Nuclei

Atomic Masses and Composition of Nucleus

An atom is composed of electrons, protons and neutrons. The protons and neutrons reside inside the nucleus of the atom which is at its centre, while the electrons revolve around the nucleus in some specific orbits, called stationary orbits or stationary shells, in which they do not radiate out energy.

The maximum number of electrons in an orbit can be $2n^2$, where n is the number of that orbit. The various orbits around the nucleus for n = 1, 2, 3, 4, 5, 6, 7, ... are named as K, L, M, N, O, P, Q, ... respectively and these orbits accommodates at the most 2, 8, 18, 32, 50, 72, 98, ... electrons respectively. The energy of electrons in different orbits are different and this energy increases with the increase in the number n of that orbit.

- The mass of an atom is so small that it is inconvenient to express it in kilograms.
- The unit in which atomic and nuclear masses are measured is called atomic mass unit (amu).
- One amu is defined as 1/12th of the mass of an atom of ${}_6C^{12}$ isotope.

Avogadro's number = 6.023×10^{23}

$\therefore$ Mass of 6.023×10^{23} atoms of C^{12} = 12 g

$$\text{Mass of 1 atom of } C^{12} = \frac{12}{6.023 \times 10^{23}} \text{ g}$$

$$1 \text{ amu} = \frac{1}{12} \times \frac{12}{6.023 \times 10^{23}} \text{ g}$$

$$\boxed{\therefore \text{amu} = 1.66 \times 10^{-27} \text{ kg}}$$

- Atomic masses can be measured using a mass spectrometer.
- The different types of atoms of the same element which have similar chemical properties but different masses are called isotopes.

Nucleus

- The nucleus has the positive charge possessed by the protons. For an atom of atomic number Z, the total charge on an atomic electron is ($-Ze$), while the charge of the nucleus is ($+ Ze$).
- The composition of a nucleus is described using the followings terms and symbols:

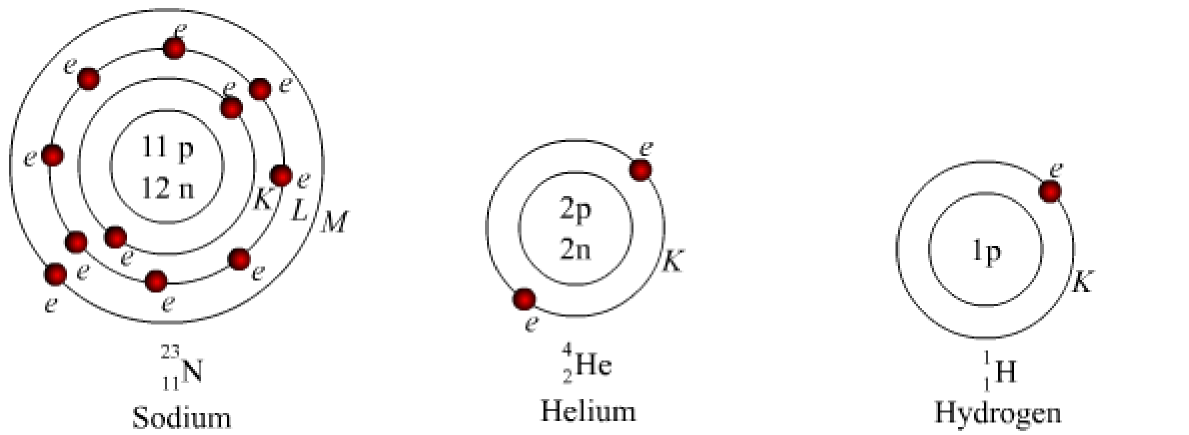
Z = atomic number = number of protons

N = neutron number = number of neutrons

A = mass number = $Z + N$ = total number of protons and neutrons

- Nuclear species can be shown by the notation ${}_{Z}^{A}X$, where X is the chemical symbol of the species.

Some Atmoic Models



Model of the sodium atom **Model of the helium atom** **Model of the hydrogen atom**

Isotopes

- They are the atoms of an element whose nuclei have the same number of protons, but different numbers of neutrons.
- They have the same atomic numbers, but have different mass numbers.
- They have identical chemical properties and are placed in same location in the periodic table.
- Deuterium ${}_{1}^{2}\mathrm{H}$ and tritium ${}_{1}^{3}\mathrm{H}$ are isotopes of hydrogen.

Isotones

- The nuclei with the same number of neutrons (A - Z) are called isotones.
- The nuclei ${}_{80}^{198}\mathrm{Hg}$ and ${}_{79}^{197}\mathrm{Au}$ are isotones. They do not have identical chemical properties and are placed in different locations in the periodic table.

Isobars

- They are the atoms of different elements with the same atomic weight, but with different atomic numbers.
- The nuclei ${}_{1}^{3}\mathrm{H}$ and ${}_{2}^{3}\mathrm{He}$ are isobars.

Size of Nucleus

- It was found experimentally that the volume of a nucleus is proportional to its mass number (A).
- Let

$R \rightarrow$ Radius of the nucleus

$\therefore$Volume $= \frac{4}{3}\pi R^3$

$\therefore \frac{4}{3}\pi R^3 \propto A$

$\Rightarrow R \propto A^{\frac{1}{3}}$

$R = R_0 A^{\frac{1}{3}}$

Where, R_0 is a constant = 1.2×10^{-15} m is the range of nuclear force

- The density of nuclei of all the atoms is same as it is independent of mass number.
- Mass is another form of energy. One can convert mass-energy into other form of energy.
- Mass-energy equivalence relation is $E = mc^2$

  Where,

  $m \rightarrow$ Mass

  $c \rightarrow$ Speed of light

Nuclear Binding Energy

- The difference in mass of a nucleus and its constituents is called the mass defect.
- Binding energy of a nucleus is the energy with which nucleons are bound in the nucleus.

Expression for Binding Energy

- In a nucleus ${}_Z X^A$,

  Z = Number of protons

  A = Number of protons + Number of neutrons

  Let m_p = Mass of a proton

  m_n = Mass of a neutron

  m_N = Mass of nucleus ${}_Z X^A$

  $\therefore$Mass defect,

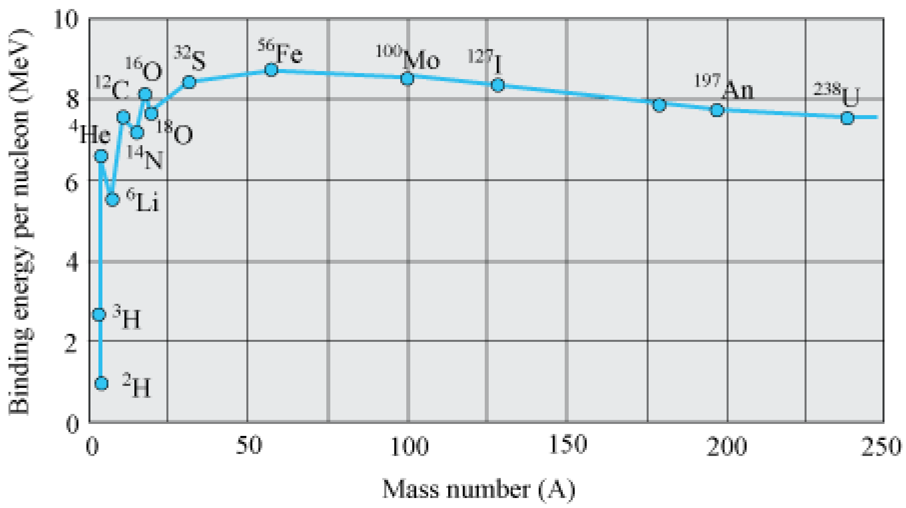
$\Delta m = [Zm_p + (A - Z)\, m_n - m_N]$

- Using Einstein's mass-energy equivalence,

  Binding energy = ΔmC^2

  $$= \left[Zm_p + (A-Z)m_n - m_N\right]C^2$$

- Average binding energy per nucleon is given by the total binding energy divided by the mass number of the nucleus.



- Binding energy per nucleon is practically constant for mass number. ($30 < A < 170$)
- Binding energy per nucleon is lower for both light nuclei ($A < 30$) and heavy nuclei ($A > 170$).
- **Importance of Binding energy curve**
- As we move from heavy nuclei region to the middle region of the plot, there is a gain in the overall binding energy and hence, in the release of energy. This indicates that energy can be released when a heavy nucleus breaks into roughly two equal fragments.

  This process is called nuclear fission.

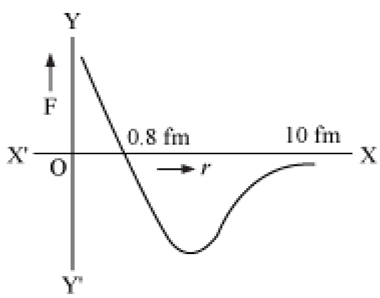
- When we move from lighter nuclei to heavier nuclei, there will be gain in the overall binding energy and release of energy. This is called nuclear fusion.

Nuclear Force

- It is the strong force of attraction which holds together the nucleons (neutrons and protons) in the nucleus of an atom, in spite of strong electrostatic forces of repulsion between protons.

Characteristics:

- They do not depend on the electric charge.
- They are the strongest forces in nature.
- They are very short range forces.
- Nuclear force is negligible when distance between nucleons is more than 10 Fermi. Attraction develops when brought closer. However, when the distance between them is less than 0.8 Fermi, they repel strongly.



Radioactivity

There are three types of radioactive decay:

(i) α- decay

(ii) β- decay

(iii) γ- decay

Law of radioactive decay

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

Where,

N = Number of nuclei in the sample

ΔN = Amount undergoing decay

Δt = Time

$$\frac{\Delta N}{\Delta t} = \lambda N$$

Where,

λ = Decay constant or disintegration constant

$\Delta t = 0$

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

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

On integrating both sides, we get

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

$\ln N - \ln N_0 = -\lambda\,(t - t_0)$

At $t_0 = 0$,

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

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

Decay rate (R) $= -\dfrac{dN}{dt}$

$$R = -\frac{dN}{dt} = \lambda N_0 e^{-\lambda t}$$
$$R = R_0 e^{-\lambda t}$$
$$R = \lambda N$$

The total decay rate R of a sample is called the activity of that sample.

SI unit for activity is Becquerel.

1 Becquerel = 1 Bq = 1 decay per second

Half life

The half life of a radioactive substance is defined as the average time for which the nuclei of the atoms of the radioactive substance exist.

$$t = t_{1/2}$$
$$R = \frac{1}{2} R_0$$

$$\therefore t_{1/2} = \frac{\ln 2}{\lambda}$$
$$= \frac{0.693}{\lambda}$$

Average life or mean life (τ)

$$\tau = \frac{\lambda N_0 \int_0^\infty t e^{-\lambda t} dt}{N_0}$$
$$= \lambda \int_0^\infty t e^{-\lambda t} dt$$
$$\tau = \frac{1}{\lambda}$$
$$\therefore T_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2$$

Alpha Decay

- Nucleus emits an alpha particle (a helium nucleus, ${}^4_2\mathrm{He}$)

$${}^A_Z\mathrm{X} \longrightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^4_2\mathrm{He}$$

- Q value of an alpha decay:

$$Q = (m_\mathrm{X} - m_\mathrm{Y} - m_\mathrm{He})c^2$$

Beta Decay

- Nucleus emits an electron or a positron

$$_{Z}A^{A} \longrightarrow {}_{Z+1}Y^{A} + {}_{-1}e^{0} + E_{\beta}$$

- In beta-minus decay,

$$n \rightarrow p + e^{-} + \bar{v}$$

- In beta-plus decay,

$$p \rightarrow n + e^{+} + \bar{v}$$

Gamma Decay

When a nucleus is in an excited state, it can make a transition to a lower energy state by the emission of electromagnetic radiation. The stream of photons emitted by the nuclei is known as gamma ray, and the gamma ray has MeV energies.

Nuclear Energy

- Energies involved in conventional energy sources are of the order of electron volts per atom, but energy involved in nuclear processes are million times larger.

Fission

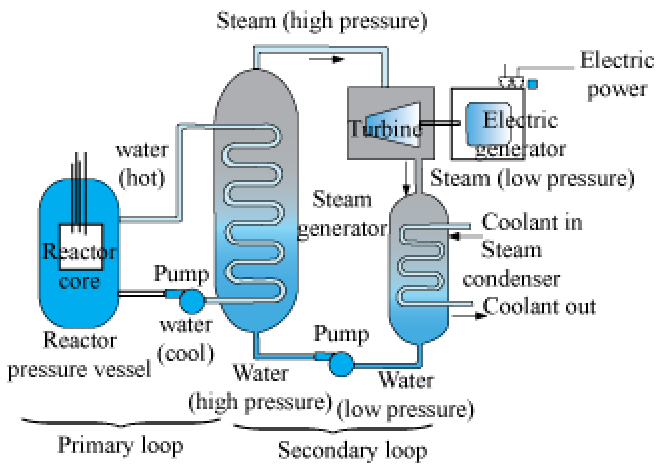
- When neutrons bombard various elements, new radioactive elements are produced.
- When a neutron is bombarded on a uranium target, the uranium nucleus breaks into nearly equal fragments releasing great amount of energy.

$${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U \rightarrow {}_{56}^{144}Ba + {}_{36}^{89}Kr + 3{}_{0}^{1}n$$

- Fission of uranium does not always produce Ba and Kr. It can produce any other pair also.
- Fragment nuclei produced in fission are highly neutron rich and unstable. Therefore, they emit beta particle until they reach a stable end product.
- Enormous amount of energy released in an atom bomb comes from uncontrolled nuclear fission reaction.

Nuclear Reactor

- When ${}^{235}_{92}U$ undergoes fission, it produces neutron, which initiates another ${}^{235}_{92}U$ nucleus to undergo fission.
- When this chain reaction is controlled suitably, we can obtain a steady energy output.
- This phenomenon is used in a nuclear reactor.
- Average energy of a neutron produced in fission of ${}^{235}_{92}U$ is 200 MeV. Unless slowed down, it will escape from the reactor without interacting with the uranium nuclei.



- Light nuclei called moderator is provided in the reactor along with the nuclei for slowing down fast neutrons.
- Commonly used moderators are water, heavy water (D_2O), and graphite.
- Moderator helps to increase the ratio of number of fission produced by a given generation of neutrons to the number of the proceeding generation. This ratio is called multiplication factor (K).
- The factor K should be brought close to unity to avoid explosion.
- Reaction rate is controlled through control rods made of neutron absorbing material such as cadmium.
- Safety rods are also added to reduce K rapidly.
- Core of the reactor is the site for nuclear fission.
- Core is surrounded by reflector to reduce leakage.
- Energy released in fission is continuously removed by a suitable coolant.
- Whole assembly is shielded to check harmful radiation from coming out.

- Wastes produced by nuclear reactors are hazardous.

Nuclear Fusion

- Two light nuclei fuse to form a larger nucleus, and energy is released in the process.

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H + 4.03 \text{ MeV}$$

- Two nuclei must come close enough so that attractive short range nuclear force is able to affect them.
- When fusion is achieved by raising the temperature, it is called thermonuclear fusion.
- Fusion reaction also takes place in sun in which the hydrogen is burnt into helium.
- Reaction occurring in sun is

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + e^{+} + \nu + 0.42 \text{ MeV}$$
$$e^{+} + e^{-} \rightarrow \nu + \nu + 1.02 \text{ MeV}$$
$$^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + \nu + 5.49 \text{ MeV}$$
$$^{3}_{2}H + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H + 12.86 \text{ MeV}$$

Four hydrogen atoms combine to form a $^{4}_{2}He$ atom with the release of 26.7 MeV of energy.

- After 5 billion years, the hydrogen burning will stop and the sun will begin to cool. The outer envelope of the sun will expand, turning it into the so called ‘red giant’.