^{9}_{4}Be + {}^{4}_{2}He = {}^{12}_{6}C + {}^{1}_{0}n$ | ... (3) |
| $\alpha, p$: | ${}^{14}_{7}N + {}^{4}_{2}He = {}^{17}_{8}O + {}^{1}_{1}H$ | ... (4) |

**Note:** (1) The first artificial nuclear reaction carried out with **artificially** accelerated projectiles.
(2) This reaction gives one of the highest non-fission energies (22.2 MeV) recorded for light atoms.
(3) The neutron was discovered through this reaction.
(4) The first artificial nuclear reaction studied.

**Neutral particle reactions:**

- Neutrons are used as projectiles. Accelerated neutrons are not necessary.
- Slow neutrons with energies less than one eV are more effective that fast neutrons.
- Neutrons of high energy are slowed down through moderators such as graphite, heavy water.
- Neutron induced reactions may be (n, γ), (n, p) or (n, α) type.

| | | |
|---|---|---|
| $n, \gamma$: | ${}^{238}_{92}U + {}^{1}_{0}n = {}^{239}_{92}U + \gamma$ | ... (1) |
| $n, p$: | ${}^{14}_{7}N + {}^{1}_{0}n = {}^{14}_{6}C + {}^{1}_{1}H$ | |
| $n, \alpha$: | ${}^{6}_{3}Li + {}^{1}_{0}n = {}^{4}_{2}He + {}^{3}_{1}H$ | ... (2) |

**Note:** (1) Important for the production of plutonium.
(2) Important for the production of **tritium** for various experimental work. It is also obtained as

$${}^{2}_{1}H + {}^{2}_{1}H = {}^{3}_{1}H + {}^{1}_{1}H; \quad {}^{9}_{4}Be + {}^{2}_{1}H = {}^{8}_{4}Be + {}^{3}_{1}H$$

- Nuclear reactions may also be classified according to overall transformation.

**Projectile capture (Radiative capture) reactions**

- The projectile is absorbed by the target nucleus and no massive particles other than the product nucleus is emitted. γ-radiation may or may not be emitted.

$${}^{85}_{37}Rb + {}^{1}_{0}n \rightarrow {}^{86}_{37}Rb + \gamma \text{ and } {}^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{7}N + \gamma$$

**Projectile capture particle emission reactions**

- A massive particle is commonly ejected in addition to the product nuclei. With projectiles of high energy, more than one particle may also be produced.

(i) ${}^{9}_{4}Be + {}^{1}_{1}H \rightarrow {}^{6}_{3}Li + {}^{4}_{2}He$, (ii) ${}^{11}_{5}B + {}^{1}_{1}H \rightarrow {}^{11}_{6}C + {}^{1}_{0}n$,

(iii) ${}^{11}_{5}B + {}^{4}_{2}He \rightarrow {}^{14}_{7}N + {}^{1}_{0}n$, (iv) ${}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$,

(v) ${}^{16}_{8}O + {}^{2}_{1}H \rightarrow {}^{14}_{7}N + {}^{4}_{2}He$, (vi) ${}^{19}_{9}F + {}^{1}_{0}n \rightarrow {}^{16}_{7}N + {}^{4}_{2}He$,

(vii) ${}^{27}_{13}Al + {}^{4}_{2}He \rightarrow {}^{30}_{14}Si + {}^{1}_{1}H$, (viii) ${}^{31}_{15}P + {}^{2}_{1}H \rightarrow {}^{32}_{15}P + {}^{1}_{1}H$.

**Q-value of a nuclear reaction**

- In nuclear chemistry, the energetics of nuclear reactions is determined by its **Q**-value.
- The overall energy released or taken up in a nuclear reaction is known as nuclear reaction energy which is also termed as **Q-value** of the reaction.
- The **Q**-value of a nuclear reaction is the difference between the sum of the masses of the initial reactants and the sum of the masses of the final products, in energy units (usually in MeV).
- This is also the corresponding difference of the binding energies of the nuclei (not per nucleon), since nucleon number is conserved in a reaction.
- The value of **Q** may be *positive* when the reaction is said to be **exoergic** or exothermic.
- The value of **Q** may be *negative* when the reaction is said to be **endoergic** or endothermic.

**Calculation of Q value**

- Let us consider the complete equation for Rutherford's transmutation reaction should be

Q is called the nuclear reaction energy.

- The value of Q for the above reaction can be calculated from the masses of the reactants and products. Thus,

Sum of mass of reactants = 14.0031 + 4.0026 = 18.0057 amu.

Sum of mass of products = 16.9991 + 1.0078 = 18.0069 amu.

$\therefore$ $\Delta M$ = Masses of products – Masses of reactants = 18.0069 – 18.0057 = 0.0012 amu.

The reaction, evidently, involves *increase of mass* by 0.0012 amu. An equivalent amount of energy is therefore *absorbed* in this case. Hence, the Q value, by convention, is *negative*.

Since, 1 amu = 931.5 MeV, Q = - 0.0012 amu x 931.5 MeV/amu = - 1.118 MeV

The reaction is, evidently, *endoergic.*

- The Q values for most of the nuclear reactions are within 10 MeV.

$${}^{6}_{3}Li + {}^{2}_{1}H \rightarrow 2\,{}^{4}_{2}He$$

But in the reaction, the Q value is quite high.

Sum of the mass of the reactants = 7.01601 + 1.00783 = 8.02384 amu.

Sum of the mass of the product = 2 x 4.00260 = 8.00520 amu.

$\therefore$ $\Delta M$ = Mass of the product – Masses of the reactants

= 8.00520 – 8.02384 = - 0.01864 amu.

There is a decrease of mass and hence the energy is *released*. The Q value is, therefore, *positive*. Thus,

Q = 0.01864 amu x 931.5 MeV/amu = 17.36 MeV

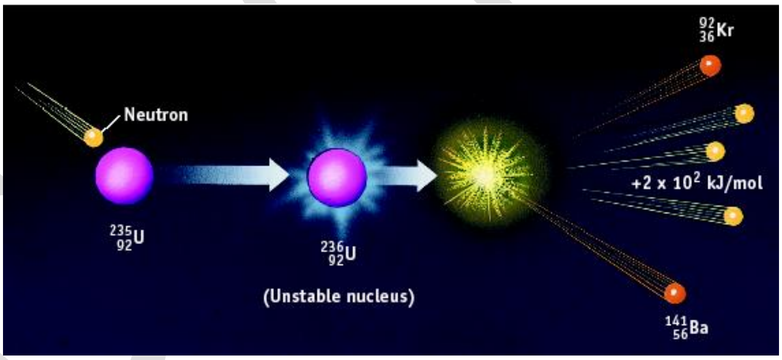
The reaction is, evidently, *exoergic.*

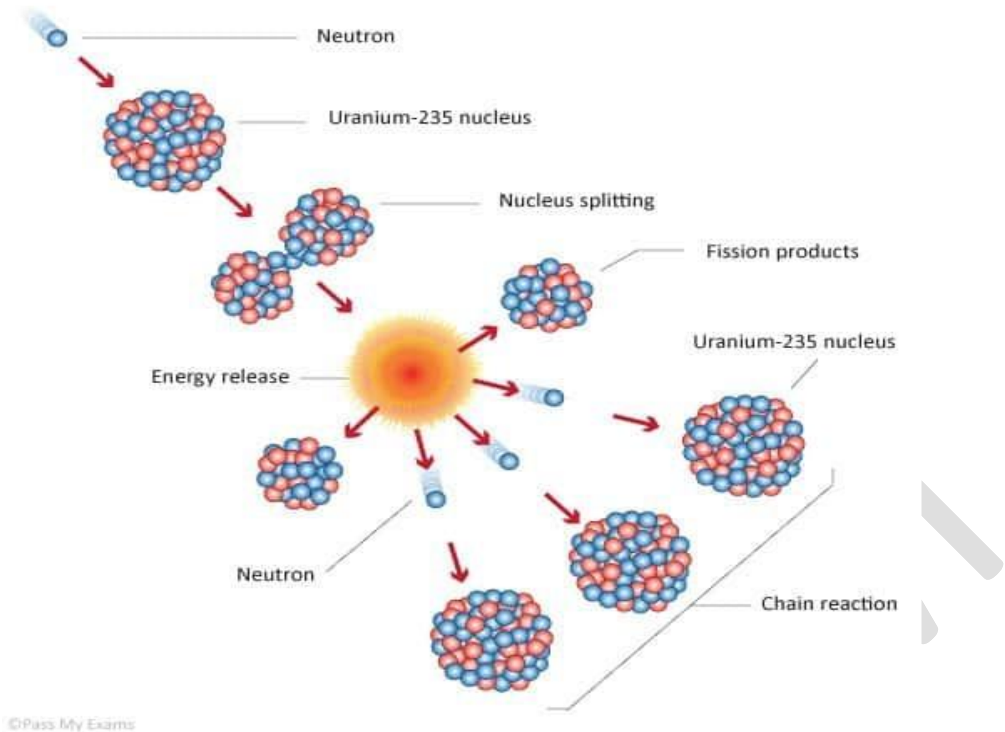
**Artificial or induced radioactivity**

- Induced radioactivity, also called artificial radioactivity or man-made radioactivity, is the process of using radiation to make a previously stable material radioactive.
- The husband-and-wife team of I. J. Curie and F. J. Curie discovered induced radioactivity in 1934 and they shared the Noble prize in 1935.
- Neutron activation is the main form of induced radioactivity. It occurs when an atomic nucleus captures one or more free neutrons. This new, heavier isotope may be either stable or unstable (radioactive), depending on the chemical element involved. Slow neutron is preferable for the process.
- A less common form of induced radioactivity results from removing a neutron by photodisintegration. In this reaction, a high energy photon (γ-ray) strikes a nucleus with an energy greater than the binding energy of the nucleus, which releases a neutron. This reaction has a minimum cutoff of 2-10 MeV of energy. Many radionuclides do not produce gamma rays with energy high enough to induce this reaction.
- Induced radioactivity increases the amount of nuclear waste that must eventually be disposed, but it is not referred to as radioactive contamination unless it is uncontrolled.

**Nuclear fission (O. Hahn and F. Strassman, 1939)**

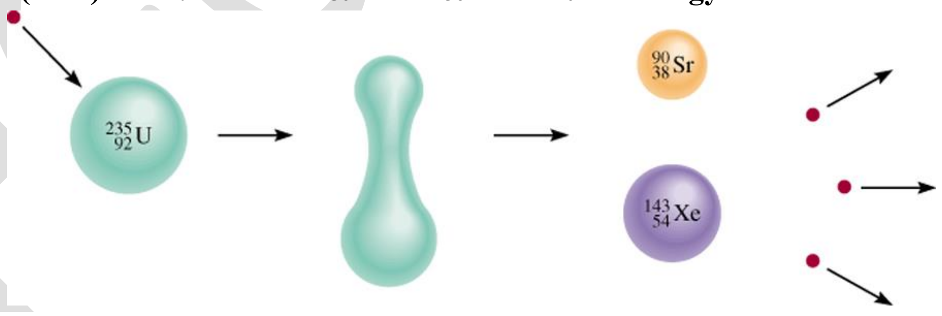
- Nuclear fission is either a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei).
- The fission process often produces free neutrons and gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay.
- Fission is a form of nuclear transmutation because the resulting fragments are not same element as the original atom. When neutron strikes U-235 is converted to U-236.






- The group of J. Curie and Savitch carried out chemical analysis on the uranium compounds bombarded by slow neutrons. They noticed a chemical species having property close to that of Z= 56-57 far away from Z= 92 in the periodic table.
- The group of Otto Hahn and Strassman established Barium (Z = 56) as one of the products in the reaction ${}^{235}_{92}U + n$
- The Barium produced showed β activity. In the analysis Krypton (Z = 36) was also proved.
- Since the product nuclides were much lighter than the starting nuclide, Meinter and Frisch suggested that the Uranium nucleus on being bombarded by slow neutron splits into two lighter fragments of comparable size, and the process was termed as Nuclear Fission.

  $\mathbf{{}^{235}_{92}U + {}^{1}_{0}n(slow) \rightarrow {}^{236}_{92}U^{*} \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + energy}$




$${}^{236}_{92}U^{*} \rightarrow {}^{140}_{56}Ba + {}^{93}_{36}Kr + 3{}^{1}_{0}n$$
$${}^{236}_{92}U^{*} \rightarrow {}^{146}_{57}La + {}^{87}_{35}Br + 3{}^{1}_{0}n$$
$${}^{236}_{92}U^{*} \rightarrow {}^{133}_{55}Cs + {}^{101}_{37}Rb + 2{}^{1}_{0}n$$
$${}^{236}_{92}U^{*} \rightarrow {}^{139}_{54}Xe + {}^{95}_{38}Sr + 2{}^{1}_{0}n$$
$${}^{236}_{92}U^{*} \rightarrow {}^{137}_{52}Te + {}^{96}_{40}Zr + 3{}^{1}_{0}n$$
$${}^{236}_{92}U^{*} \rightarrow {}^{133}_{51}Sb + {}^{99}_{41}Nb + 4{}^{1}_{0}n$$

**Nuclear fusion- thermonuclear reaction**

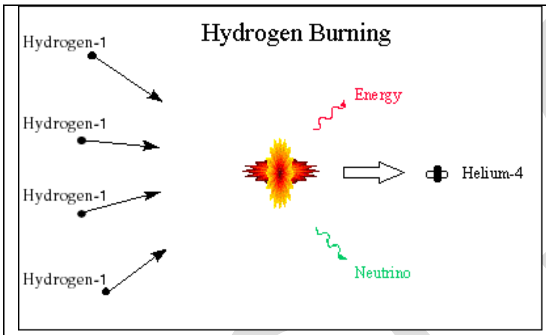
- Nuclear fusion reactions occur when two or more atomic nuclei come close enough for the strong nuclear force pulling them together to exceed the electrostatic force pushing them apart. This process takes light reactions nuclei and forms a heavier one through a nuclear reaction.

- Nuclear Fusion occurs at a tremendously high temperature with the liberation of tremendous amount of energy.
- For fusion to take place, the colliding nuclei must possess enough kinetic energy to overcome the initial repulsion between the positively charged cores.
- This is done by raising the temperature of the reacting system to exceedingly high level and therefore, such reactions are also known as thermonuclear reaction.
- Theoretically, any atom could be fused. However, fusion of hydrogen nucleus to give helium is ideal due to its small charge.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6 \text{ MeV}$$

**Energy generation in Sun/star**

- The energy source of stars/sun is a continuous fusion process at very high temperature.
- The energy radiated by the sun occurs by fusion of protons to helium (H. A. Bethe, 1939) at the core temperature of about 1.5 x $10^7$ K.
- The energy liberated in the process is about 27 MeV (6.5 x $10^8$ kJ per g hydrogen) per four protons on conversion.
- All protons in the sun is anticipated to get converted to He in about 3 x $10^{10}$ years.
- The fusion reaction taking place in stars would be extremely slow on earth due less availability of fusion materials.
- It is an exothermic reaction.




$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + \beta^{+} + \upsilon$ 1.44 MeV

$^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + \gamma$ 5.49 MeV

$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + 2(^{1}_{1}H)$ 12.86 MeV

$4(^{1}_{1}H) \rightarrow ^{4}_{2}He + 2\beta^{+} + 2\upsilon + 2\gamma$ (Overall)

**Hydrogen bomb**

- In the thermonuclear bomb or hydrogen bomb, fusion reaction between various hydrogen nuclides is initiated by a fission reaction ($^{235}U$ or $^{239}Pu$ functions as detonator) in the core. The final product is helium nuclei. The probable reaction found in hydrogen bomb is

$$^{3}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17 \text{ MeV}$$
$$^{3}_{1}H + ^{1}_{1}H \rightarrow ^{4}_{2}He + 20 \text{ MeV}$$
$$^{3}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + 2\,^{1}_{0}n + 11 \text{ MeV}$$

- There is no critical size of hydrogen bomb and hence hydrogen bomb of any size can be prepared.

**In age determination**

- Age of minerals and rocks: He dating may be used to estimate the age of certain mineral deposits.
- U minerals decay by emitting α-particles, thus producing He. (1 g U produces about $10^{-7}$ g of He per year).
- The age of the mineral can be estimated if both the U and He contents are known.
- Let $N^t$ U-238 and $N^t$ Pb-206 represent the number of $^{238}U$ and $^{206}Pb$ atom in a rock at the present time t then number of $^{238}U$ atoms present at t=0 is

$N^0$ U-238 = $N^t$U-238 + $N^t$Pb-206 therefore, $N^t$U-238=$N^t$U-238exp(-kt) = ($N^t$U-238+$N^t$Pb-206) exp(-kt)

$N^t$ Pb-206 = $N^t$U-238{exp(kt)-1}

1 = (1+ $N^t$Pb – 206/ $N^t$U-238) exp(-kt)

**Radiocarbon dating (W. Libby, 1940 and 1960 Noble prize)**

- Measurements of radioactivity are used to estimate the age of archaeological objects.
- Radiocarbon dating is a method for determining the age of an object containing organic material by using the properties of radiocarbon ($^{14}C$).
- $^{14}C$ is continuously produced in the atmosphere through bombardment of $^{14}N$ by neutrons from cosmic rays. $^{14}N + {}^{1}_{0}n \rightarrow {}^{14}C + {}^{1}H$
- The radio-carbon is oxidized to radioactive $^{14}CO_2$ and gets mixed with normal $CO_2$ of the atmosphere.
- $^{14}CO_2$ is incorporated into plants by photosynthesis, animals then acquire $^{14}C$ by eating the plants and maintains a steady value of $^{14}C$ in the body.
- The intake of $CO_2$ ceases as soon as the living body dies and thereby reducing the $^{14}C$ activity.
- Measuring the amount of $^{14}C$ in a dead living body (piece of wood or a fragment of bone), information that can be used to calculate when the animal or plant died can be obtained.

  Age = (2.303/λ)log (original activity/final activity)
- The older a sample is, the less $^{14}C$ there is to be detected (half-life=5730 years).
- Measurement of radiocarbon was originally done by beta-counting devices, which counted the amount of β-radiation emitted by decaying $^{14}C$ atoms in a sample.
- More recently, accelerator mass spectrometry has become the method of choice.
- The development of radiocarbon dating has had a profound impact on archeology.

**Nuclear reactions comparison with Chemical reaction**

| Chemical Reactions | Nuclear Reactions |
|---|---|
| 1. These reactions involve changes in the valence<br>2. Law of conservation of mass holds good in chemical reactions<br>3. These reactions are affected by temperature and pressure<br>4. Energy change involved in these reactions is relatively low<br>5. Isotopes of element give same chemical reactions | 1. These reactions involve changes in the nucleus<br>2. Law of conservation of mass does not hold good in nuclear reactions<br>3. These reactions are not affected by temperature and pressure<br>4. Energy change involved in these reactions is very large, million times more than chemical reactions<br>5. Isotopes of an element give different nuclear reactions |

**Differences between Nuclear Fission and Nuclear Fusion**

| Nuclear Fission | Nuclear Fusion |
|---|---|
| A bigger (heavier nucleus splits into smaller (lighter) nuclei. | 1. Lighter nuclei fuse together to form the heavier nucleus. |
| 2. It does not require high temperature. | 2. Extremely high temperature is required for fusion to take place. |
| 3. A chain reaction sets in. | 3. It is not a chain reaction. |

| | |
|---|---|
| 4. It can be controlled and energy released can be used for peaceful purposes.<br>5. The products of the reaction are radioactive in nature.<br>6. At the end of the reaction nuclear waste is left behind. | 4. It cannot be controlled and energy released cannot be used properly.<br>5. The products of a fusion reaction are nonradioactive in nature.<br>6. No nuclear waste is left at the end of fusion reaction |

**Fermi theory of β-decay:**

In 1934, Fermi formulated a successful theory of beta decay which is based on Pauli's neutrino hypothesis. Fermi theory provides an expression for the transition probability (or rate) for beta decay. The theory is based on following considerations:

1. The electron and neutrino do not exist before the decay process, and therefore the theory must account for the formation of those particles
2. The electron and neutrino must be treated relativistically
3. The continuous distribution of electron energies must result from the calculation
4. An interaction causing beta decay is weak compared with the interaction that forms the quasi-stationary states. In other words, the (time-dependent) potential responsible for beta decay is small compared to the nuclear potential (time independent) which forms stationary states. Therefore, time-dependent perturbation theory can be applied to the beta decay process, as we can treat decay-causing interaction as weak perturbation.

There is a relation between the decay constant of a β-decaying nuclide and its end point energy. Sargent reported an empirical relation (analogous to Geiger-Nuttal's law for α decay), according to which greater the end point energy $E_{max}$ larger the decay constant. Sargent showed that if logλ is plotted against log $E_{max}$ for different naturally occurring β-emitters, the points fall on two straight lone, or are close to them.

**Auger effect:**

In the process of electron capture and ejection of conversion electrons, vacancies are created in the inner electron orbitals (K and L shells). The inner vacancy therefore gets rapidly filled by the successive transfer of electrons from the outer orbitals. The process of vacancy filling gives rise to two distinct effects viz. radiation emission (fluorescence mode) and electron emission (Auger effect)

As an outer electron jumps into inner vacancy, the emitted energy ($E_x$) is given by $h\nu_1 = E_x = E_{B1} - E_{B2}$; where $E_{B1}$ and $E_{B2}$ are the binding energies of the inner and outer level electrons. The vacancy is pushed outward and the process goes on till each vacancy is filled by the jumping in of the next outer electron, emitting at each stage corresponding radiation $h\nu_i = E_{Bi} - E_{B(i+1)}$

The excess energy ($E_x$) may be non-radiatively transferred to the next outer electron causing its ejection (such as internal conversion). If, the electron initially lost from the innermost shell is $e_1$, and the electrons jumped in to fill the vacancy is $e_2$, the electron now ejected is $e_3$; the kinetic energy of this (second to be lost) is given by $E_3 = E_{B1} - (E_{B2} + E_{B3})$ where; $E_{B3}$ is the binding energy of the electron $e_3$.

Ejection of $e_3$ would be possible only if $E_{B1} > (E_{B2} + E_{B3})$ so that the kinetic energy of $e_3$ has a finite positive value (at this stage the atom has a charge of +2). The process of emission of further electrons $e_4$, $e_5$, $e_6$……$e_n$ from successive outer orbitals can go on as long as the value of $E_n$ is positive.

The successive emission of electrons by such a process (non-radiative transfer of energy to the next outer electrons causing their ejection) is defined as Auger effect (discovered by Peter Auger).

As filling of one inner vacancy results in two vacancies in the outer orbital (mentioned above), the filling of these two vacancies leads to the creation of four vacancies in the next outer orbital, and the atom will have +4 charge. The process repeats on the principle that the filling of one inner vacancy results in two vacancies in the outer orbital. Thus,

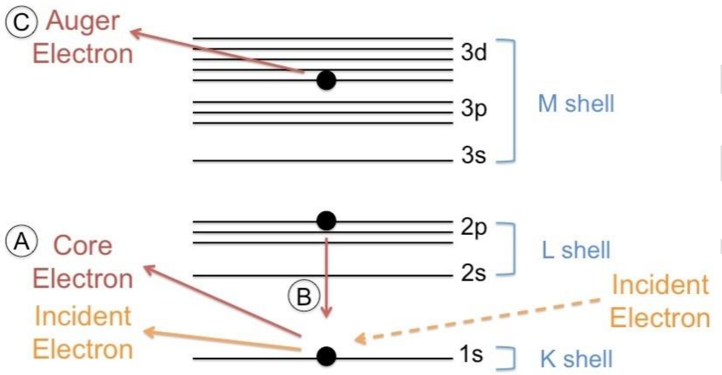
K (1 K initial vacancy) ← LL →

→ 2 L vacancies after the process; one L electron goes to fill the K vacancy and second L electron is ejected

Similarly,

L (2 L initial vacancies) ← MM →

→ 4 M vacancies after the process; and so on




The vacancy cascades outwards to the valency shell, and the atom is left in a highly positively charged state. The formation of highly positively charged species of atoms following electron capture, isomeric transition and internal conversion process are common.

Q. 1 How many α and β particles are emitted in passing down from $^{232}{}_{90}$Th to $^{208}{}_{82}$Pb?

Q. 2 $^{210}{}_{82}$Pb is a β-emitter and $^{226}{}_{88}$Ra is an α-emitter. What will be the atomic masses and atomic numbers of daughter elements of these radioactive elements? Predict the position of daughter elements in the periodic table.

Q. 3 Calculate the half-life of radium-226 if 1 g of it emits $3.7 \times 10^{10}$ alpha particles per second.

Q. 4 Calculate the disintegration constant of cobalt 60 if its half-life to produce nickel – 60 is 5.2 years.

Q. 5 The half-life period of radon is 3.825 days. Calculate the activity of radon. (atomic weight of radon = 222)

Q. 6 Cobalt-60 disintegrates to give nickel-60. Calculate the fraction and the percentage of the sample that remains after 15 years. The disintegration constant of cobalt-60 is 0.13 $yr^{-1}$

Q. 7. The amount of carbon-14 in a piece of wood is found to be one-sixth of its amount in a fresh piece of wood. Calculate the age of old piece of wood.

Q. 8 A bone taken from a garbage pile buried under a hill-side had 14C/12C ratio 0.477 times the ratio in a living plant or animal. What was the date when the animal was buried?

Q. 9 Write the nuclear equation for the change that occurs in radium-226 when it emits an alpha particle.

Q. 10 Cobalt–60 decays by emission of a beta particle. Predict the atomic number, mass number, and name of the isotope formed

Q. 11 Complete the nuclear equation

$^{238}_{92}U + ^{4}_{2}He \rightarrow ? + ^{1}_{0}n$

Q. 12 What is the binding energy for $^{11}_{5}B$ nucleus if its mass defect is 0.08181 amu?

Q. 13 Calculate the binding energy per nucleon (in Mev) in He-atom $^{4}_{2}He$ which has a mass of 4.00260 amu. Mass of an electron = 1.008655 amu and mass of 1 hydrogen atom = 1.007825 mass.