Modern Physics
(Lec-10)

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OUTLINES

- Classification of Nucleus
- Nuclear binding energy
- Mass defect
- Nuclear stability
- Fundamental forces and their contribution.

Basic properties of a Nucleus:

Some of the basic properties of a nucleus are given below:

(i) The nucleus is made up of protons and neutrons, collectively known as *nucleons*.

(ii) Nucleons interact with one another with *a* strong short-range force known as nuclear force.

(iii) All nuclei are positively charged ($+1.6\times10^{-19}$ C).

(iv) No electron can exist inside the nucleus.

(v) All nuclei have approximately spherical symmetry structure.

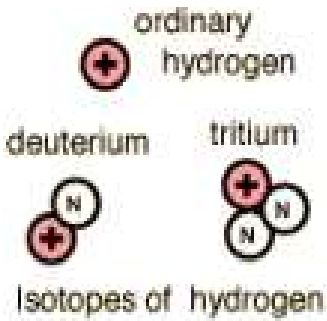
Constituent of the nucleus:

The nucleus is composed of Z protons and N neutrons. The atomic number Z determines the chemical properties of the atom. The mass number $A=Z+N$ determines approximately the mass of the nucleus in atomic mass units.

A particular nucleus defined by A and Z is known as a *nuclide*.

Cont....

- ✓ Atoms (or nuclei) with the **same *Protons*** but **different *neutron*** are known as ***isotopes***. These have **different masses** but the same chemical properties.



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

Notation for the different isotopes of the chemical element carbon.

There are about 400 stable isotopes.

- ✓ Elements with the same *atomic mass* but differing Z (and N) are known as ***isobars***. These will have approximately the same mass but different chemical properties (determined by Z).

$$^{40}_{18}Ar \text{ and } ^{40}_{19}K$$

- ✓ Nuclei with the same *neutron number* but differing Z are known as ***isotones***.

$$^{16}_{8}O \text{ and } ^{15}_{7}N$$

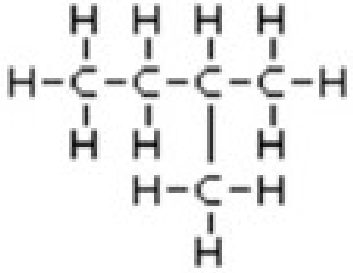
- ✓ Each of two or more atomic nuclei that have the same atomic number and the same mass number but different energy states are known as **Isomers.** As an example, as shown below C_5H_{12} has three different structures.

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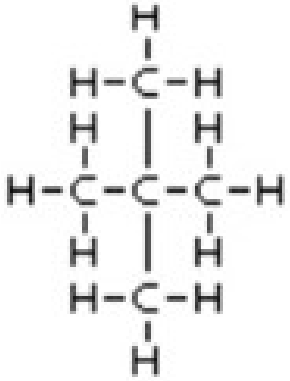
Pentane

36 °C (Boiling point)



Isopentane

28°C (Boiling point)



Neopentane

9.5°C (Boiling point)

- ✓ **Mirror Nuclei:** Nuclei having the same Mass number A, but with the proton and neutron number interchanged are called Mirror nuclei.

$$^{7}_{4}Be \text{ and } ^{7}_{3}Li$$

Sizes:

Since the force between nucleons is short range and experiment shows that nuclei are roughly spherical. Nucleus is composed of protons and neutrons. So, total number of protons and neutrons are known as mass number A.

But for spherical shape

$$V \alpha R^3$$

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

Experimentally, it is observed that $Volume\ of\ the\ nucleus \propto A$

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

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

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

Where, $R_0 \approx 1.2 \times 10^{-15} m \approx 1.2\ Fermi$

$A = Mass\ of\ the\ nuclei$

Problem: The radius of $^{165}_{67}H_0$ is 7.731 fermi. Deduce the radius of $^{4}_{2}He$.

Nuclear Mass:

We know that nucleus consists of protons and neutrons. Nuclear mass should be $= ZM_p + NM_n$, where M_p and M_n are the masses of protons and neutrons respectively. Nuclear masses can be accurately measured by mass spectrometer.

Nuclear Density:

Since the size of the nucleus is extremely small and its mass is very large, its density is unbelievably high. The nuclear density can be calculated from →

$$\rho_N = \frac{Nuclear\ mass}{Nuclear\ Volume}$$

Now, Nuclear mass

$$= ZM_p + NM_n = A\,M_n \cong A.(1.67\ x\ 10^{-27}\ kg)$$

Nuclear Volume

$$= \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(R_0 A^{\frac{1}{3}})^3 = \frac{4}{3}\pi A\ {R_0}^3$$

$$\therefore \rho_N = \frac{A.(1.67\ x\ 10^{-27}\ kg)}{\frac{4}{3}\pi A\ {R_0}^3} = 1.816\ x\ 10^{17} Kg/m^3$$

This is an extremely high value. This shows that nuclear matter is in an extremely compressed state.

Mass Defect:

The mass of a nucleus consisting of nucleons is not equal to sum of the masses of individual nucleons. The difference between the actual nuclear mass and the mass of all the individual nucleons is called the mass defect. The energy equivalent of the mass defect is the binding energy of the nucleus. Mass defect of the nucleus defined as

$$\Delta M = ZM_p + NM_n - M(A,Z)$$

Where,

Z= Number of proton

$N = Number\ of\ neutron$

$M_p = Mass\ of\ proton = 1.00727647\ a.m.u. and\ 1\ a.m.u. = 1.66054\ x\ 10^{-27}\ kg$

$M_n = Mass\ of\ neutron = 1.008664\ a.m.u.$

$M(A,Z) = Actual\ mass\ of\ the\ nucleus.$

Nuclear Binding Energy

Binding energy keeps the nucleons inside the nucleus. It is also the energy that required splitting the nucleus into its constituent that is protons and neutrons. Binding energy of a nucleus can be written as

$$B.E. = \Delta Mc^2$$

$$\therefore B.E. = \{ZM_p + NM_n - M(A,Z)\}c^2$$

$$where\ c = 3\ x\ 10^8\ m/s\ and\ 1\ eV = 1.60218\ x\ 10^{-19}\ joules$$

Radioactivity:

French scientist Henry Becquerel discovered radioactivity in 1896. The spontaneous emission of radioactive rays from radioactive element is called radioactivity. Due to radioactivity the nucleus of the element transformed into the nucleus of a new element so the radioactivity is a nuclear phenomenon. The SI unit of radioactivity is Becquerel (Bq).

$$1Bq = 1\frac{decay}{Second}$$

Earlier a unit named Curie (Ci) was used for radioactivity.

$$1\ Ci = 3.7\ x\ 10^{10}\frac{decay}{Sec} = \ 3.7\ x\ 10^{10}\ Bq$$

Radioactive particles

The radioactive radiations emitted by these elements are found to consist of the following:

- ***Alpha (α) rays or α -particle:*** The ***α*** -particles are doubly-ionized helium atoms *i.e.,* helium atoms with both of their electrons removed. Obviously, an -particle has double the charge of a hydrogen nucleus (*or proton*) and a mass number or atomic weight four times as great. It is represented by the symbol $_2He^4$.

- ***Beta (β) rays or β -particle:*** The ***β*** -particles consist of ordinary electrons with a mass equal to 1/1836 of the mass of the proton. Since it carries a unit negative charge and its mass is negligible, symbol for electron is $_{-1}e^0$.

- ***Gamma (γ) rays or γ -particle:*** ***γ*** -rays are electromagnetic radiations having high frequency. They have no charge.

Properties of α-particle

- α -particles are doubly-ionized helium atoms *i.e.* helium atoms with both of their electrons removed.
- α -particle has double the charge of a hydrogen nucleus (*or proton*) and a mass number or atomic weight four times as great.
- It is represented by the symbol ${}_2He^4$.

Properties of β-particle

- The β -particles consist of ordinary electrons with a mass equal to 1/1836 of the mass of the proton
- β -particle has negative charge and a mass number equal to that of an electron.
- It is represented by the symbol $-{}^0_1e$.

Properties of γ-ray

- Gamma rays are not charged particles like α and β particles, having no mass.
- γ -rays are electromagnetic radiation with high frequency.
- γ -rays move with the velocity of light.

Activity of Radioactive Substance

The activity of a sample of any radioactive nuclide is the rate at which the nuclei of the constituent atoms decay. If N is the number of nuclei present in the sample at a certain time, its activity R is given by

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

The minus sign is used to make R a positive quantity since dN/dt is, of course, negative.

Radioactivity is two types of kind.

1) Natural
2) Artificial

Natural radioactivity: The spontaneous emission of radiations from unstable nuclei is known as natural radioactivity.

Artificial radioactivity: Not all nuclear reactions are spontaneous. These reactions occur when stable isotopes are bombarded with particles such as neutrons. This method of inducing a nuclear reaction to proceed is termed artificial radioactivity.

There are three modes of beta decay. These are:

(i) ***Electron emission:*** When an atom of a substance emits electron its mass number remains the same and its atomic number is increased by one unit. As there is increase in the atomic number the atom is transformed into a new atom of a new element whose atomic number is more than one unit of the atomic number of the original atom. *i.e.*

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$$

For example, Carbon with A = 14 and Z 6 emits -particles. Therefore, the new substance formed is Nitrogen with A = 14 and Z = 7.

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

Thus, it is evident that the emission of electron by the nuclei of the atom of an element transforms it into the atoms of the higher element.

(i) Positron emission(e^+,β^+): Emission of positron (anti electron/antimatter) by proton decreases atomic number by one unit and mass number remains the same. As there is decrease in the atomic number the atom is transformed into a new atom of a new element whose atomic number is less than one unit of the atomic number of the original
atom. *i.e.*

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}e$$

For example, Copper with $Z = 29$ and $A = 64$ emits positron. Therefore, the new substance formed is Nickel with A = 64 and Z =90.

$$^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni + {}^{0}_{1}e$$

Thus, it is evident that the emission of positron by proton of the atom of an element changes its proton t o a neutron.

(i) ***Electron capture:*** Capture of electron by the proton of the atom decreases atomic number by one unit and mass number remains the same. As there is decrease in the atomic number the atom is transformed into a new atom of a new element whose atomic number is less than one unit of the atomic number of the original atom. *i.e.*

$$_{Z}^{A}X + _{-1}^{0}e \rightarrow _{Z-1}^{A}Y$$

For example, Copper with $Z = 29$ and $A = 64$ capture electron. Therefore, the new substance formed is Nickel with $Z = 90$ and $A = 234$.

$$_{29}^{64}Cu + _{-1}^{0}e \rightarrow _{28}^{64}Ni$$

Thus, it is evident that the capture of electron by the proton of the atom of an element changes its proton to a neutron.

Gamma (γ) decay: The emission of gamma radiation results from an energy change within the atomic nucleus. Gamma emission changes neither the atomic number nor the mass number. *i.e.*

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

Where, X^* = Original unstable atom, X = Stable atom.

For example, Strontium (*excited state*) with $Z = 87$ and $A = 38$ emits energy in the form gamma radiation and unstable nucleus becomes stable.

$$^{87}_{38}Sr^{*} \rightarrow {}^{87}_{38}Sr + \gamma$$