is denoted by Z. The total number of protons and neutrons in a nucleus is called its mass number of the element and is denoted by A.

Number of protons in an atom = Z

Number of electrons in an atom = Z

Number of nucleons in an atom = A

Number of neutrons in an atom = $N = A - Z$.

Nuclide

- It is a specific nucleus of an atom which is characterised by its atomic number Z and mass number A. It is represented by $_ZX^A$ where X is the chemical symbol of the element.

Nuclear Radius

- Nuclear radius $R = R_0 A^{1/3}$
  where R_0 is a constant and A is the mass number.
  Nuclear radius is measured in fermi.
  $1 \text{ fm} = 10^{-15}$ m

Nuclear Density

- Nuclear density is independent of A and is order of the 10^{17} kg m^{-3}.

Isotopes

- Isotopes of an element are the atoms of the element which have the same atomic number but different mass numbers. *e.g.* $_1H^1$, $_1H^2$, $_1H^3$, are the three isotopes of hydrogen.

Isobars

- Isobars are the atoms of different elements which have the same mass number but different atomic numbers. *e.g.* $_{11}Na^{22}$ and $_{10}Ne^{22}$.

Isotones

- Isotones are the nuclides which contain the same number of neutrons *e.g.* $_{17}Cl^{37}$ and $_{19}K^{39}$.

Illustration 5

Given the mass of iron nucleus as 55.85 u and A = 56, find the nuclear density?

Soln.: $m_{Fe} = 55.85$, $1\text{u} = 1.66 \times 10^{-27}$ kg

The density of matter in neutron stars (an astrophysical object) is comparable to this density. This shows that matter in these objects has been compressed to such an extent that they resemble a big nucleus.

$$\text{nuclear density} = \frac{\text{mass of nucleus}}{\text{volume of nucleus}}$$

$$= \frac{A \times 1\text{u}}{\frac{4}{3}\pi R^3} = \frac{A \times 1\text{u}}{\frac{4}{3}\pi\left(R_0 A^{1/3}\right)^3}$$

$$= \frac{55.85 \times 1.66 \times 10^{-27}}{\frac{4\pi}{3} \times \left(1.2 \times 10^{-15}\right)^3} \times \frac{1}{56} = 2.29 \times 10^{17} \text{ kg m}^{-3}$$

Illustration 6

(a) Two stable isotopes of lithium ^6_3Li and ^7_3Li have respective abundances of 7.5% and 92.5%. These isotopes have masses 6.01512 u and 7.01600 u, respectively. Find the atomic mass of lithium.

(b) Boron has two stable isotopes, $^{10}_5\text{B}$ and $^{11}_5\text{B}$. Their respective masses are 10.01294 u and 11.00931 u, and the atomic mass of boron is 10.811 u. Find the abundances of $^{10}_5\text{B}$ and $^{11}_5\text{B}$.

Soln.: Abundance of ^6_3Li is 7.5% and abundance of ^7_3Li is 92.5%

hence atomic mass of lithium

$$= \frac{7.5\,(6.01512\text{ u}) + 92.5\,(7.01600\text{ u})}{100}$$

Atomic mass of lithium

$$A = \frac{45.1134 + 648.98}{100}\text{ u}$$

$$A = 6.941\text{ u}$$

(b) Let abundance of $^{10}_5\text{B}$ is x% than abundance of $^{11}_5\text{B}$ will be $(100 - x)$%

Atomic mass of boron

$$= \frac{x[10.01294\text{ u}] + (100 - x)[11.00931\text{ u}]}{100}$$

$$100 \times 10.811\text{ u} = 1100.931\text{ u} - 0.99637x\text{ u}$$

Solving we get, $x = \frac{19.831}{0.99637} = 19.9$

So, relative abundance of $^{10}_5\text{B}$ isotope = 19.9%

Relative abundance of $^{11}_5\text{B}$ isotope = 80.1%

RADIOACTIVITY

- The phenomenon of spontaneous emission of radiation or particles from the nucleus is called radioactivity. The substances which emit these radiations are called as radioactive substances. It was discovered by Henry Becquerel for atoms of radium. Later it was discovered that many naturally occurring compounds of heavy elements like radium, thorium etc also emit radiations.
- At present, it is known that all the naturally occurring elements having atomic number greater than 82 are radioactive. For example some of them are; radium, polonium, thorium, actinium, uranium, radon etc. Later on Rutherford found that emission of radiation always accompanied by transformation of one element (transmutation) into another. Actually radioactivity is the result of disintegration of an unstable nucleus. Rutherford studied the nature of these radiations and found that these mainly consist of α, β, γ rays.
- **α-Particles ($_2He^4$)**
  - These carry a charge of $+2e$ and mass equal to $4m_p$. These are nuclei of helium atoms. The energies of α-particles vary from 5 MeV to 9 MeV and their

velocities vary from 0.01-0.1 times of c (velocity of light). They can be deflected by electric and magnetic fields and have low penetrating power but high ionizing power.

- β-Particles ($_{-1}e^0$)
  - These are fast moving electrons having charge equal to $-e$ and mass $m_e = 9.1 \times 10^{-31}$ kg. Their velocities vary from 1% to 99% of the velocity of light (c). They can also be deflected by electric and magnetic fields. They have low ionizing power but high penetrating power. β^+ particles are positrons.
- γ-Radiation ($_0\gamma^0$)
  - These are electromagnetic waves of nuclear origin and of very short wavelength. They have no charge and no mass. They have maximum penetrating power and minimum ionising power. The energy released in a nuclear reaction is mainly emitted in the form of γ radiation.

LAWS OF RADIOACTIVE DECAY

Rutherford-Soddy Laws (Statistical Laws)

- The disintegration of a radioactive substance is random and spontaneous.
- Radioactive decay is purely a nuclear phenomenon and is independent of any physical and chemical conditions.

  The radioactive decay follows first order kinetics, *i.e.*, the rate of decay is proportional to the number of undecayed atoms in a radioactive substance at any time t. If dN be the number of atoms (nuclei) disintegrating in time dt, the rate of decay is given as dN/dt. From first order of kinetic rate law $\frac{dN}{dt} = -\lambda N$, where λ is called as decay or disintegration constant.
- Let N_0 be the number of nuclei at time $t = 0$ and N_t be the number of nuclei after time t, then according to integrated first order rate law, we have

$$N_t = N_0 e^{-\lambda t} \Rightarrow \lambda t = \ln\frac{N_0}{N_t} = 2.303 \log\frac{N_0}{N_t}$$

- The half life ($T_{1/2}$) period of a radioactive substance is defined as the time in which one-half of the radioactive substance is disintegrated. If N_0 be the number of radioactive nuclei at $t = 0$, then in a half life $T_{1/2}$, the number of nuclei decayed will be $N_0/2$.

$$N_t = N_0 e^{-\lambda t} \quad \text{...(i)}$$

$$\Rightarrow \frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}} \quad \text{...(ii)}$$

From (i) and (ii), we get

$$\frac{N_t}{N_0} = \left(\frac{1}{2}\right)^{t/T_{1/2}} = \left(\frac{1}{2}\right)^n$$

n = number of half lives

- The mean life (T_m) of a radioactive substance is equal to the sum of life times of all atoms divided by the number of all atoms. It is given by

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

Illustration 7

The mean lives of a radio active substance are 1620 and 405 years for α-emission and β-emission respectively. Find out the time during which three fourth of a sample will decay if it is decaying both the α-emission and β-emission simultaneously.

Soln.: When a substance decays by α and β emission simultaneously, the average rate of disintegration λ_{av} is given by

$\lambda_{av} = \lambda_\alpha + \lambda_\beta$

where λ_α = disintegration constant for α-emission only.

λ_β = disintegration constant for β-emission only.

Mean life is given by

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

$$\Rightarrow \lambda_{av} = \lambda_\alpha + \lambda_\beta \Rightarrow \frac{1}{T_m} = \frac{1}{T_\alpha} + \frac{1}{T_\beta}$$

$$= \frac{1}{1620} + \frac{1}{405} = 3.08 \times 10^{-3}$$

$$\lambda_{av} t = 2.303 \log\frac{100}{25}$$

$$(3.08 \times 10^{-3})t = 2.303 \log\frac{100}{25}$$

$$\Rightarrow t = 2.303 \times \frac{1}{3.08 \times 10^{-3}} \log 4 = 450.17 \text{ years.}$$

Soddy Fajan Laws (Group-Displacement Laws)

- When a nuclide emits one α-particle ($_2He^4$), its mass number (A) decreases by 4 units and atomic number (Z) decreases by 2 units.

$$_ZX^A \rightarrow _{Z-2}Y^{A-4} + _2He^4 + \text{Energy}$$

- When a nuclide emits a β-particle, its mass number remains unchanged but atomic number increases by one unit.

$$_ZX^A \rightarrow _{Z+1}Y^A + _{-1}e^0 + \bar{\upsilon} + \text{Energy}$$

  where $\bar{\upsilon}$ antineutrino.
- In the nucleus, due to conversion of neutron into proton, antineutrino is produced. It has no charge or mass, but has momentum. When a proton is converted to a neutron, a neutron and a +ve β-particle is produced, which is called as positron. β rays are electrons and β^+ are the antielectrons or positrons.

$$_0n^1 \rightarrow _1p^1 + _{-1}e^0 + \bar{\upsilon}\,(\text{antineutrino})$$

$$_1p^1 \rightarrow _0n^1 + _{+1}e^0\,(\text{positron}) + \upsilon(\text{neutrino})$$

- Antineutrino and neutrino share the energy of electrons and positrons. That is the reason why the energy of β is continuous and β rays has a maximum energy.

  When a γ particle is produced, both atomic and mass number remain constant.

Activity of a Radioactive Isotope

- The activity of a radioactive substance (or radioisotope) means the rate of decay per second or the number of nuclei disintegrating per second. It is generally denoted by A.