MODERN ELECTRONIC THEORY OF ATOMS: RADIOACTIVITY

NUCLEAR AND RADIOCHEMISTRY

- **Nuclear and radiochemistry is concerned with reaction which occurs in the nucleus of an atom**
- **Atom is composed of three primary particles, viz; Electrons, Protons and Neutrons**
- **Nucleus is composed of neutrons and protons, and both neutron and proton have almost the same mass.**
- **Electrons are revolving round the nucleus and the mass of external electron is negligible**
- **Mass of an atom is proportional to the mass of protons and neutrons and the combined total of the masses is known as MASS NUMBER represented as A**
- **NUCLIDES: This is the term used to signify species of known atom characterized by the number of protons and neutrons.**
- **A nuclide is an atomic species in which all atoms have the same number of proton and neutron** ($^{2}_{1}H$, $^{4}_{2}He$, $^{6}_{3}Li$)
- **The nuclides of chlorine atoms are represented as** $^{35}_{17}Cl$, $^{37}_{17}Cl$
- **Nuclides with the same mass number A are called ISOBARS e.g.** $^{3}_{1}H$, $^{3}_{2}He$
- **Nuclides of the same atomic number (proton number) but different neutron number are called ISOTOPE e.g.** $^{1}_{1}H$, $^{2}_{1}H$ and $^{3}_{1}H$ are hydrogen, deuterium and tritium respectively
- **Nuclides with the same neutron but different atomic number(z) are called ISOTONES e.g.** $^{3}_{1}H$, $^{4}_{2}He$

NUCLEUS STABILITY

- **Certain combination of proton and neutron produce stable nuclide whereas others do not**
- **Nucleus stability is achieved when the number of protons is approximately equal to the number of neutron i.e. n approximately equal to p (z), n/p or n/z = 1 especially for light elements such as $^{2}_{1}H$, $^{4}_{2}He$, $^{6}_{3}Li$ etc.**
- **Above calcium (z=20,n=20) no stable nucleus exist equal number of protons and neutrons because as z increases repulsive force increases at a greater force rate than attractive force ^{200}Hg n/p = 1.5 , ^{208}Pb n/p =1.53**
- **If nuclide is rich in neutron, it will be unstable and stability may be achieved by conversion of neutron into proton within the nucleus i.e.**

  $$n \longrightarrow p + e + \gamma$$
- **On the other hand if the nucleus is very rich in proton, it becomes unstable and stability is also achieved through an increase in n/p i.e converting excess proton into neutron i.e $p + e \longrightarrow n + \gamma$**
- **ASSIGNMENT: DISCUSS NUCLEUS STABILITY DIAGRAM**

NUCLEAR RADIOACTIVITY AND RADIOACTIVITY DECAY

- **Radioactivity** is the spontaneous emission of radiation by an element and such an element is called radioactive element
- A **radioactive element** emits radiation continually and spontaneously
- **Radiation types** being emitted are alpha (α), beta (β), gamma (γ) rays, x-ray, positron, neutron etc.
- Radioactivity is always associated with release of energy at least about a million times as great as that liberated during any chemical reaction
- **Radioactive decay** is the spontaneous disintegration of the nucleus of an atom in emitting any of (α), beta (β), gamma (γ) rays, x-ray, positron, neutron etc.
- During disintegration, the parent nucleus/nuclide undergoes a change in atomic number and become the nuclide of a different element called **daughter nucleus**.

TYPES OF RADIOACTIVITY

- There are two types of radioactivity, viz;
  - (i) Natural radioactivity and
  - (ii) Artificial or Induced radioactivity

NATURAL RADIOACTIVITY

- This is the type of radioactivity that occur naturally by emitting some or all of alpha (α), beta (β) and gamma (γ) rays.
- Natural radioactivity occurs in heavy radioactivity elements whose atomic number lie between 81 to 92 and they have the longest half life period.
- Its decay is by a series of alpha (α), beta (β) emission and produce radioactive elements which successively more stable until finally a stable isotope reached
- EXAMPLES
  - Alpha Decay Process

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}\alpha\ ({}^{4}_{2}He)$$

$${}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha\ ({}^{4}_{2}He)$$

  - Beta Decay Process

$${}^{239}_{92}U \longrightarrow {}^{239}_{93}Np + {}^{0}_{-1}e\ (\beta)$$

$${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e\ (\beta)$$

$${}^{32}_{15}P \longrightarrow {}^{32}_{16}Np + {}^{0}_{-1}e\ (\beta)$$

$${}^{227}_{89}Ac \longrightarrow {}^{227}_{90}Th + {}^{0}_{-1}e\ (\beta)$$

$$\mathbf{{}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}X + {}^{0}_{-1}e\ (\beta)}$$

(Electron Emission)

$^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{+1}\beta$

$^{23}_{11}Na \longrightarrow ^{23}_{10}Ar + ^{0}_{+1}\beta$

$$^{A}_{Z}X \longrightarrow ^{A}_{Z-1}X + ^{0}_{+1}e\ (\beta)$$

(Positron Emission)

$^{73}_{33}As + ^{0}_{-1}\beta\ (e) \longrightarrow ^{73}_{32}Ge$

$^{55}_{55}Fe + ^{0}_{-1}\beta\ (e) \longrightarrow ^{55}_{25}Mn$

$$^{A}_{Z}X + ^{0}_{-1}e\ (\beta) \longrightarrow ^{A}_{Z-1}X$$

(Electron Capture)

- Isomeric Transition Process: Here energy is simply emitted from a metastable

$$^{60}_{27}Co \longrightarrow ^{60}_{27}Co + \text{energy}$$

INDUCED OR ARTIFICIAL RADIOACTIVITY

- This occurs when a nuclear reaction is brought about by bombarding a stable nucleus/isotope by a nuclear particle (such as proton, alpha, beta, gamma etc) or nuclei of other atoms such as carbon
- The bombarding particle may be captured by the nucleus, and the nucleus may undergo fission or fusion or two small nuclei may occur, depending on the condition of the bombardment
- Natural radiation may be used to induced nuclear reaction but this limits the energy of bombarding particles i.e. what happens exactly depends on the nature and energy of the bombarding particles.

- Artificial radioactivity can occur in the following ways:-
  - (a) **Neutron Bombardment**

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U$$

$$^{59}_{27}Co + ^{1}_{0}n \longrightarrow ^{60}_{27}Co$$

  - (b) **Neutron-Alpha Reaction (n,α)**

$$^{27}_{13}Al + ^{1}_{0}n \longrightarrow ^{24}_{11}Na + ^{4}_{2}He\ (\alpha)$$

$$^{6}_{3}Li + ^{1}_{0}n \longrightarrow ^{3}_{1}H + ^{4}_{2}He\ (\alpha)$$

  - (c) **Neutron-Gamma Reaction (n, γ)**

$$^{23}_{11}Na + ^{1}_{0}n \qquad ^{60}_{27}Na + \gamma$$

$$^{59}_{27}Co + ^{1}_{0}n \longrightarrow ^{60}_{27}Co + \gamma$$

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U + \gamma$$

    - This reaction (n, γ) is widely used to prepare new isotopes but their products are chemically identical to the target element. They are not easily separated

  - (d) **Atomic Transmutation (n, p reaction)**
    - Artificial transmutation is the change of one element into another element by human effort. This is carried out by accelerating an highly energetic neutron.

$$^{35}_{17}Cl + ^{1}_{0}n \longrightarrow ^{35}_{17}S + ^{1}_{1}H\ (p)$$

$$^{31}_{15}P + ^{1}_{0}n \longrightarrow ^{31}_{14}Si + ^{1}_{1}H\ (p)$$

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

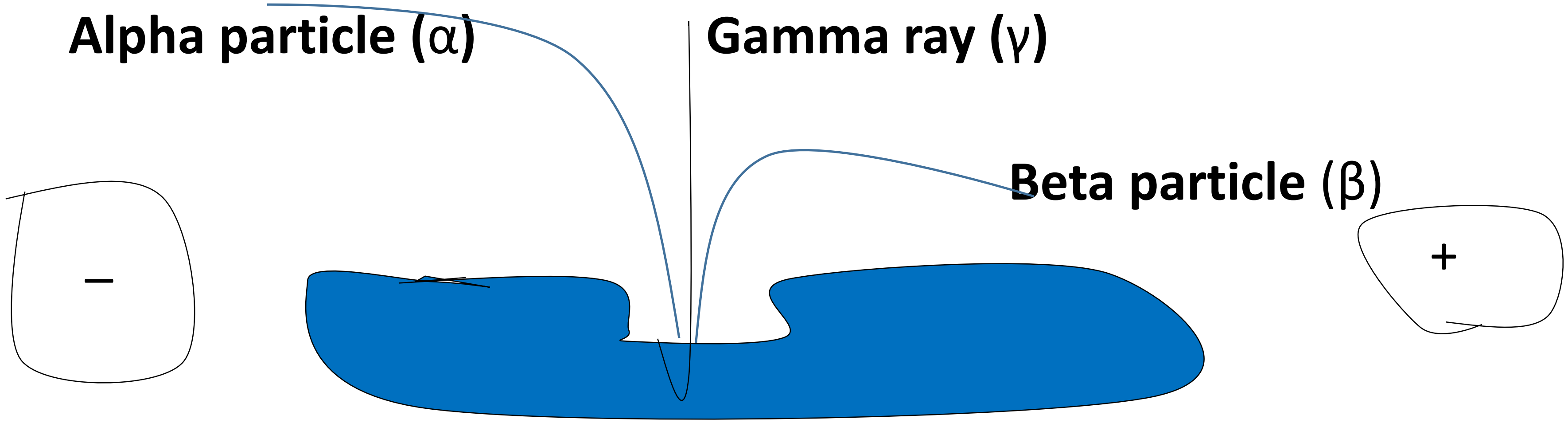
- The product of this type of reaction can be easily recovered because they are chemically different.

- (e) **Neutron-Gamma Reaction followed by β- emission**

$$^{198}_{98}Pt + ^{1}_{0}n \longrightarrow ^{199}_{98}Pt + \gamma \longrightarrow ^{199}_{99}Es + ^{0}_{-1}e$$

NATURE OF NUCLEAR RADIATION

- Simple experiment has shown that nuclear radiation consist of three distinct emission called alpha (α), beta(β) and gamma (γ)



- Radium is enclosed in a block placed between two powerful magnets
- It was discovered that some of the rays were deflected in the opposite direction (alpha(α) and beta (β) rays) while gamma (γ) rays are not deflected
- PROPERTIES OF ALPHA, BETA AND GAMMA RAYS

PARTICLES	ALPHA (α)	BETA (β)	GAMMA (γ)
NATURE	Helium nucleus $^{4}_{2}He^{2+}$	Electron $^{0}_{-1}e$ **(β)** Positron $^{0}_{+1}e$ **(β)**	Electromagnetic
CHARGE	+2	-1 or +1	Nil
RELATIVE PENETRATING POWER	Low (1)	Medium (100)	High (10,000)
RANGE IN AIR	A few centimetre	A few metres	A few kilometre
STOPPED BY	Air or Paper	Thin Aluminium	Thick lead
EFFECT OF ELECTRIC OR MAGNETIC FIELD	Deflected towards negative	Strongly deflected towards positive	Undeflected

NUCLEI DISINTEGRATION

EMISSION	PARENT ATOM	DAUGHTER PRODUCT
α- Particle	A, Z	A-4, Z-2
β - Particle	A, Z	A, Z+1
γ - Particle	A, Z	A, Z

- The radioactive displacement law states that when alpha (α)- emission takes place, there is a movement two places down the periodic table and when there is a beta (β)-emission there is a movement one place up the periodic table.

RADIOACTIVE DECAY RATE

- The spontaneous decay of radioactive nuclei is a first order process.
- The number of disintegration per second is proportional to the number of atom present at that time
- If N is the number of atom present at time t and dN is the number of atom disintegrating in the material then,

$$-dN \,\alpha\, N$$

$$-dN = \lambda N \quad \text{(where } \lambda \text{ is the decay constant)}$$

- Integrating between the limit of N=No at time zero and N at time t

$$dN =- \lambda N$$

$$-\lambda = dN/N$$

$$\int -\lambda = \int \frac{dN}{N} = /\ln N/ {}^{N}_{NO}$$

$$\ln /N-No/ = -\lambda t$$

$$e^{-\lambda t} = \frac{N}{No}$$

$$N = No e^{-\lambda t}$$

- **HALF LIFE $T_{½}$** of an element is the time interval at the end in which half the material would have disintegrated i.e. $T_{½}$ is the time at which N=No/2 or 2N=No

$$N = No e^{-\lambda t}$$

$$e^{-\lambda t} = \frac{N}{No}$$

$$\frac{N}{2N} = e^{-\lambda T_{½}}$$

$$\mathbf{½} = e^{-\lambda T_{½}}$$

$$\log_{e} \mathbf{½} = \log_{e} e^{-\lambda T_{½}}$$ **(e = 2.718)**

$$-\log_{e} 2 = -\lambda T_{½}$$

$T_{½}$ **= 0.693/** λ **or** λ **= 0.693/** $T_{½}$

- CLASSWORK
  - (i) 0.030g of Cs by β- emission to produce table zeron. If the half life of this material is 5.5 years. How many Cs will be left after 16.5 years? (0.00375g).
  - (ii) The half life of ^{214}Pb is 28minutes. If a 0.048g of pure ^{214}Pb was prepared by 9 am. (a) What is the decay constant? (b) How many grammes of ^{214}Pb would remain in the sample at 11.14 a.m. (c) if the ^{214}Pb are weighed twice as much as 9 O'clock in the morning, what would be the weight of ^{214}Pb at 11.14 am?
  - (iii) A gas desk is contaminated with radioactive $^{32}_{16}P$ having half life 14.30days, how many will you emit until original value is completely disintegrate and how many days is this?
  - (iv) if 8×10^{10} atoms of Radon is separated from Radium, how many Radon atoms will be left after 11.46days (Half life for Radon is 3.82days) (v) 0.06g of $^{208}_{82}Pb$ by beta particle to produce stable krypton if the half life of $^{208}_{82}Pb$ is 11 years. How many Pb will be left after 44 years.
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NUCLEAR REACTIONS

- Nuclear reaction may occur either there is nuclear stability or not
- If there is nuclear instability a spontaneous reaction will take place and such a reaction is called radioactivity (natural)
- A nuclear reaction can also be induced when the nucleus is struck by a high velocity particle. The kinetic energy of the particle will supply the energy for the reaction. This is called Induced reaction or artificial radioactivity.
- Induced reaction consists of two types, viz; (i) Fission and (ii) Fusion
- **NUCLEAR FISSION**
- This is brought about by splitting heavy nuclei into approximately equal pieces
- When an heavy nuclei is bombarded with light energy neutrons, the extra energy may be sufficient to split the already distorted nucleus into two fragments
- An example is ${}^{235}_{92}U$, when bombarded with high energy neutron, different products are formed depending on how the nucleus split up e.g.

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{139}_{54}Xe + {}^{95}_{38}Sr + 2({}^{1}_{0}n)$$

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{143}_{56}Ba + {}^{90}_{36}Kr + 3({}^{1}_{0}n)$$

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{135}I + {}^{97}Y + 4({}^{1}n)$$

- Here several neutrons are formed by initial fission and if this attack other uranium atoms they release even more neutrons which attack more uranium atom and so on, so that a very large number of fission will occur very rapidly.

NUCLEAR FUSION

- Light elements are less stable and the joining of two light nuclei which result in a more stable nucleus is called FUSION with liberation of extra energy.
- The components of the two nuclei must be brought together against repulsive forces and this is accompany by accelerating particles of a high velocity.
- Fusion releases very high amount of energy.

$${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}H + {}^{1}_{0}n$$

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

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

$${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{4}_{2}He + \gamma$$

$${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{2}_{2}He + {}^{1}_{0}n$$

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

NUCLEAR REACTORS OR WEAPON

- Fission reactions are used in nuclear reactors
- The release of energy from chain reactions is controlled so that it takes place gradually over a relatively long period of time.
- In nuclear reactors, the chain reaction is uncontrolled, causing an explosion.
- Fissile material is brought together to form a critical mass, and the energy is released in a short but devastating burst.
- A fission chain reaction occurs rapidly by bringing the atomic bomb material together to form a critical mass.
- The critical mass is large enough to ensure that the majority of the neutrons being emitted do not escape but bring about further fissions.
- For obvious reasons the nuclear material must be kept below the critical mass until the moment when the explosion is required.
- A small explosion is used to bring the separate pieces of the nuclear material together
- Nuclear reactions are means of thermal power generating.

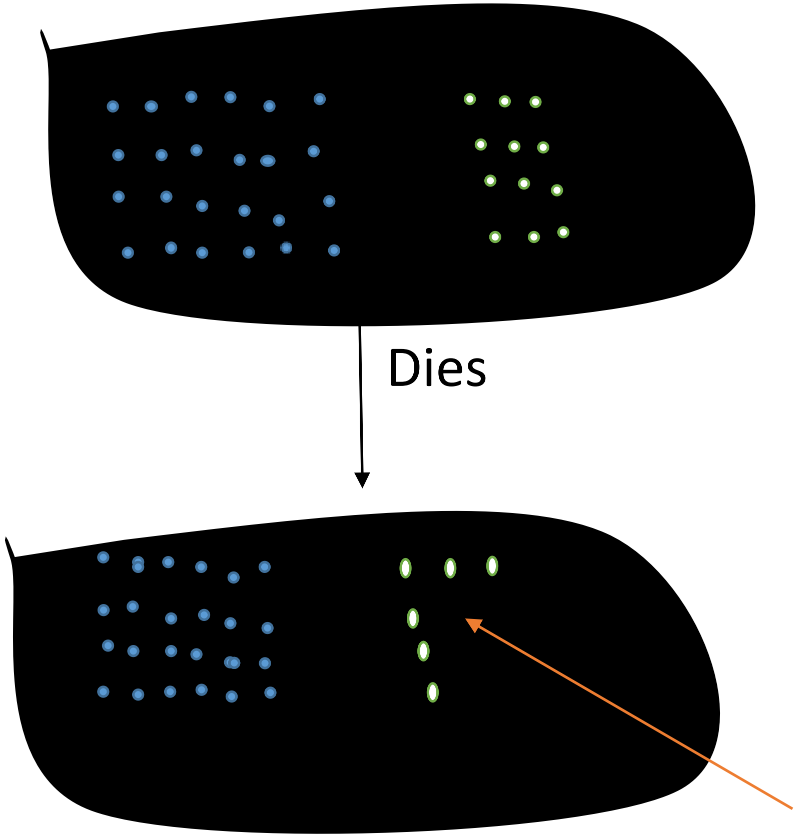
RADIOACTIVE CARBON DATING

- This is one of the application of radioactivity
- The radioactivity dating uses isotope ^{14}C and its half life is 5568 years.
- The ^{14}C isotope is continually being produced in the upper atmosphere where it combines with oxygen to form $^{14}CO_{2.}$
- Gradually, $^{14}CO_2$ mixes with the non radioactive $^{12}CO_2$ in the atmosphere and absorbed by plants during their metabolism.
- Animals, by eating plants and secreting waste products, continually have an intake and output of ^{14}C because of the many different carbon compounds formed from the metabolism and catabolism in the animal body.
- However, as soon as a plant or animal dies, its ^{14}C intake terminates and the ^{14}C present in the dead species then undergoes radioactive decay.
- Hence any material which is constructed from plants and animals will have ^{14}C incorporated in them and the amount of ^{14}C present will give the age of the material

- The principle of radiocarbon dating can be illustrated thus:

$^{12}_{6}C$ from $^{12}_{6}CO_2$ $^{14}_{6}C$ from $^{14}_{6}CO_2$ $(^{14}_{7}N + ^{1}_{0}n \rightarrow ^{12}_{6}C + ^{1}_{1}H)$

Living Material



Ratio of $^{12}_{6}C$ to $^{14}_{6}C$ is 2 to 1 and is kept constant

Dead Material

Ratio of $^{12}_{6}C$ to $^{14}_{6}C$ is 4 to 1 and gradually changes

The missing $^{14}_{6}C$ atoms have decayed to $^{14}_{7}N$

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

- Radioactive carbon dating relies on measuring the amount of carbon-14 in once living matter.
- The uptake of carbon from the environment stops on death.
- As the carbon-14 decays, the proportion of it in the sample gradually increases.
- The relative amount of carbon-12 to carbon-14 is a measure of the length of time that the material has been dead.

APPLICATIONS/USES OF RADIOACTIVITY

- (i) Nuclear reactor or weapon for war fare
- (ii) Radioactive carbon dating in knowing the age of material
- (iii) Study of reaction mechanism
- (iv) Determination of molecular structure
- (v) Medicinal applications: Location of tumor and treatment of goitre
- (vi) Industrial applications

  (a) Location of linkages (b) Determination of flow (c) Detection of metal fatigue (d) testing for wear in steel (e) Checking for uniformity in plastics (f) As source of power in remote locations

- (vii) Agricultural applications
  - (a) Insect control (b) seed preservation (c) food preservation
- (viii) Chemical applications
  - (a) Determination of the solubility of sparingly soluble salts
  - (b) Help to trace the course of a reaction by the use of radioactive tracers

MASS DEFECT AND BINDING ENERGY

- The forces within the nucleus are often described in terms of binding energy which is attributed to the difference of the means of a particles when they are in the nucleus from their separate masses.
- Mass loss accompanies all energy changes, although it is normally far too small to detect.
- The loss or difference in mass between the nucleus and the separated nucleons (i.e proton and neutron) is called **MASS DEFECT**

$$\Delta m = \sum m(products) - \sum m(reactants)$$

$$= \sum m({}^{A}_{z}X\ nucleus) - (Z \times M_p + (A-Z)\, M_n)$$

Where A= mass number, Z = Proton Number, M_p = Mass atomic unit of proton ^1H = 1.0078u, M_n = Mass atomic unit of neutron n = 1.0087u

- For example , the helium nucleus ${}^{4}_{2}He$ contains two protons and two neutrons which is expected to have mass of $(2 \times M_p + 2 \times M_n) = (2 \times 1.0078 + 2 \times 1.0087) = 4.033u$. The actual mass of helium nucleus as found by spectrometry is 4.0015u i.e. a decrease of 0.0315 mass unit is observed. This decrease/difference/loss in mass is referred to as Mass defect.
- The mass loss is measurable and the observed change in mass can be used to calculate the energy released in accordance with Einstein law $E= mc^2$

where m is the loss in mass and c is the velocity of light 3×10^8 m/s

- The energy released is equal in magnitude to the binding energy of the nucleus.
- The nuclear binding energy is defined as the energy required to separate a nucleus into its individual nucleons i.e. its protons and neutrons
- The nuclear binding energy E_{bind}, is the energy released when Z protons and A-Z neutrons come together to form.
- It is used as a measure of the stability of a nuclide.
- The greater the binding energy of a nucleon, the lower is its energy in the nuclide.
- The nuclear binding energy is proportional to the difference in mass Δm between the nucleus and the separated nucleons
- $E_{bind} = \Delta mc^2$ (Einstein's Formula)

- **Question**

Calculate the nuclear binding energy of the helium nucleus, if a helium nucleus has a mass of 4.0026amu given that Mass atomic unit of proton ^{1}H = 1.0078amu, Mass atomic unit of neutron n = 1.0087amu and 1amu = 1.6605×10^{-27}Kg.

Answer

The mass difference **Δm =** $\sum \boldsymbol{m(products)}$ **-** $\sum \boldsymbol{m(reactants)}$

= $\sum \boldsymbol{m}({}^{A}_{z}X\ \boldsymbol{nucleus})$ **-** **(**$Z \times M_p$ + $(A\text{-}Z)\, M_n$**)**

Since Helium nuclide = ${}^{4}_{2}He$ i.e. 2 protons, 4-2 =2 neutrons, m(nucleus)= 4.0026amu

Δm = 4.0026 – (2 × **1.0078 + 2** × 1.0087**) = -0.0304amu**

To convert amu to Kg:

Δm = -0.0304 $\times 1.6605 \times 10^{-27}$Kg = -5.05×10^{-29}Kg

The binding energy E = Δmc^2 ($c = 3 \times 10^8$m/s)

= $-5.05 \times 10^{-29} \times (3 \times 10^8)^2$

= -4.55×10^{-12}J

The molar binding energy = binding energy (E) × Avogadro's constant (6.02×10^{23})

= $-4.55 \times 10^{-12} \times 6.02 \times 10^{23}$ = -2.7×10^{9}KJ/mol

- ASSIGNMENT
  - (i) If $^{238}_{92}U$ has a mass of 238.051amu. Calculate the binding energy per nucleon for $^{235}_{92}U$
  - (ii) Calculate the molar binding energy of carbon-12nuclei (Answer= -8.7×10^{9}KJ/mol)
  - (iii) Calculate the binding energy and molar binding energy of uranium-235 nuclei. The mass of one uranium atom is 235.0439u
  - (iv) Calculate the binding energy per nucleon for (a) ^{4}He, 4.0026u, (b) ^{239}Pu, 239.0522u (c) ^{2}H, 2.0141u (d) ^{56}Fe, 55.9349u. Which nuclide is the most stable? (1u= 1.6605×10^{-27}Kg). Also calculate the molar binding energy per nucleon for (a), (b), (c) and (d)
  - (v) Calculate the binding energy per nucleon for (a) ^{98}Mo, 97.9055u, (b) ^{151}Eu, 150.919u (c) ^{20}B,10.0129u (d) ^{232}Th, 232.0382u. Which nuclide is the most stable?