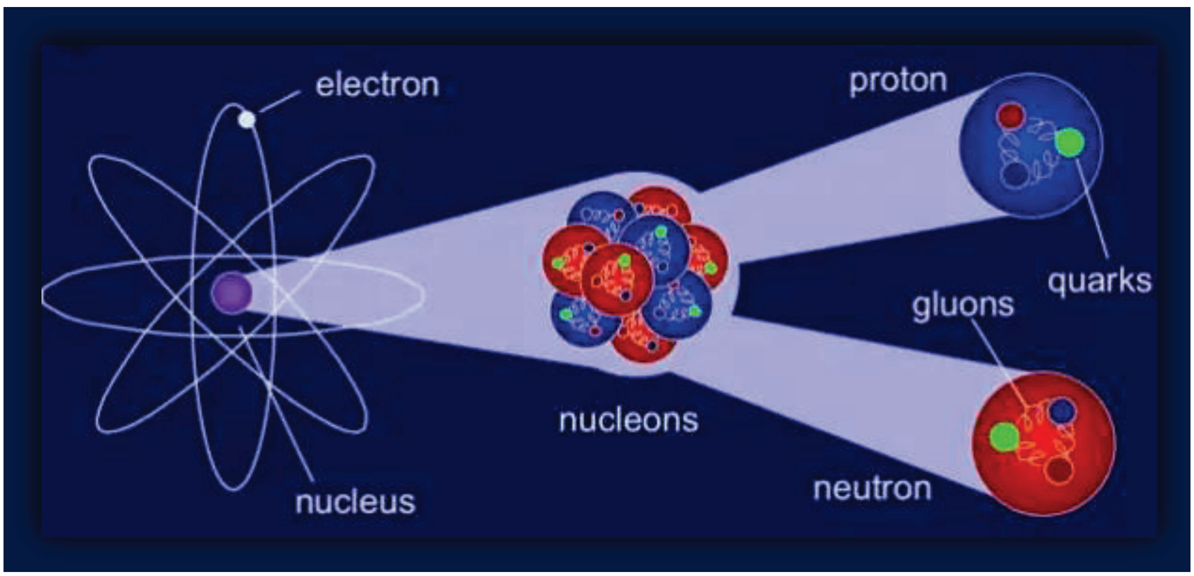
NUCLEI



Nuclei

Atomic nucleus

All atomic nuclei are made up of fundamental particles called protons and neutrons. A proton has a positive charge of the same magnitude as that of an electron. A neutron is electrically neutral and has the mass nearly equal to that of proton. The protons and the neutrons are together called nucleons.

Terms used

- **Nucleons:** Constituents of an atomic nucleus are called nucleons. Protons and neutrons are the nucleons.
- **Chemical Symbol:** The chemical symbol for an atom (or its nucleus) is ${}^{A}_{Z}X$ or ${}_{Z}X^{A}$.

  The symbol A represents the numbers of nucleons and is called the mass number. Z represents proton number in an atomic nucleus as well as the number of extra nuclear electron in the atom. The symbol n represents the number of neutrons in an atomic nucleus. Thus, $A = Z + n$; $n = A - Z$
- **Nuclide:** It is an accepted type or species of an atom characterised by its number of nucleons. A nuclide is represented by X^A. For convenience z number may also be included. For example, an oxygen nuclide is represented as ${}^{16}O$ or ${}^{16}_{8}O$ or ${}_{8}O^{16}$.

  - **Isotopes:** Nuclides with the same z are called isotopes. For example, hydrogen $({}^{1}_{1}H)$, deutron $({}^{2}_{1}D)$ and tritium $({}^{3}_{1}T)$ are the isotopes. The word isotope implies more than one species occupying the same place in the periodic table. The element like beryllium or aluminium has only one species in nature, and is said to form a single stable nuclide, rather than a single stable isotope. Unstable nuclides (natural or artificial) are called radioactive nuclides or radionuclides.
  - **Isobars:** Nuclides with the same mass numbers and different atomic numbers Z are called isobars.
    Example: ${}^{14}_{6}C$ and ${}^{14}_{7}N$ $(A = 14)$ ${}^{16}_{7}N$ and ${}^{16}_{8}O$ $(A = 16)$
  - **Isotones:** Nuclides with same neutron number n are called isotones.
    Examples: ${}^{31}_{15}P$ and ${}^{32}_{16}S$; ${}^{14}_{6}C$, ${}^{15}_{7}N$, ${}^{16}_{8}O$
  - **Isomers:** Nuclides with the same mass number (isobaric) and the same atomic number (isotopic) but different nuclear properties (such as life times, angular momentum and magnetic moment) are called Isomers. Isomeric state or level is usually denoted by the letter m attached to the mass number.
    For example ${}^{69m}Zn$ represents an isomeric state of ${}^{69}Zn$.
  - **Mirror nuclides:** Nuclides with same mass number, but neutron number of one nuclide is equal to the proton number of the other are called mirror nuclides.

    Examples:

    ${}^{11}_{6}C \to {}^{11}_{5}B + {}^{+}\beta$; $N_C = 5; Z_B = 5$

    ${}^{15}_{8}O \to {}^{15}_{7}N + {}^{+}\beta$; $N_0 = 7; Z_N = 7$

    ${}^{17}_{9}F \to {}^{17}_{8}O + {}^{+}\beta$; $N_0 = 9; Z_F = 9$

Relative abundance of isotopes of an element

Every element consists of a mixture of several isotopes. The relative abundance of different isotopes differ from one element to other.

Let the relative abundances of an element having three stable isotopes be (x) %, (y) % and (z) %. Let the atomic masses of these isotopes be M_1, M_2 and M_3. The average atomic mass of this element will be found using the following expression.

$$\text{Average atomic mass of the element} = \frac{x}{100} \times M_1 + \frac{y}{100} \times M_2 + \frac{z}{100} \times M_3$$

The sum of percentage relative abundances is 100. i.e., $x + y + z = 100$

General properties of a nucleus

1. **Constituents:** Protons and neutrons are the nuclear constituents.
2. **Mass:** It is the actual mass of the nucleus. It is slightly less then the sum of the masses of requisite number of nucleons in free state at rest constituting the nucleus.
3. **Size:** Experiments show that most nuclei are approximately proportional to the mass number A.

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

   Thus, the nuclear radius R is approximately proportional to the cube root of the mass number

   $R \propto A^{1/3} \Rightarrow R = R_0 A^{1/3}$ where $R_0 = 1.2 \times 10^{-15}$ m = 1.2 fm
4. **Nuclear density:** It is the ratio of the nuclear mass of a nucleus to its volume. It is of the order of 10^{17} kg m^{-3}. It is nearly the same for all nuclei.
5. **Nuclear charge:** The charge of a nucleus is the total charge of its protons.

   $q_N = +Ze$, where e $\rightarrow$ magnitude of the electron charge, Z $\rightarrow$ atomic number of the nucleus
6. **Nuclear spin:** Many nuclides have an intrinsic nuclear angular momentum, or spin. Associated with the spin is the nuclear magnetic moment. The measured nuclear magnetic moments are of the order of 10^{-27} J T^{-1}. The nuclear magnetic moments are expressed in terms of a quantity called **nuclear magneton (μ_N)**

   $\mu_N = \frac{eh}{4\pi m_p} = 5.05 \times 10^{-27} JT^{-1} = 3.153 \times 10^{-8} eVT^{-1}$, where e $\rightarrow$ magnitude of the electron charge,

   h $\rightarrow$ planck's constant, $m_p \rightarrow$ mass of the proton. (Recall : Magnetic moment of an electron (I-orbit) in orbital motion $= \mu_l = \left(\frac{eh}{4\pi m_e}\right)$

   Magnetic moment of proton = 2.793 μ_N. Though the charge of the neutron is zero, it has a spin magnetic moment $\mu_n = -1.913\ \mu_N$. These results suggests that proton and neutron have complex structures.

Nuclear forces

It is clear from the stability of the nuclei, that there must be a strong attractive force which holds the nucleons together. This force which binds the neutrons and protons together in a nucleus is called nuclear force. Like gravitational and electromagnetic forces, nuclear force is also a basic force in nature.

Characteristics

- Nuclear force is the strongest force in nature ($F_{nuclear} > F_{electric} >> F_{gravitation}$)
- Nuclear force is charge independent ($F_{pp} = F_{nn} = F_{pn}$)
- Nuclear force is of short range (~ a few fermi)
- Nuclear force between nucleons within a nucleus is generally attractive
- Nuclear forces is saturated
- Nuclear forces has a non-central feature also.
- Nuclear forces is an exchange force (Exchange particle : π-meson)
- Nuclear force is spin dependent

Einstein's mass - energy relation

Einstein established from his theory of relativity, that mass and energy are equivalent. The energy equivalent of mass m is given by $E = mc^2$, where, c is the speed of light in vacuum.

Applications

1. **Mass defect and binding energy** of a nucleus are explained using mass-energy relation
2. During **nuclear reactions** such as **fission** and **fusion**, the total mass of the products is less than the total mass of the reactants. It is this difference in mass which appears as energy.

3. **Annihilation of matter:** When an electron and a positron come very close to each other, they annihilate. Their mass, appears as energy and is radiated in the form of γ-rays.

4. **Pair production:** A γ-ray photon (minimum energy $\simeq$ 1.02 mev) collides with a nucleus to create an electron position pair. In this process, energy is converted into mass.

Atomic mass unit

Atomic mass unit (u) is defined as $\left(\frac{1}{12}\right)^{th}$ the mass of a neutral carbon-12 atom.

$$1\text{ u} = \frac{1}{12}\left[\frac{12}{6.023\times10^{26}}\right]\text{ kg} = 1.66\times10^{-27}\text{ kg}$$

Relation between amu and eV

According to Einstein's mass energy relation $E = mc^2$. The energy equivalent of 1 u = 931.5 MeV

- **The following table gives the masses of some elementary particles expressed in u and kg**

Particle	Mass (in u)	Mass in (kg)
	1	1.6605×10^{-27}
Electron	0.00055	9.1094×10^{-31}
Proton	1.007276	1.6726×10^{-27}
Hydrogen atom	1.007825	1.6735×10^{-27}
Neutron	1.008665	1.6749×10^{-27}

- **Electron Volt**

  One **electron volt** is defined as the energy gained by a particle carrying one elementary electric charge (no matter whether it is an electron or any singly charged positive or negative ion), when it is accelerated due to a potential difference of 1 volt.

  $1\text{ eV} = 1.6 \times 10^{-19}$ joule, $1\text{ MeV} = 1.6 \times 10^{-13}$ J.

Mass defect

Mass defect is the amount of mass which would be converted to energy if a nucleus were to be assembled from the requisite numbers of protons and neutrons. The same amount of energy would be required to break the nucleus into its constituent particles. Thus, the energy equivalent of the mass defect is a measure of binding energy of the nucleus.

The mass of the constituent particles is the sum of the masses of Z protons, (A – Z) neutrons. The mass defect of a nucleus can be calculated by, $\Delta m = [Zm_p + (A-Z)m_n] - M_{Z,A}$ (nuclear mass)

Binding energy

The nucleons i.e., protons and neutrons, are bound together in a nucleus. **The energy needed just to take all the nucleons in a nucleus apart, so that they are completely separated, is called the binding energy of the nucleus.**

$BE = \Delta m\ (u) \times 931.5$ MeV

Binding energy divided by the number of nucleons in a nucleus gives its binding energy per nucleon, also called Specific binding energy (SBE).

Binding energy curve

A graph showing the variation of binding energy per nucleon with the mass number of nuclides is known as Binding energy curve (of the element).

Some of features of the BE curves are as follows: