UNIT 9 ATOMIC AND NUCLEAR PHYSICS

Warm greetings:

Dear students

Welcome all. In this section we learnt about nuclei. Now we are going to discuss about

- Nuclei
- Composition of nucleus
- Atomic and nuclear masses

Introduction:

- In the previous section, we have discussed about various preliminary atom models, Rutherford's alpha particle scattering experiment and Bohr atom model.
- These played a vital role to understand the structure of the atom and the nucleus. In this section, the structure of the nuclei and their properties, classifications are discussed.

Composition of nucleus:

- Atoms have a nucleus surrounded by electrons. The nucleus contains protons and neutrons. The neutrons are electrically neutral (q = 0) and the protons have positive charge (q = + e) equal in magnitude to the charge of the electron (q = –e). The number of protons in the nucleus is called the atomic number and it is denoted by Z.
- The number of neutrons in the nucleus is called neutron number (N). The total number of neutrons and protons in the nucleus is called the mass number and it is denoted by A. Hence, A = Z+N.
- The two constituents of nucleus namely neutrons and protons, are collectively called as nucleons. The mass of a proton is 1. 6726X 10^{-27} kgwhich is roughly 1836 times the mass of the electron. The mass of a neutron is slightly greater than the mass of the proton and it is equal to 1.6749 X10^{-27}kg.
- To specify the nucleus of any element, we use the following general notation

  $^{A}_{Z}X$

where X is the chemical symbol of the element, A is the mass number and Z is the atomic number.

- ☞ For example, the nitrogen nucleus is represented by $_7^{15}N$. It implies that nitrogen nucleus contains 15 nucleons of which 7 are protons (Z = 7) and 8 are neutrons (N = A – Z = 8).
- ☞ Note that once the element is specified, the value of Z is known and subscript Z is sometimes omitted. For example, nitrogen nucleus is simply denoted as ^{15}N and we call it as 'nitrogen fifteen'.
- ☞ Since the nucleus is made up of positively charged protons and electrically neutral neutrons, the overall charge of the nucleus is positive and it has the value +Ze.
- ☞ But the atom is electrically neutral which implies that the number of electrons in the atom is equal to the number of protons in the nucleus.

Isotopes, isobars, and isotones

Isotopes:

- ➢ In nature, there are atoms of a particular element whose nuclei have same number of protons but different number of neutrons. These kinds of atoms are called isotopes.
- ➢ In other words, isotopes are atoms of the same element having same atomic number Z, but different mass number A.
- ➢ For example, hydrogen has three isotopes and they are represented as ^1_1H(hydrogen),$_1^2H$(deuterium),and $_1^3H$(tritium). Note that all the three nuclei have one proton and, hydrogen has no neutron, deuterium has 1 neutron and tritium has 2 neutrons.
- ➢ The number of isotopes for the particular element and their relative abundances (percentage) vary with each element.
- ➢ For example, carbon has four main isotopes: $_6^{11}C$,$_6^{12}C$,$_6^{13}C$and $_6^{14}C$. But in nature, the percentage of $_6^{12}C$is approximately 98.9%, that of $_6^{13}C$ is 1.1% and that of $_6 1^4C$ is 0.0001%. The other carbon isotope $_6^{11}C$, does not occur naturally and it can be produced only in nuclear reactions in the laboratory or by cosmic rays.
- ➢ Since the chemical properties of any atom are determined only by electrons, the isotopes of any element have same electronic structure and same chemical properties. So the isotopes of the same element are placed in the same location in the periodic table.

Isobars:

- Isobars are the atoms of different elements having the same mass number A, but different atomic number Z.
- In other words, isobars are the atoms of different chemical elements which have same number of nucleons. For example $_{16}^{40}S$, $_{17}^{40}Cl$, $_{18}^{40}Ar$, $_{19}^{40}K$ and $_{20}^{40}Ca$ are isobars having same mass number 40 but different atomic numbers. Unlike isotopes, isobars are chemically different elements. They have different physical and chemical properties.

Isotones:

- Isotones are the atoms of different elements having same number of neutrons. $_{5}^{12}B$ and $_{6}^{13}C$ are examples of isotones with 7 neutrons each.

Atomic and nuclear masses:

- The mass of nuclei is very small (about 10^{-25} kg or less). Therefore, it is more convenient to express it in terms of another unit namely, the atomic mass unit (u). One atomic mass unit (u) is defined as the (1/12)th of the mass of the isotope of carbon $_{6}^{12}C$ which is more abundant in naturally occurring isotope of carbon.
- In other words

$$1\,u = \frac{\text{mass of } _{6}^{12}C \text{ atom}}{12} = \frac{1.9926\times10^{-26}}{12}$$
$$= 1.660\times10^{-27}\,\text{kg}$$

In terms of this atomic mass unit, the mass of the neutron = 1.008665 *u*, the mass of the proton =1.007276 *u*, the mass of the hydrogen atom = 1.007825 *u* and the mass of $_{6}^{12}C = 12u$ Note that usually mass specified is the mass of the atom, not mass of the nucleus.

To get the nuclear mass of particular nucleus, the mass of electrons has to be subtracted from the corresponding atomic mass. Experimentally the atomic mass is determined by the instrument called Bainbridge mass spectrometer.

If we determine the atomic mass of the element without considering the effect of its isotopes, we get the mass averaged over different isotopes weighted by their abundances.

Size and density of the nucleus:

The alpha particle scattering experiment and many other measurements using different methods have been carried out on the nuclei of various atoms. The nuclei of atoms are found to be approximately spherical in shape. It is experimentally found that radius of nuclei for $Z > 10$, satisfies the following empirical formula

$$R = R_0 A^{\frac{1}{3}} \qquad (9.19)$$

Here A is the mass number of the nucleus and the constant R_0 = 1.2 F,

where 1 F = 1 $\times 10^{-15}$ m.The unit fermi (F) is named after Enrico Fermi.

Mass defect and binding energy:

It is experimentally found out that the mass of any nucleus is always less than the sum of the masses of its individual constituent particles. For example, consider the carbon-12 nucleus which is made up of 6 protons and 6 neutrons.

Mass of 6 neutrons = 6X1.00866u= 6.05196u

Mass of 6 protons =6X1.00727u = 6.04362 *u*

Mass of 6 electrons =6X 0.00055 u = 0. 0033*u*

The expected mass of carbon-12 nucleus = 6.05196+ 6.04362u = 12. 09558u

But using mass spectroscopy, the atomic mass of carbon-12 atom is found to be 12 *u*. So if we subtract the mass of 6 electrons (0.0033 *u*) from 12 *u*, we get the nuclear mass of carbon-12 atom which is equal to 11.9967 *u*. Hence the experimental mass of carbon-12 nucleus is less than the total mass of its individual constituents by Λm=0. 09888.. This difference in mass Λ*m* is called mass defect. In general, if M, m_p, and m_n are mass of the nucleus ($_Z^AX$), the mass of a proton and the mass of a neutron respectively, then the mass defect is given by

$$\Delta m = \left(Zm_p + Nm_n\right) - M \qquad (9.20)$$

Where has this mass disappeared? The answer was provided by Albert Einstein with the help of famous mass-energy relation($E = mc^2$). According to this relation, the mass can be converted into energy and energy can be converted into mass.

In the case of the carbon-12 nucleus, when 6 protons and 6 neutrons combine to form carbon-12 nucleus, mass equal to mass defect disappears and an energy equivalent to missing mass. This energy is called the binding energy of the nucleus (BE) and is equal to $(\Delta m)c^2$.

In fact, to separate the carbon-12 nucleus into individual constituents, we must supply the energy equal to binding energy of the nucleus.

We can write the equation (9.20) in terms of binding energy

$$BE = \left(Zm_p + Nm_n - M\right)c^2 \qquad (9.21)$$

It is always convenient to work with the mass of the atom rather than with the mass of the nucleus. Hence by adding and subtracting the mass of the *Z* electrons, we get

$$BE = \left(Zm_p + Zm_e + Nm_n - M - Zm_e\right)c^2 \quad (9.22)$$

$$BE = \left[Z\left(m_p + m_e\right) + Nm_n - M - Zm_e\right]c^2$$

where $m_p + m_e = m_H$ (mass of hydrogen atom)

$$BE = \left[Zm_H + Nm_n - (M + Zm_e)\right]c^2 \quad (9.23)$$

Here $M + Zm_e = M_A$ where M_A is the mass of the atom of an element ${}^{A}_{Z}X$.

Finally, the binding energy in terms of the atomic masses is given by

$$BE = \left[Zm_H + Nm_n - M_A\right]c^2 \qquad (9.24)$$

Binding energy curve :

In the previous section, the origin of the binding energy is discussed. Now we can find the average binding energy per nucleon *BE* . It is given by

$$\overline{BE} = \frac{\left[Zm_H + Nm_n - M_A\right]c^2}{A} \qquad (9.25)$$

The average binding energy per nucleon is the energy required to separate single nucleon from the particular nucleus. When *BE* is plotted against A of all known nuclei. We get BE aveage curve as shown in Figure 9.24

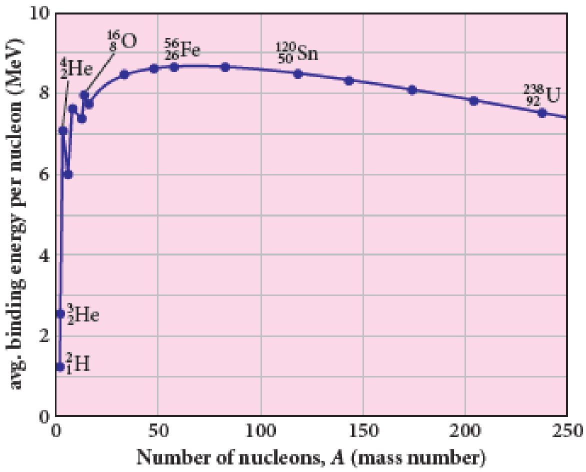

Figure 9.24 Avg. binding energy of the nucleons

Important inferences from of the average binding energy curve:

(1) The value of *BE* rises as the mass number increases until it reaches a maximum value of 8.8 MeV for A = 56 (iron) and then it slowly decreases.

(2) The average binding energy per nucleon is about 8.5 MeV for nuclei having mass number lying between A = 40 and 120. These elements are comparatively more stable and not radioactive.

(3) For higher mass numbers, the curve drops slowly and *BE* for uranium is about 7.6 MeV. Such nuclei are unstable and exhibit radioactive. From Figure 9.24, if two light nuclei with A<28 combine with a nucleus with A<56, the binding energy per nucleon is more for final nucleus than initial nuclei. Thus, if the lighter elements combine to produce a nucleus of medium value A, a large amount of energy will be released. This is the basis of nuclear fusion and is the principle of the hydrogen bomb.

(4) If a nucleus of heavy element is split (fission) into two or more nuclei of medium value A, the energy released would again be large. The atom bomb is based on this principle and huge energy of atom bombs comes from this fission when it is uncontrolled.

NUCLEAR FORCE:

Nucleus of the atoms contains protons and neutrons. From electrostatics, we learnt that like charges repel each other.

In the nucleus, since the protons are separated by a distance of about a few fermi ($10^{-15}m$), they must exert on each other a very strong repulsive force.

$$F = k \times \frac{q^2}{r^2} = 9 \times 10^9 \times \frac{(1.6 \times 10^{-19})^2}{(10^{-15})^2} \approx 230 N$$

The acceleration experienced by a proton due to the force of 230 N is

$$a = \frac{F}{m} = \frac{230N}{1.67 \times 10^{-27} kg} \approx 1.4 \times 10^{29} m s^{-2}.$$

This is nearly 1028 times greater than the acceleration due to gravity. So if the protons in the nucleus experience only the electrostatic force, then the nucleus would fly apart in an instant. Then how the protons are held together in the nucleus?

From this observation, it was concluded that there must be a strong attractive force between protons to overcome the repulsive Coulombic force. This attractive force which holds the nucleons together is called strong nuclear force. The properties of the nuclear force were understood through various experiments carried out between 1930s and 1950s.

A few properties of the nuclear force are

(i) The nuclear force is of very short range, acting only up to a distance of a few fermi. But inside the nucleus, the repulsive Coulomb force or attractive gravitational forces between two protons are much weaker than the nuclear force between two protons. Similarly, the gravitational force between two neutrons is also much weaker than nuclear force between the neutrons. So nuclear force is the strongest force in nature.

(ii) The nuclear force is attractive and acts with an equal strength between proton-proton, proton-neutron, and neutron – neutron.

(iii) Nuclear force does not act on the electrons. So it does not alter the chemical properties of the atom.

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