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Chapter-13

NUCLEI

(1) The nucleus contains more than 99.9% of mass of an atom.
It was discovered by Rutherford in 1911 (experiment on scattering of α-particles from thin metal foil.)
The radius of nucleus is smaller than the radius of an atom by a factor of about 10^4

☆ Atomic masses & Constituent of nucleus

Atomic mass unit

It is defined as $1/12^{th}$ the mass of C-12 atom.

i.e. [$1\,U = 1.67\times10^{-27}\,kg$]

Atomic mass unit & Kg relation

$$6.023\times10^{23} \text{ atom in } {}_6C^{12} = 12\,Kg$$

$$1 \text{ atom} = \frac{12}{6.023\times10^{23}}\,Kg$$

$$1\,U = \frac{1}{12}\times\frac{12}{6.023\times10^{23}}\,g$$

$$\frac{1}{6.023\times10^{23}}\times\frac{1}{10^3}\,Kg$$

$$\frac{1000}{6023}\times10^{-26}$$

$$\frac{10000}{6023}\times10^{-27}\,Kg = [1.67\times10^{-27}\,Kg]$$

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→ accurate measurement of atomic masses is carried out with a mass-spectrometer

* Atomic number (Z) :- Total number of Protons

* Atomic mass (A) :- Total number of neutrons & protons (mass number)

* Total charge on nucleus

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

Nuclei types

→ Isotopes → Same atomic no. & Different mass no.

eg $^{12}_{6}C$ $^{13}_{6}C$ $^{14}_{6}C$

→ Isobars → Different atomic no. & same ~~atomic~~ mass no.

eg $^{14}_{7}N$ $^{14}_{6}C$

→ Isotones → Different atomic no. & same no. of neutrons.

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e.g $^{198}_{80}Hg$ & $^{197}_{79}Au$

→ Nuclide → Collection of nuclei with same atomic no. & same no. of neutrons.

eg $^{32}_{16}S$

NOTE → Gold has 32 isotopes ranging from $A = 173$ to $A = 204$.

Discovery of Neutrons

→ James chadwick observed emission of nutral radiant when Beryllium nuclei were bombarded with α-particles.

→ He found that this neutral radiant knock out p^+ from lighter nuclei such as those of He, Carbon & nitrogen.

→ Chadwick satisfactorily solved the problem & conclude that neutral radiations consist of new type of particle called neutrons.

$$[m_n = 1.674 \times 10^{-27} \text{ kg}]$$

→ A free neutron unlike a free proton is unstable

→ It decays into a p^+, e^- & an antineutrino having a mean life of about 1000 s.

* [Z + N = A]

Size Of the Nucleus

→ Rutherford was the postulated & established the existence of atomic nucleus.

→ By performing charge no. of experiment, it has been ~~foint~~ found that. Size of nucleus is.

$$[R = R_0 A^{1/3}] \quad R_0 = 1.2 \times 10^{-15} m$$

1 fermi (F) = 10^{-15} m

also density is given as (nucleus)

$$\rho = \frac{mA}{\frac{4}{3}\pi R^3}$$

$$\rho = \frac{mA}{\frac{4}{3}\pi \times R_0^3 A} \quad \text{from above}$$

$$\rho = \frac{3mA}{4\pi R_0^3 \times A} \Rightarrow \rho = \frac{3m}{4\pi R_0^3}$$

density is independent of A.

* Mass Energy & Nuclear Binding energy

⇒ Einstein showed that mass is another form of energy & one can convert mass energy into other forms of energy

$$\left[E = mc^2\right] = \frac{1.66 \times 10^{-27} \times [3 \times 10^8]^2}{1.6 \times 10^{-19}} = 933.75 \text{ MeV}$$

Conserved law of energy-

It states that initial energy & the final energy are equal provided the energy associated with mass is also included.

⇒ It is found that nuclear mass is always less than the sum of masses of its constituents.

* Mass defect

The difference in mass of a nucleus & its constituents is defined as mass defect.

$$\left[\Delta M = [Zm_p + (A-Z)m_n] - M\right]$$

→ Binding energy is given by

$$\left[E_b = [Zm_p + (A-Z)m_n - M]c^2\right]$$

* Binding energy per nucleon.

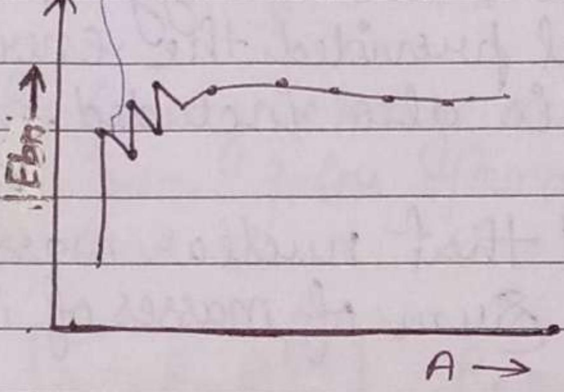
It is defined as the ratio of binding energy of a nucleus to the no. of nucleons (A).

$$\left[E_{bn} = \frac{E_b}{A}\right] \qquad \frac{\text{Total Binding energy}}{\text{No. of nucleons}}$$

OR

It is Considered as average energy per nucleon needed to separate a nucleus into its individual nucleons.

* Ebn Vs A graph is as follows-



Conclusion

(i) Ebn is ~~con~~ practically constant. i.e. independent of atomic no. for nuclei of middle mass no. (90 < A < 170) & about 8.75 MeV.

(ii) Ebn is lower for both light nuclei & heavy nuclei

NOTE → The constancy of BE in the range 30 < A < 170 tells us that nuclear force is a short range force.

iii) A very heavy nucleus say A = 240 has lower B.E. per nucleon compared to that of a nucleus with A = 120.

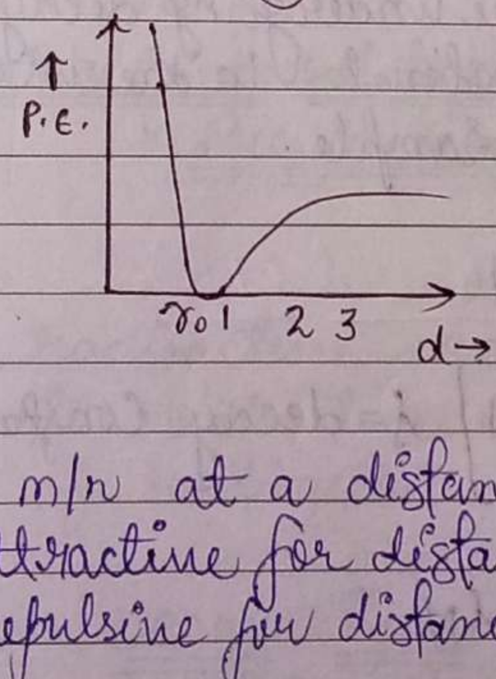
(v) The B.E/nucleon of fused heavier nuclei is more than the B.E/nucleon of lighter nuclei. ~~Thus~~ this means that the final system is more tightly bound than the initial system.

Nuclear Force

i) Nuclear force is the strongest force known today.

ii) The nuclear force b/w 2 nucleons falls rapidly to zero as their distance is more than a few femtometres.

Potential energy for a pair of nucleons Vs distance graph.



→ P.E. is m/n at a distance r_0. (m/n = minimum)
→ It is attractive for distance larger than 0.8 fm.
→ It is repulsive for distances less than 0.8 fm.

iii) The nuclear force does not depend on electric charge.

iv) There is no any mathematical form of a nuclear force.

'Radioactivity'

i. Phenomena discovered by A.H. Becquerel in 1896 accidentally while experiment of fluorescence & phosphorescence of compounds irradiated with visible light.

ii. Radioactivity was a nuclear phenomenon in which an unstable nucleus undergoes a decay with emission of radiation like (α, β, γ)

* Law of radioactive decay

No. of nuclei undergoing decay per unit is directly propotional to the total no. of nuclei in the sample

$$\frac{\Delta N}{\Delta t} \propto N$$

or $\left[\frac{dN}{dt} \propto N\right]$ λ = decay constant.

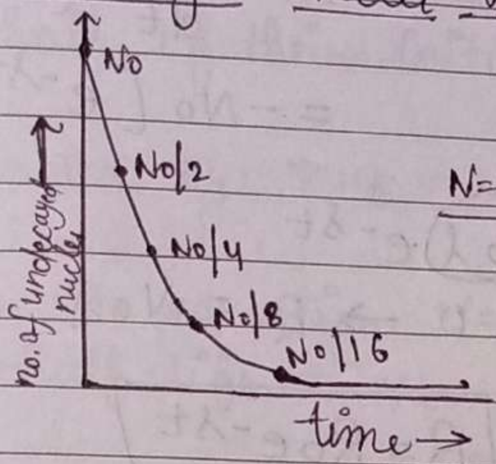
or $\frac{dN}{dt} = -\lambda N$

or $\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{t_0}^{t} dt$

$\log \frac{N}{N_0} = -\lambda t$

$$[N_{(t)} = N_0 e^{-\lambda t}]$$

No of undecayed Nuclei Vs time graph.



$N = N_0 e^{-\lambda t}$

NOTE

It is also known as Exponential Decay Law
→ followed only by radio nuclides.

Terminologies related to Radiactive Decay

① Decay rate
② Activity to radioactive sample.
③ Half-life of radioactive sample.
④ Mean-life of radioactive sample.

1. Decay Rate

- The number of nuclei decaying per unit time
- It is denoted by R

$$R = -\frac{dN}{dt}$$

$$N = N_0 e^{-\lambda t} \quad \therefore R = \frac{-d}{dt}\left(N_0 e^{-\lambda t}\right)$$

$$= -N_0\left[e^{-\lambda t}(-\lambda)\right]$$

Bacqueral (Bq)
Curie
3.7×10^{10}

$$R = N_0 \lambda e^{-\lambda t}$$

At $t = 0 \rightarrow R_0 = N_0 \lambda$

$$\therefore \boxed{R = R_0 e^{-\lambda t}}$$

2. Activity of radioactivity Sample

- It means total decay rate R of a sample of one or more radionuclides.

- SI unit :- Bacqueral (Bq)

$$1\,Bq = \text{decay per second}$$

- other unit :- curie

$$1\,ci = 3.7 \times 10^{10}\,Bq$$

3. Half-life of radioactive sample

- It means time at which no. of nuclei reduces to one-half of their initial values.

- It is denoted by $T_{1/2}$

From the equation $N = N_0 e^{-\lambda t}$

At half-life, $t = T_{1/2}$, $N = \frac{N_0}{2}$

$$\therefore \frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}} \Rightarrow \frac{1}{2} = e^{-\lambda T_{1/2}} \Rightarrow e^{\lambda T_{1/2}} = 2$$

Taking log on both sides, we get.

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

$$\Rightarrow T_{1/2} = \frac{\log_e 2}{\lambda} = \frac{\log_{10} 2 \times 2.303}{\lambda} = \frac{0.3010 \times 2.303}{\lambda}$$

$$\left[T_{1/2} = \frac{0.6931}{\lambda} \right] \qquad \because \log_{10} 2 = 0$$

After n half-life the number of atoms left undecayed is given by

$$\left[N = N_0 \left(\frac{1}{2}\right)^n \right]$$

4. Mean life of radioactive sample.

- It means average life of a nuclei in the radioactive sample.

$$\tau = \frac{\text{Total life time of all nuclei}}{\text{Total number of nuclei}}$$

Mean life of radioactive sample short derivation

$N = N_0 e^{-\lambda t}$

$\frac{N_0}{e} = N_0 e^{-\lambda t}$

$e^{-1} = e^{-\lambda t}$

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

$$\int_0^{N_0} \frac{t \cdot dN}{N_0} = \int_\infty^0 \frac{-\lambda N_0 e^{-\lambda t}\, dt \times t}{N_0}$$

$$\left[\because dN = -\lambda (N_0 e^{-\lambda t}) dt\right]$$

$$= \lambda \int_0^\infty t e^{-\lambda t} dt = \lambda \left[\left\{ t \frac{e^{-\lambda t}}{-\lambda} \right\}_0^\infty - \int_0^\infty \frac{e^{-\lambda t}}{-\lambda} dt\right]$$

$$= \lambda \left(0 + \frac{1}{\lambda} \int_0^\infty e^{-\lambda t} dt\right) = \int_0^\infty e^{-\lambda t} dt = \left[\frac{e^{-\lambda t}}{\lambda}\right]_0^\infty$$

$$= 0 - \frac{1}{-\lambda} = \frac{1}{\lambda}$$

$$\Rightarrow \tau = \frac{1}{\lambda} = \frac{1}{0.6931 / T_{1/2}} \quad \text{or} \quad \boxed{\tau = 1.44\, T_{1/2}}$$

RADIOACTIVE DISPLACEMENT LAWS

- The law of radioactive displacement is also known as Fajans & Soddy law
- It is the rule governing the transmutation of elements during radioactive decay.

* Alpha (α) decay

- Alpha particle is emitted
- Daughter nucleus is formed from parent nucleus.
- Atomic no. decreases by 2
- Mass no. decreases by 4
- It is Spontaneous process

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

$\downarrow$ Parent $\qquad$ $\uparrow$ Daughter.

* Q-Value of alpha decay-

It is difference b/w initial mass energy & final mass energy of decay products.

$$Q = (m_X - m_Y - m_{He})c^2$$

where $Q > 0$ for exothermic processes such as α-decay.

* Beta decay (β)

neutron to proton

- Electron or positron is emitted.
  - Beta minus decay → electron is emitted.

β^--decay $\Rightarrow {}_{15}^{32}P \Rightarrow {}_{16}^{32}S + e^- + \bar{\nu}$ → anti neutrino

At. no. increase by 1.

Proton to neutron

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- Beta plus decay → Positron is emitted

β^+-decay ⇒ $^{22}_{11}Na \longrightarrow ^{22}_{10}Ne + e^+ + \nu$ neutrino.

At. no. decreases by 1
Mass No. remains same

* Q-Value in Beta decay

Beta minus decay → Electron is emitted

β decay: Neutrino & anti neutrino

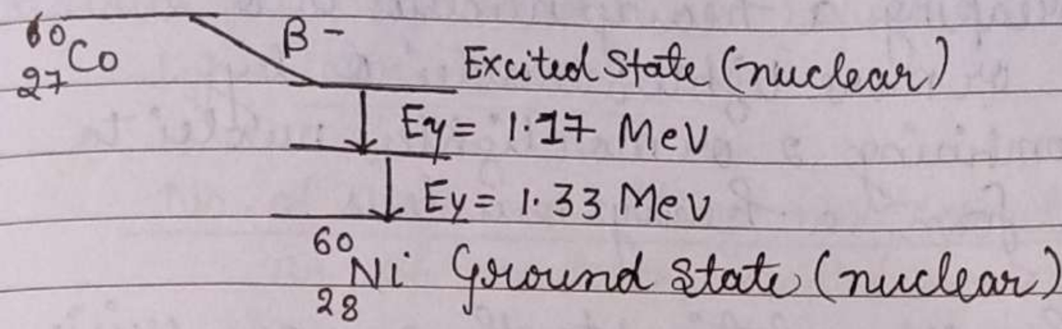
- These are neutral particle
- They ~~a~~ have negligible mass.
- They have extremely high penetration power.
- They have weak interaction with matter.

★ Gamma (γ) decay

- Gamma rays are emitted
- Mostly daughter nuclei of α-decay & β-decay are left in excited state.
- They undergo transition to ground state emitting gamma rays.

The General equation for γ-decay is given by—

$$^{A}_{Z}X \longrightarrow ^{A}_{Z}X + ^{0}_{0}\gamma$$



* Nuclear Radiation

Alpha Particle	Beta particle	Gamma rays
Stream of alpha particles deflected by electric field	Stream of electrons deflected by electric field	(don't have any charge) radiation undeflected by electric field
Deflected by magnetic field	Deflected by magnetic field	undeflected
Penetrating power is low	Greater	largest
Ionizing power is high	lesser	least.

Nuclear energy

- Energy obtained from nucleus ~~into~~ ~~2~~ by either

- Breaking a heavy nucleus into 2 or more lighter nuclei or by
- Combining 2 or mor lighter nuclei to from a heavy nucleus.

- A possible solution to the energy crisis of the world.

Nuclear Fission

→ Nuclear fission is the phenomenon of splitting of a heavy nucleus (usually A>230) into ~~two~~ 2 or more lighter nuclei by the bombardment of proton, neutron, α-particle etc.

e.g. $^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n + Q$

→ High amount of energy is released.

Nuclear chain Reaction

- There is a release of extra ~~proton~~ neutron.
- The extra neutrons in turn initiate fission process, producing still more neutrons & so on.
- Thus a chain of nuclear fission is set up called nuclear chain reaction

* uncontrolled chain reaction

- Reaction is uncontrolled & rapid
e.g. Atom bomb.

$$\frac{\text{No. of neutrons hitting next target}}{\text{no. of neutrons emitted}} > 1$$

* Controlled chain reaction

- Reaction is Controlled & steady
e.g. Nuclear reactor

The reaction is controlled in such a way that only one of the neutrons emitted in a fission causes another fission, then the fission rate remain constant & the energy is released steadily.

$$K = \frac{\text{Rate of production of neutrons}}{\text{Rate of loss of neutrons}}$$

If $K = 1$, operation of reactor is said to be critical.

$K > 1$, in this case, reaction is super critical.

$K < 1$, reaction gradually stops & condition is called sub critical.

$$\frac{\text{No of neutrons hitting next target}}{\text{no. of neutrons emitted}} < 1$$

Date: Page:

* Application of Nuclear Fission

→ Nuclear reactors to produce electricity,
→ To produce Atom bombs.

* Application :- Nuclear Reactor

- An arrangement to generate, electricity making use of nuclear fission.

Requirement for controlled nuclear fission in reactor.

1. Neutrons to be slowed down.
2. Excess neutrons to be absorbed.

* How slow down the Neutrons?

→ Moderators are light nuclei which slow down fast moving neutrons by elastic collision

→ Commonly used moderators
- water
- Heavy water
- Graphite

* Consequences of use of Moderators

→ Multiplication factors of neutrons increases.

→ High multiplication factor results in uncontrolled chain reaction.

* Excess Neutrons to be absorbed by Control rods.

→ Controls rods are made of neutron absorbing materials.

→ It decreases the multiplication factor of neutrons to a very small value.

* **Advantages of Nuclear reactor.**

→ Energy released is extremely large.
→ Need fuel in extremely small quantity

* **Disadvantages of Nuclear reactor**

→ Spent fuel is highly radioactive & extremely hazardous to all life forms.

→ Accumulation of radioactive waste.

Nuclear Fusion

* Combination of two lighter nuclei to form a relatively heavier nucleus.

* Huge amount of energy is released.

* Temperature at which protons would have enough energy to overcome the Coulomb's barrier is very high.

$$\begin{bmatrix} {}_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + {}_1e^+ + \nu + 0.42\ MeV \\ {}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1 + 3.27\ MeV \\ {}_1H^2 + {}_1H^2 \rightarrow {}_1H^3 + {}_1H^1 + 4.03\ MeV \end{bmatrix}$$

Thermonuclear Fusion

→ Increasing the temperature of the material until the particles have enough energy due to their thermal motions alone to overcome the coulomb barrier

→ For thermonuclear fusion, extreme conditions of temp. ~~of~~ & pressure are required.

→ Application → Energy generation in stars.

Energy Generation in Sun

→ Energy generation in sun is multi-step process in which hydrogen is fused into helium.

→ It is termed as Proton-proton Cycle

→ Four hydrogen atoms combine to form an ${}_2^4He$ atom with a release of 26.7 MeV of energy.

Nuclear Reactor

It is a device that can initate a Self-Sustaining Controlled chain reaction of a fissionable material. They are used at nuclear power plants for generating electricity & in Propulsion of ships.

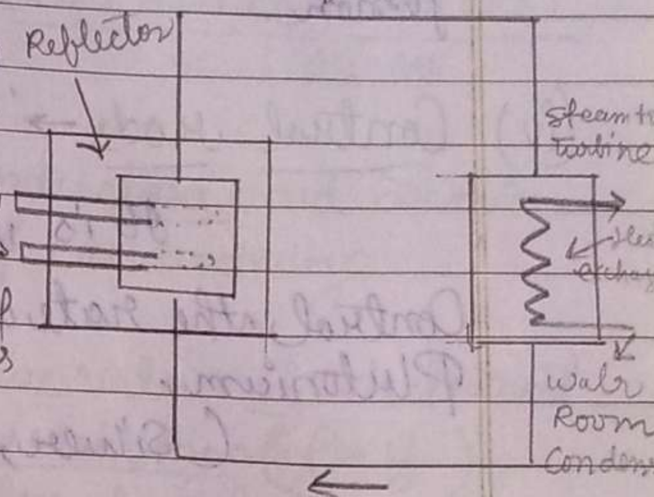


Fig- Nuclear reactor

Construction

(i) Nuclear fuel

It is a material that can be burned by nuclear fission or fusion to derive nuclear energy.

The Common fuels used in nuclear reactor are ^{233}U, ^{235}U, ^{239}Pu etc

(ii) Nuclear reactor Core

It is the portion of a nuclear reactor containing the nuclear fuel Components where the nuclear reaction takes place.

(iii) Moderator

It is the medium to slow down the fast

moving secondary neutrons produced during the fission.

(iv) Control rods →

It is used in nuclear reactor to Control the rate of fission of uranium & Plutonium.

(Silver, indium, boron & calcium)

(v) Coolant

It is a liquid used to remove heat from nuclear reactor & transfer it to electrical Generator & environment.

(vi) Shielding

It is the protective covering made of concrete wall to protect from harmful radiation.