If the mass lost or mass defect is ΔM amu, then the energy into which this lost mass is converted is equal to $(\Delta M \times 931.5)$ MeV.

Hence the binding energy of the nucleus (B) = ΔM (in amu) $\times$ 931.5 MeV

13.4.5 Binding Energy Per Nucleon ($\bar{B}$):

The binding energy of a nucleus (B) divided by the sum of the protons (p) and neutrons (n) *i.e.*, nucleons present in the nucleus is called binding energy per nucleon ($\bar{B}$) (بائنڈنگ انرجی فی نیوکلیان کا مطلب ہے کہ ایک نیوکلیان کے حصے جو انرجی آتی ہے). Thus $\bar{B}$ is given by

$$\text{Binding energy per nucleon } (\bar{B}) = \frac{\text{Binding energy of the nucleons (B)}}{\text{Number of nucleons in the nucleus}}$$

or

$$\bar{B} = \frac{\text{Mass defect } (\Delta M) \times 931.5}{\text{Number of nucleons in the nucleus}} \text{ MeV}$$

or

$$\boxed{\bar{B} = \frac{\Delta M \times 931.5}{p+n} \text{ MeV} = \frac{\Delta M \times 931.5}{A} \text{ MeV}}$$

Here A is the mass number which is equal to $(p + n)$.

Binding energy per nucleon ($\bar{B}$) is a measure of the stability of the nucleus (نیوکلیس کے استحکام کی نشانی ہے). Greater is the magnitude of binding energy per nucleon ($\bar{B}$), greater is the stability attained by the nucleus greater. In other words there is force holding the nucleons together in the nucleus.

13.4.6 Variation of Binding Energy per Nucleon ($\bar{B}$) and Stability of Nucleons:

The magnitude of $\bar{B}$ varies with the mass numbers (A) of the isotopes. It can be studied with the help of the plot shown in Fig. (13.5).

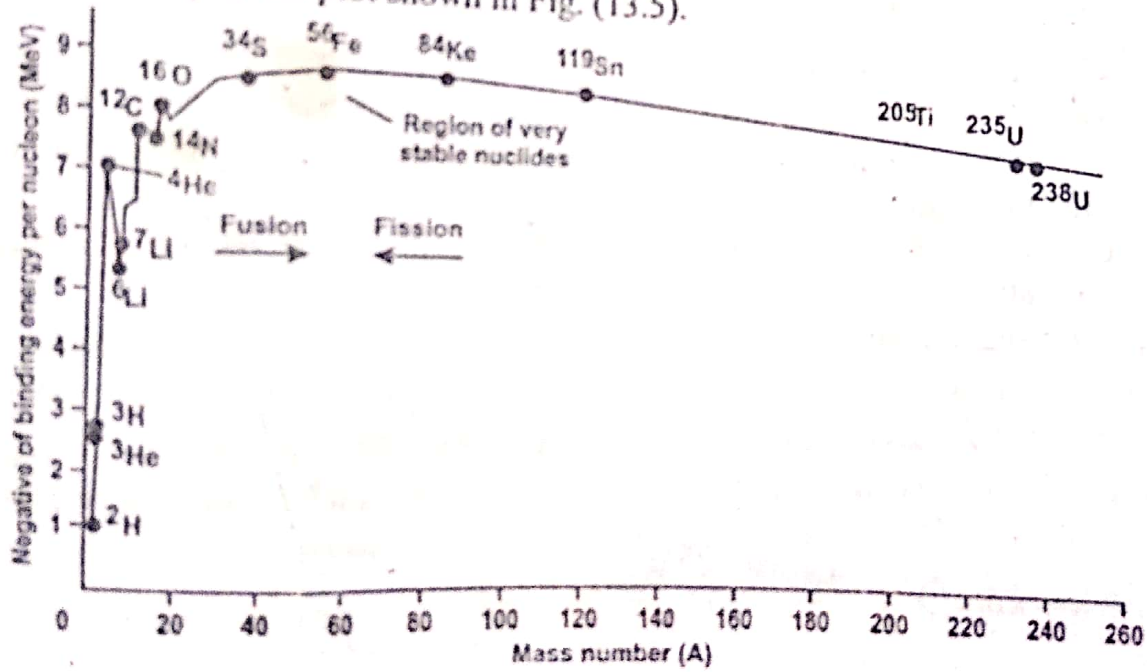

Fig. (13.5): The variation in binding energy per nucleon. A plot of the negative of the binding energy per nucleon vs. mass number shows that nuclear stability is greatest in the region near ^{56}Fe.

This is a graph between the binding energy per nucleon (in MeV) of a number of isotopes and their corresponding mass numbers. This plot is called **binding energy curve** (بائنڈنگ انرجی کا خم دار گراف). From the binding energy curve the following points may be noted.

Important Conclusions:

(i) The nuclei having very low mass numbers *i.e.*, lighter nuclei like $^{1}_{1}H$, $^{2}_{1}H$, $^{3}_{1}H$ have very small $\bar{B}$ values and hence these nuclei are unstable. Being unstable they combine together to give heavy nuclei and a huge amount of energy is also liberated (خارج ہو جاتی ہے). This is **fusion** (اکٹھا ہونے کا عمل) process. Examples of nuclear fusion reactions are

$$^{1}_{1}H + ^{2}_{1}H \xrightarrow{\text{Fusion}} ^{3}_{2}He + 5.50 \text{ MeV}$$

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6 \text{ MeV}$$

$$4\,^{1}_{1}H \longrightarrow ^{4}_{2}He + 2\,^{0}_{+1}e \text{ (positron)} + 24.64 \text{ MeV}$$

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He + ^{1}_{0}n + 3.3 \text{ MeV}$$

(ii) There is **rapid increase** (تیز اضافہ) **in $\bar{B}$ values** for the nuclei whose mass numbers are **multiples of** (ضرب کھائی ہوئی) 4 or multiples of helium nucleus. They have equal number of protons and neutrons ^{4}**He**, ^{12}**C**, ^{16}**O**, ^{20}**Ne**, ^{24}**Mg**, ^{28}**Si** etc.

$\bar{B}$ values for the above said light nuclei are high i.e., for $^{4}_{2}He$ = 7.0747 MeV, for $^{12}_{6}C$ = 7.61833 MeV, and for $^{16}_{8}O$ = 7.976 MeV. So, these nuclei are stable.

> **Do you know that!**
>
> $^{8}_{4}$**Be** is an exception. It splits into two alpha particles ($^{8}_{4}Be \longrightarrow 2\,^{4}_{2}He$).

> **Stability of α-particle**
>
> It may also be concluded that helium nucleus has quite stable structure and this is the reason why α-particles are emitted by many radioactive elements.

(iii) At mass number 56, for $^{56}_{26}$**Fe**, the value of $\bar{B}$ becomes maximum *i.e.*, 8.542 MeV. This value shows that the nucleus of iron is **exceptionally stable** (غیر معمولی استحکام) and hence iron is found in large **abundance in nature** (قدرتی طور پر اکثریت).

(iv) The plot for the nuclei having mass numbers in the **range 60 – 80** is almost flat. It means that the values of $\bar{B}$ for the above nuclei do not change very much.

(v) As the mass number increases beyond 80, the values of $\bar{B}$ start decreasing hence these nuclei are unstable. Their unstable nature is evident from the fact that when ^{235}U nucleus (**$\bar{B}$ = 7.1 MeV**), heavy nucleus, is bombarded by slow moving neutrons (آہستہ چلتے نیوٹرانز), it is splitted (ٹوٹ جاتا ہے) into lighter nuclei (ہلکے نیوکلیس میں) *viz.* ^{139}**Ba** and ^{94}**Kr** and a large amount of energy (کثرت سے انرجی خارج ہوتی ہے) is released. This process is called **fission** (ٹوٹنا).

$$^{235}_{92}U \text{ (Heavy nucleus)} + ^{1}_{0}n \text{ (slow)} \xrightarrow{\text{Fission}} \underbrace{^{139}_{56}Ba + ^{94}_{36}Kr} + 3\,^{1}_{0}n + \text{Energy}$$

13.4.7 Calculation of $\bar{B}$ values for $^{4}_{2}$HE nucleus:

The actual atomic mass of He atom is,

$$M = 4.00260 \text{ amu.}$$

We know that $^{4}_{2}He$ atom contains 2 protons, 2 electrons and 4 – 2 = 2 neutrons.

∴ Mass of (2 protons + 2 electrons + 2 neutrons)

$= 2 \times 1.007825 + 2 \times 1.008665 = 2.015650 + 2.017330$

$= 4.032980$ amu

Thus M' = 4.032980 amu ; M = 4.00260 amu (given)

Mass defect (ΔM) = M' − M = 4.032980 − 4.002600 = 0.030380 amu

∴ Since 1 amu = 931.5 MeV,

0.030380 amu = 0.030380 × 9031.5 MeV = 28.298 MeV

Thus binding energy of helium nucleus (B) = 28.298 MeV

There are four nucleons in He atom.

∴ **Binding energy per nucleon** ($\bar{B}$) $= \frac{28.298}{4} = \boxed{7.0745 \text{ MeV}}$

Since $1 \text{ ev} = 1.602 \times 10^{-19}$ J

So, $\bar{B} = 7.0745 \times 10^{6}$ eV $= 7.0745 \times 10^{6} \times 1.602 \times 10^{-19}$ J

$\boxed{\bar{B} = 11.33 \times 10^{-13} \text{ J}}$

13.4.8 Magic Number and Stability of Nucleus:

A nuclear shell which contains a specific number of neutrons and or protons in it is called a **filled shell** and this filled shell is more stable than other shells. These specific numbers are **2, 8, 20, 28, 50, 82** and **126** which are called **magic numbers** (جادوئی نمبرز). These magic numbers indicate that the nucleons exist in pairs in the nucleus. The nuclei having either protons or neutrons or both equal to the magic numbers given above are called **magic nuclei** and these nuclei are very stable. Being stable, these nuclei are also called **noble nuclei** (شریف نیوکلائی). The greater stability associated with these nuclei is confirmed by the following facts.

(i) The nuclei with magic numbers are found in **greater abundance in nature** (قدرت میں زیادہ کثرت سے) as compared to other isotopic forms of the same element.

(ii) These nuclei **cannot capture a neutron** (نیوٹران کو قابو نہیں کر سکتے) because the nuclear shells in their respective nuclei are already filled with nucleons. So they cannot contain an extra neutron.

There are two groups of nuclei having the magic number.

(i) Nuclei in which only protons or neutrons are magic numbers. Such nuclei are called **single magic number nuclei**. For example $^{17}_{8}O$ ($p = 8, n = 17 - 8 = 9$), $^{207}_{82}Pb$ ($p = 82, n = 207 - 82 = 125$) and $^{209}_{83}Bi$ ($p = 83, n = 209 - 83 = 126$).

(ii) Nuclei in which protons and neutrons both are magic numbers. Such nuclei are called **double magic number nuclei**. Examples are $^{4}_{2}He$ ($p = 2, n = 2$), $^{16}_{8}O$ ($p = 8, n = 8$), $^{40}_{20}Ca$ ($p = 20, n = 20$), $^{208}_{82}Pb$ ($p = 82, n = 126$).

13.4.9 Magic Number and Number of Isotopes:

When a nuclide contains protons or neutrons or both equal to any of the magic numbers, we say that this nuclide has closed or filled shell. Such a nuclide gives a number of stable isotopes $_{50}Sn$ **has 50 protons**. It has **ten stable isotopes** having their mass numbers equal to 112, 114, 115, 116, 117, 118, 120, 122 and 124. $_{20}Ca$, has 20 protons, which is a magic number. It has **six stable isotopes**. The maximum number of stable isotopes occur for those nuclei which have n = 50 or 82. These numbers are also magic numbers. The nuclei having 6, 14, 28 or 40 protons or neutrons are less stable than those nuclei which have protons or neutrons or both equal to magic numbers. The numbers namely 6, 14, 28 and 40 are called **semi-magic numbers**. The nuclei having protons or neutrons other than magic numbers or semi-magic numbers are comparatively less stable.

Do you know that!

The nuclei $^{2}_{1}H$, $^{6}_{3}Li$, $^{10}_{6}B$ and $^{14}_{7}N$ are not covered under this concept of magic number.

13.4.10 Even (جفت) and Odd (جو جفت نہ ہوں) Number of Protons and Neutrons

There are more than **900 nuclides** at present which are known. Out of these only 272 **nuclides are stable** while others are radioactive. These 272 nuclides have been grouped into four classes as shown in Table (13.3). This table shows that the number of **even-*p*-odd-*n*** and **odd-*p*-even-*n*** type nuclei are nearly the same in number. The nuclei of **odd-*p*-odd-*n*** type are **only four** and hence are not found in nature. These nuclei are limited ([illegible]) only to light nuclei. **160 are the stable isotopes** found in earth's crust and are of **even-*p*-even-*n* type**. The remaining **(56%)** isotopes are of **even-*p*-odd-*n* type**. The presence of **even-*p*-even-*n*** type isotopes in the maximum percentage in the Earth's crust shows that the stable nuclei have a tendency to form ***p-p*** and ***n-n*** **pairs**.

Table (13.3): Classification of Stable Nuclides (isotopes) on the basis of even and odd number of Protons (*p*) and Neutrons (*n*)

Nuclide type	No. of protons (*p*)	No. of neutrons (*n*)	Mass number (A) = (*p* + *n*)	No. of stable nuclides or isotopes	Examples
(i) Even-*p*-even-*n* nuclides	Even	Even	Even	160	$^{4}_{2}He$, $^{24}_{12}Mg$, $^{16}_{8}O$, $^{28}_{14}Si$, $^{56}_{26}Fe$, $^{40}_{20}Ca$, $^{208}_{82}Pb$, etc.
(ii) Even-*p*-odd-*n* nuclides	Even	Odd	Odd	56	$^{17}_{8}O$, $^{25}_{12}Mg$, $^{57}_{26}Fe$ etc.
(iii) Odd-*p*-even-*n* nuclides	Odd	Even	Odd	52	$^{7}_{3}Li$, $^{19}_{9}F$, $^{27}_{13}Al$, $^{23}_{11}Na$, $^{39}_{19}K$, $^{31}_{15}P$ $^{63}_{29}Cu$, etc.
(iv) Odd-*p*-odd-*n* nuclides	Odd	Odd	Even	4	$^{2}_{1}H$, $^{6}_{3}Li$, $^{10}_{3}B$, $^{14}_{7}N$ only.
Total number of nuclides = 272					

13.4.11 Neutron-to-Proton Ratio (*n*/*p* Ratio)

To have a good understanding of nuclear stability (نیوکلیس کے استحکام کے بارے میں بہتر سمجھ بوجھ), look at Table (13.4). It contains *n*/*p* ratio values for some stable nuclides. This table shows that *n*/*p* value for these stable nuclides is equal to 1 or greater than 1 (**$n/p > 1$**). The value of *n*/*p* ratio for light stable nuclides up to $^{40}_{20}Ca_{20}$ is equal to 1 and for heavy nuclides *n*/*p* ratio value is greater than 1.

Let us plot a graph between the number of neutrons (*n*) and protons (*p*) present in the stable nuclides of various elements. This graph is shown in Fig. (13.6) and is called **Serge chart**. It is also called **stability belt** (استحکام کی پٹی).

The straight line shown in the graph is an **imaginary line** (تصوراتی خط) at which $n = p$, *i.e.*, $n/p = 1$. The strip or the zone shown in the figure is called **zone of stability** (استحکام کا میدان). The reason is that most of the **stable nuclei *i.e.*, non-radioactive nuclei** lie within this zone. This strip goes on widening (چوڑا ہونا) as the number of protons increases. **The nuclei whose *n*/*p* value lies above or below this belt are radioactive and hence spontaneously disintegrate to give stable nuclei.** The following three cases may be studied in article 13.7.12.

(وہ نیوکلائی جن کا $\frac{n}{p}$ نسبت اس زون سے اوپر یا نیچے ہو وہ استحکام پذیر نہیں ہوتے۔)

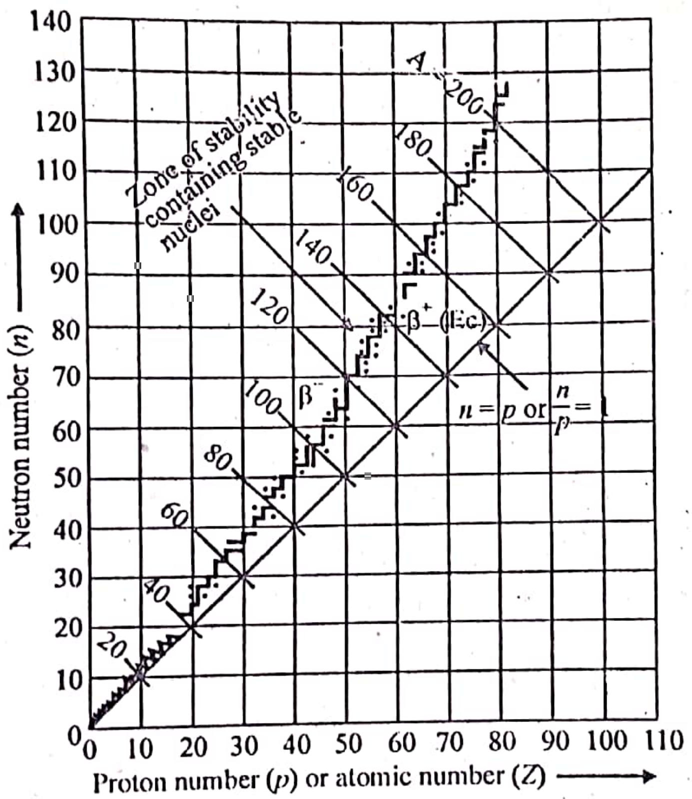

Fig. (13.6): Serge chart between number of protons on x-axis and number of neutrons on y-axis.