Lectures of Nuclear Physics

(Phy.414)

Dr. Riyadh Mnade Ramadhan

Fourth Grade

ثوابت فيزيائية

Gravitational constant	ثابت الجذب العام	G	$6.673(10) \times 10^{-11}\ \mathrm{N\ m^2\ kg^{-2}}$
Speed of light (exact)	سرعة الضوء	c	$2.99792458 \times 10^{8}\ m\ s^{-1}$
Permeability of free space	نفاذية الفراغ الحر	μ_o	$4\pi \times 10^{-7}\ N\ A^{-2}$
Permittivity of free space	سماحية الفراغ الحر	ϵ_o	$1/\mu_o c^2$
			$8.854187817\ldots \times 10^{-12}\ F\ m^{-1}$
Electric charge	شحنة الإلكترون	e	$1.60217653(14) \times 10^{-19}\ C$ $4.80320440(42) \times 10^{-10} esu$
Electric volt	الإلكترون فولت	$1eV$	$1.602176462(63) \times 10^{-19}\ J$
Planck's constant	ثابت بلانك	h	$6.6260693\ (11) \times 10^{-34}\ Js$
			$4.13566727(16) \times 10^{-15}\ eV\ s$
Universal constant	الثابت العام	$\hbar$	$h/2\pi$
			$1.054571568(18) \times 10^{-34}\ Js$
			$6.58211889(26) \times 10^{-16}\ eV\ s$
Planck's constant × speed of light	ثابت بلانك × سرعة الضوء	hc	$1.23984186(16) \times 10^{3}\ eV\ nm$
			$\cong 1240\ eV\ nm$
Inverse fine structure constant	مقلوب ثابت التركيب الدقيق	α^{-1}	$\frac{[4\pi\varepsilon_o]\hbar c}{e^2} = 137.035\ 999\ 11(46)$
Boltzmann's constant	ثابت بولتزمان	k	$1.3806503\ (24) \times 10^{-23}\ J\ K^{-1}$
			$8.6173423(153) \times 10^{-5}\ eV\ K^{-1}$
Stefan-Boltzmann constant	ثابت ستيفان - بولتزمان	σ	$2\pi^2 k^4/(15\ c^2 h^3)$
			$5.67040(40) \times 10^{-8}\ W\ m^{-2}\ K^{-4}$
Radiation constant	ثابت الإشعاع	a	$4\sigma/c$
			$7.565767(54) \times 10^{-16}\ J\ m^{-3}\ K^{-4}$
Atomic mass unit	وحدة الكتل الذرية	1u	$1.66053873(13) \times 10^{-27} kg$
		$1uc^2$	$931.494013(37)\ MeV/c^2$
Electron mass	كتلة الإلكترون	m_e	$9.10938188(72) \times 10^{-31}\ kg$
			$5.485799110(12) \times 10^{-7}\ u$
Proton mass	كتلة البروتون	m_p	$1.67262158(13) \times 10^{-27}\ kg$
			$1.00727646688(13)\ u$
Neutron mass	كتلة النيوترون	m_n	$1.67492716(13) \times 10^{-27}\ kg$
			$1.00866491578(55)\ u$
Hydrogen mass	كتلة الهيدروجين	m_H	$1.673532499(13) \times 10^{-27}\ kg$
			$1.00782503214(35)\ u$
Muon mass	كتلة الميون	m_μ	$0.113\ 428\ 9264(30)\ u$
Deuteron mass	كتلة الديوترون	m_d	$2.013\ 553\ 212\ 70(35)\ u$
α-particle mass	كتلة جسيم ألفا	m_α	$4.001\ 506\ 179\ 149(56)\ u$

first Lecture

Nuclear Constituents

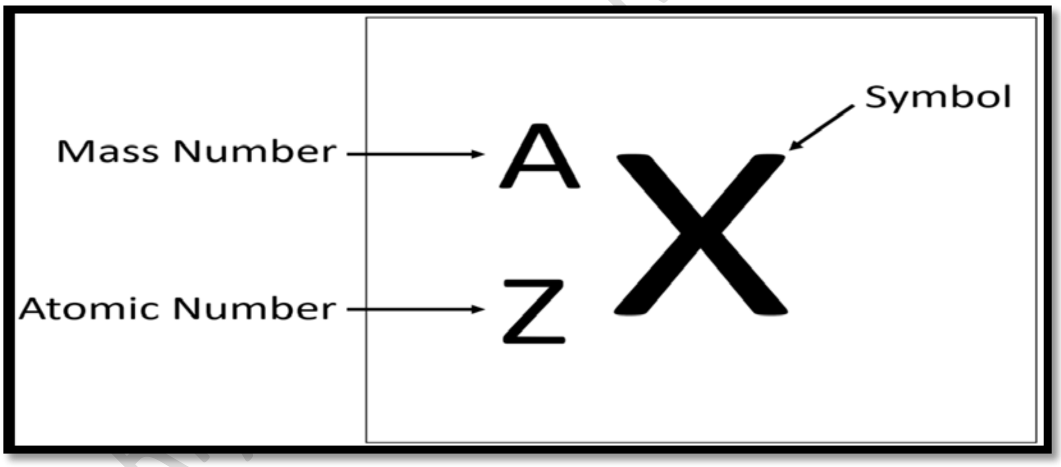
Nuclei are made up of protons (charge +e) and neutrons (no charge). Hydrogen is unique in that its nucleus has a single proton and no neutrons. The sum of the number of protons (atomic number Z) and the number of neutrons (neutron number N) is called the mass number (A) of the nuclear species or nuclide: Z+N = A. Protons and neutrons are collectively called nucleons. Each nuclide is symbolized by its chemical symbol (X) along with the values of A and Z: ${}^{A}_{Z}X$.

Basic Nuclear Concepts

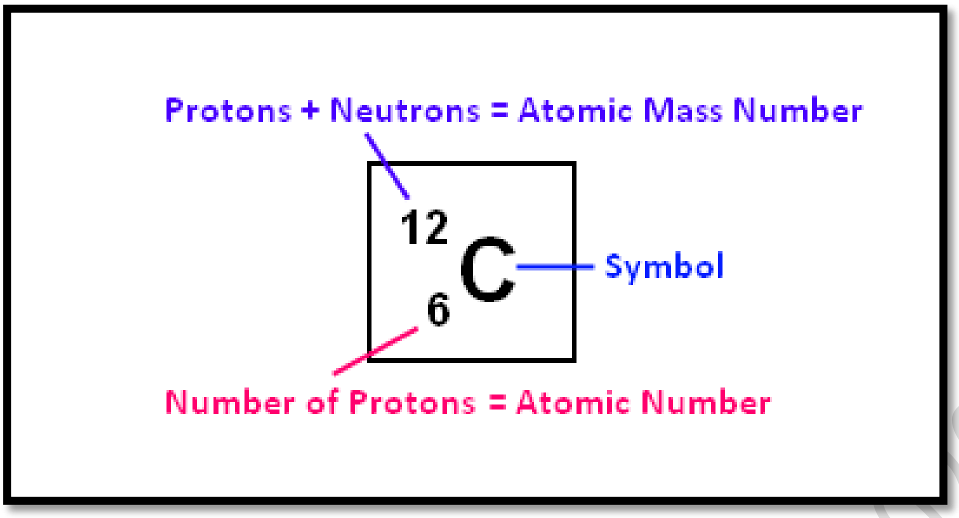
Atomic number (Z): equal to the number of protons in the nucleus. All atoms of the same element have the same number of protons.

The neutron number(N) : equals to the number of neutrons in the nucleus.

Mass number (A): equal to the sum of the number of protons and neutrons for an atom.



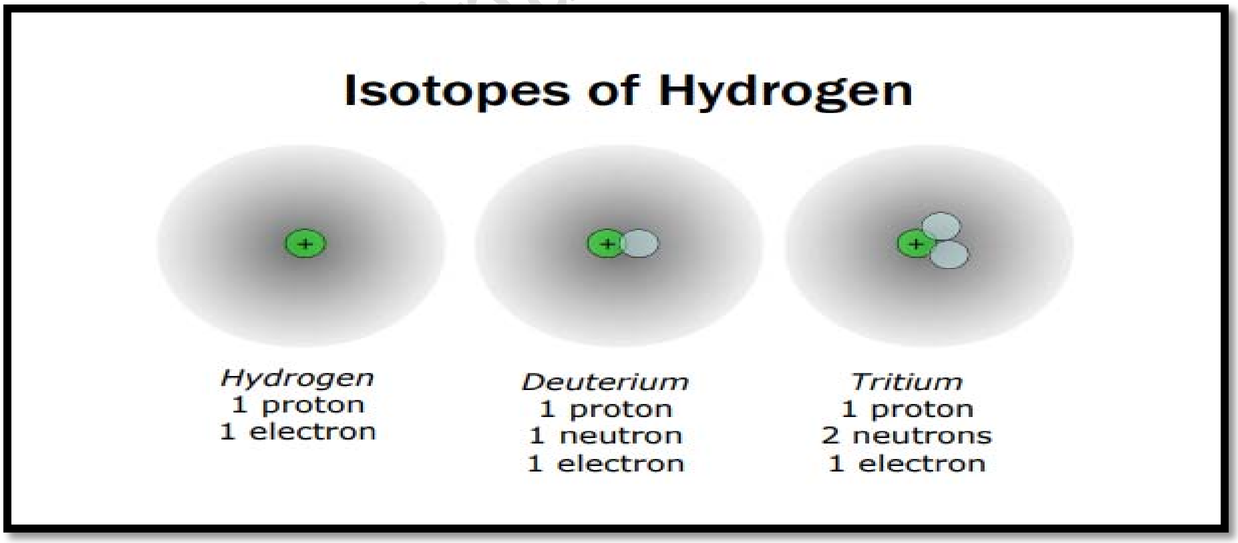
$$Z + N = A$$

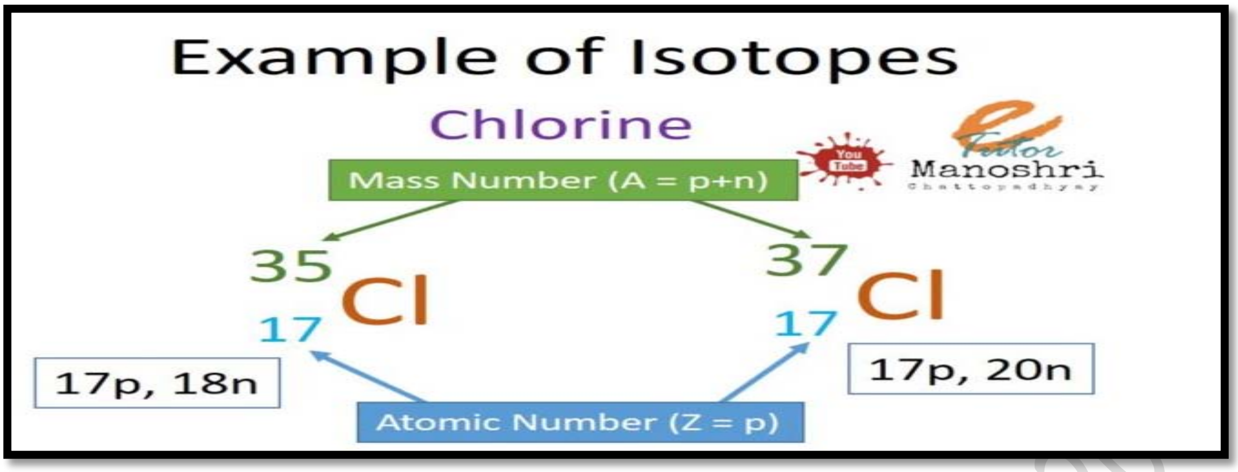


nucleons: the particles found inside nuclei

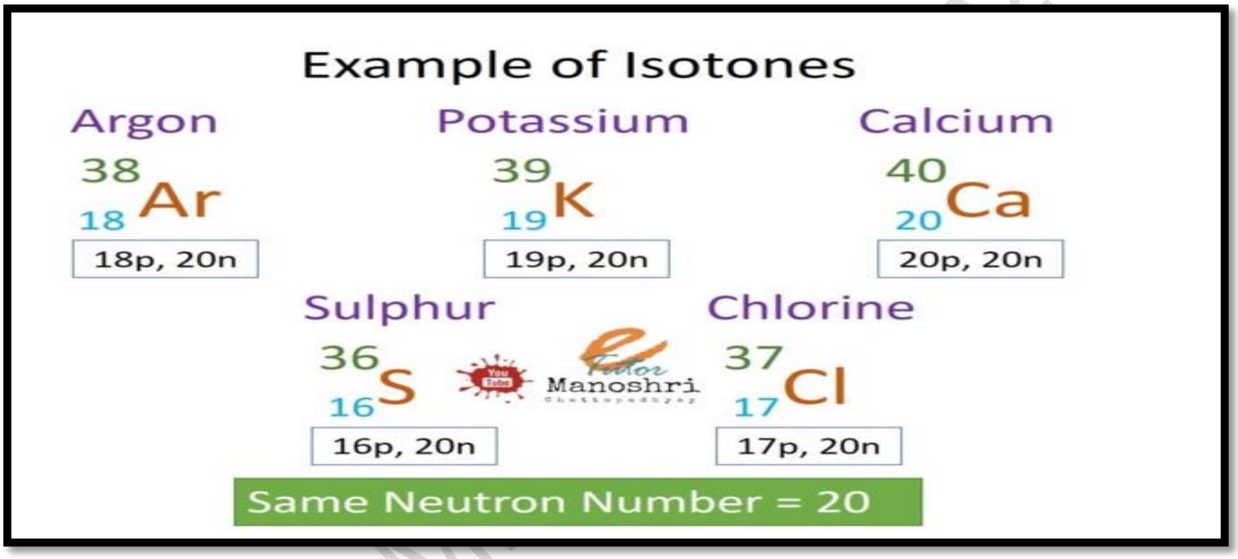
radius of a nucleus: the radius of a nucleus is $r = r_0 A^{1/3}$

Isotopes : nuclides with the same proton (atomic) number, Z

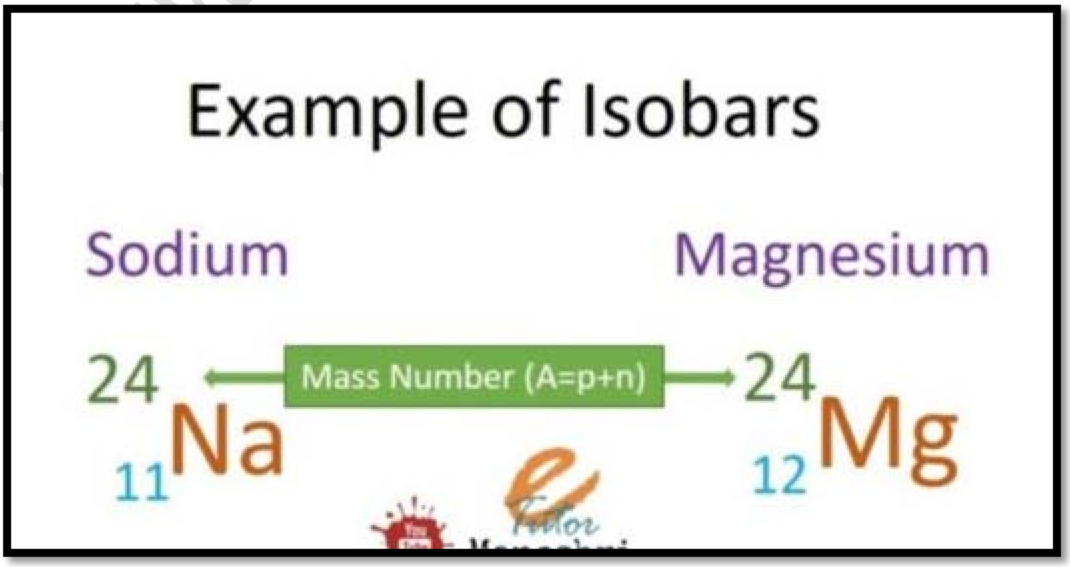




Isotones : nuclides with the same neutron number, N



Isobars : nuclides with the same mass number, A



Isomers : nuclides with the same A and Z, but different energy.

Positron: Positively charged electron of mass m_0

Charge and Mass

Accepted scientific theory of atoms:

► 1. All substances are made of atoms.

► 2. Atoms are small particles that cannot be created or destroyed.

► 3. Atoms of the same element are exactly alike.

► 4.Atoms join with other atoms to make new substances

What are the names, charges, and locations

- Proton (charge of +e, in the nucleus), Neutron (0 charge, in the nucleus), and Electron (charge of –e, outside the nucleus).
- **Proton**. This is a positively charged particle that is present in the nucleus of atoms. It has a charge of $+1.6\times10^{-19}$C.

- **Neutron**. This particle has a charge of zero; it is uncharged/neutral. It is present in the nucleus of atoms.
- **Electron**. This is a negatively charged particle that orbits the nucleus of atoms, i.e. outside the nucleus (electrons exist in the space between atomic nuclei). They have a charge of -1.6×10^{-19}C.
- The proton is approximately 1836 times as massive as the electron, and the masses of the proton and the neutron are almost equal.
- Atoms are neutral because the number of protons equals the number of electrons
- All of the mass of an atom is found in the nucleus.
- Almost all of the volume of an atom is empty space.

Atomic Mass Unit, the unit used to measure the mass of protons and neutrons.

Atoms are very tiny and hence have very low masses. For example, the mass of a H-1 atom is approximately 1.6733 x 10^{-24} g and the mass of a C-12 atom is approximately **1.9927 x 10^{-23} g**. These numbers are too small for convenience and therefore a new mass scale, based on the **atomic mass unit (amu)**, was defined for atomic masses. The atomic mass unit was defined as 1/12 of the mass of a C-12 atom,

Hence,

1 amu = 1/12 x 1.9924 x 10^{-23} g = 1.6606 x 10^{-24} g

By definition, on the **amu** scale, C-12 has an atomic mass of 12.0000 (exactly). The atomic mass of H-1(**1.6733 x 10^{-24} g**) can be calculated as shown below: **1.6733 x 10^{-24} g x 1 amu/1.6606 x 10^{-24} g = 1.0078 amu**

proton = 1.0073 amu,

electron = 0.00055 amu,

neutron = 1.0087 amu

1 amu(u)= 1.66054 x 10^{-27}Kg

Example 44.1 The Atomic Mass Unit

Use Avogadro's number to show that $1\ u = 1.66 \times 10^{-27}$ kg.

SOLUTION

Conceptualize From the definition of the mole given in Section 19.5, we know that exactly 12 g (= 1 mol) of ^{12}C contains Avogadro's number of atoms.

Categorize We evaluate the atomic mass unit that was introduced in this section, so we categorize this example as a substitution problem.

Find the mass m of one ^{12}C atom:

$$m = \frac{0.012\ \text{kg}}{6.02 \times 10^{23}\ \text{atoms}} = 1.99 \times 10^{-26}\ \text{kg}$$

Because one atom of ^{12}C is defined to have a mass of 12.0 u, divide by 12.0 to find the mass equivalent to 1 u:

$$1\ u = \frac{1.99 \times 10^{-26}\ \text{kg}}{12.0} = 1.66 \times 10^{-27}\ \text{kg}$$

Because the rest energy of a particle is given by $E=mc^2$, it is often convenient to express the atomic mass unit in terms of its rest energy equivalent. For one atomic mass unit, we have

$$E = mc^2 = (1.660540 * 10^{-27} Kg) \frac{(2.9979246 * 10^8 \, {}^{m}/_{s})^2}{(1.602177 * 10^{-19} \, {}^{J}/_{eV})}$$

$$=931.4943 \text{ MeV}$$

So, In general, physicists often express mass in terms of the unit MeV/c^2 , so here, the mass of 1 u is

1 amu = 931.4943 MeV/c^2

Size and Structure of Nuclei

Like atoms, nuclei have no precisely defined size because of the extended nature of the wave functions of nuclear constituents. However, one can define an "average" radius. From scattering experiments, we know that nuclear radii have values in the range 2 – 8 fermi ($1fm=10^{-15}$ m).

Experiments also show that nuclei are for the most part spherical. Departures from sphericity are usually slight (either elongation or flattening).

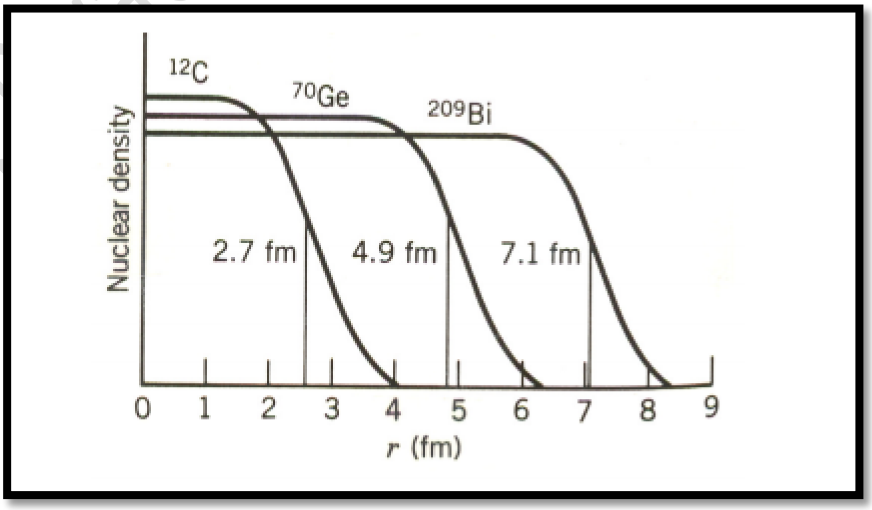


Fig.( )

Another interesting feature is that the density of the nucleons, i.e., the number of the nucleons per unit volume, is virtually independent of the mass number A of the nucleus. Hence, The nuclear density for a typical nucleus can be approximately calculated from the size of the nucleus:

$$\rho = \frac{A}{\frac{4}{3}\pi R^3} = Constant$$

Where ,

$$R = R_\circ A^{1/3}$$

where R_0 is an empirical constant of 1.2–1.5 fm, The value of R_0 must be determined experimentally. Its value depends on how the nuclear radius R is defined. One such definition is the distance (from the center of the nucleus) at which the nuclear density falls to one-half of its value at the center of the nucleus.

Example: C-12; R ≈ 2.7 fm, A = 12,

$$\rho = \frac{A}{\frac{4}{3}\pi R^3} = \frac{12}{\frac{4}{3}\pi(2.7x10\hat{} - 15m)^3}$$

$=2.4x10^{17}$ Kg/m^3

* For comparison purposes, $\rho_{water} = 10^3$ kg/m^3

Q /

1. Find the radius of an iron-56 nucleus.
2. Find its approximate density in kg/m^3, approximating the mass of ^{56}Fe to be 56 u.

Strategy and Concept

1. Finding the radius of ^{56}Fe is a straightforward application of $R = R_0A^{1/3}$, given $A = 56$.
2. To find the approximate density, we assume the nucleus is spherical (this one actually is), calculate its volume using the radius found in Part 1, and

then find its density from ***ρ = m/V***. Finally, *we will need to convert density from units of u/fm³ to kg/m³*.

<u>Solution/</u>

The radius of a nucleus is given by $R = R_0A^{1/3}$,. Substituting the values for R_0 and A yields

$R=(1.2\ fm)(56)^{1/3}=(1.2\ fm)(3.83)$

$=4.6\ fm$

and,

Density is defined to be $\rho = m/V$, which for a sphere of radius r is

$\rho=m/V=m/(4/3)\pi R^3$

Substituting known values gives

$\rho=56\ u/(1.33)(3.14)(4.6\ fm)^3 =0.138\ u/fm^3$

Converting to units of kg/m³, we find

amu or **u** $=1.66\times10^{-27}$ kg/u

$1fm= 10^{-13}cm =10^{-15}m$,

So,

$\rho=(0.138\ u/fm^3)x(1.66\times10^{-27}\ kg/u)x(1\ fm/10^{-15}\ m)$

$=2.3\times10^{17}\ kg/m^3$

Q2/ Find the nuclear radius of (a)^{197}Au;(b)^{4}He;(c)^{20}Ne?

$\boldsymbol{R = R_{\circ}A^{1/3}}$

Nuclear Stability

Nuclear stability represents a balance between:

1- Nuclear “strong force” (basically attractive)
2- Electrostatic interaction (Coulomb force) between protons (repulsive)
3- Pauli exclusion principle
4- Residual interactions (“pairing force”, etc.)

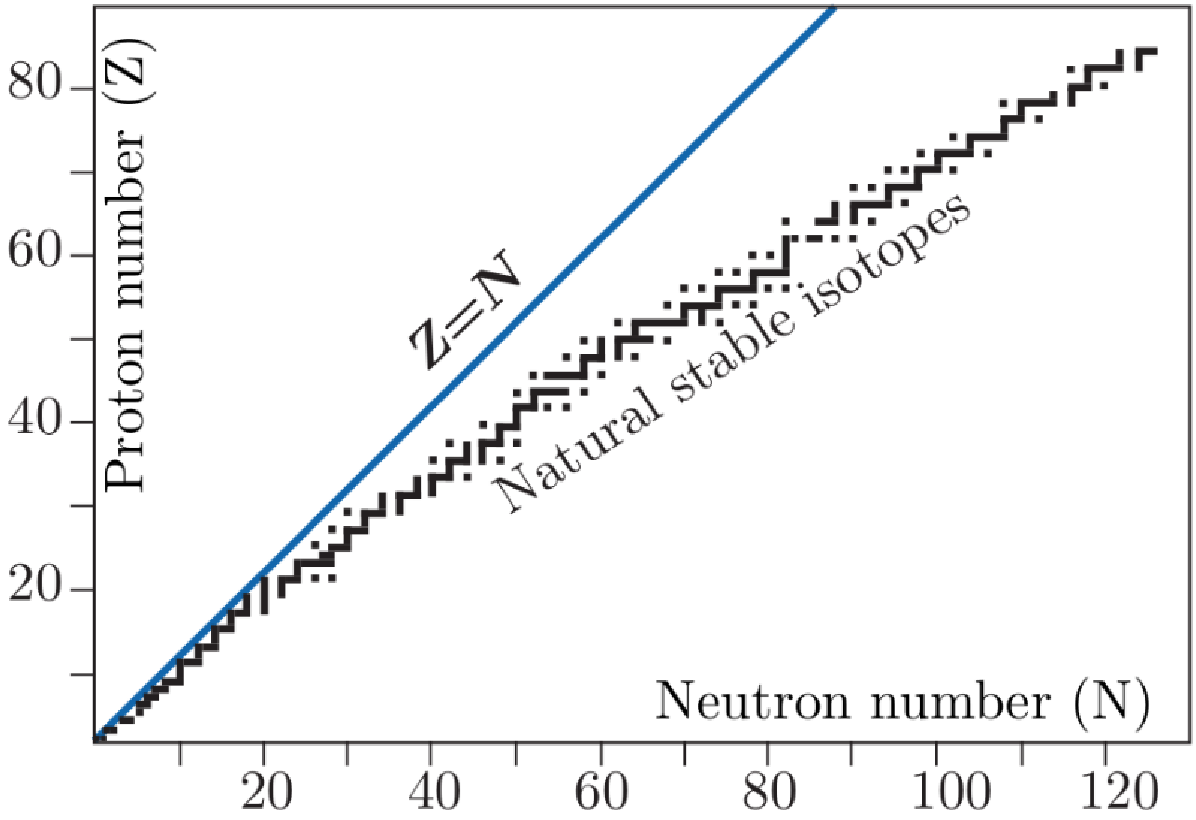
Stability strongly favors N approximately equal to (but slightly larger than) Z. This results in the “band of stability” in the Chart of the Nuclides.

» ~50% are Even-Even

» ~25% are Odd-even

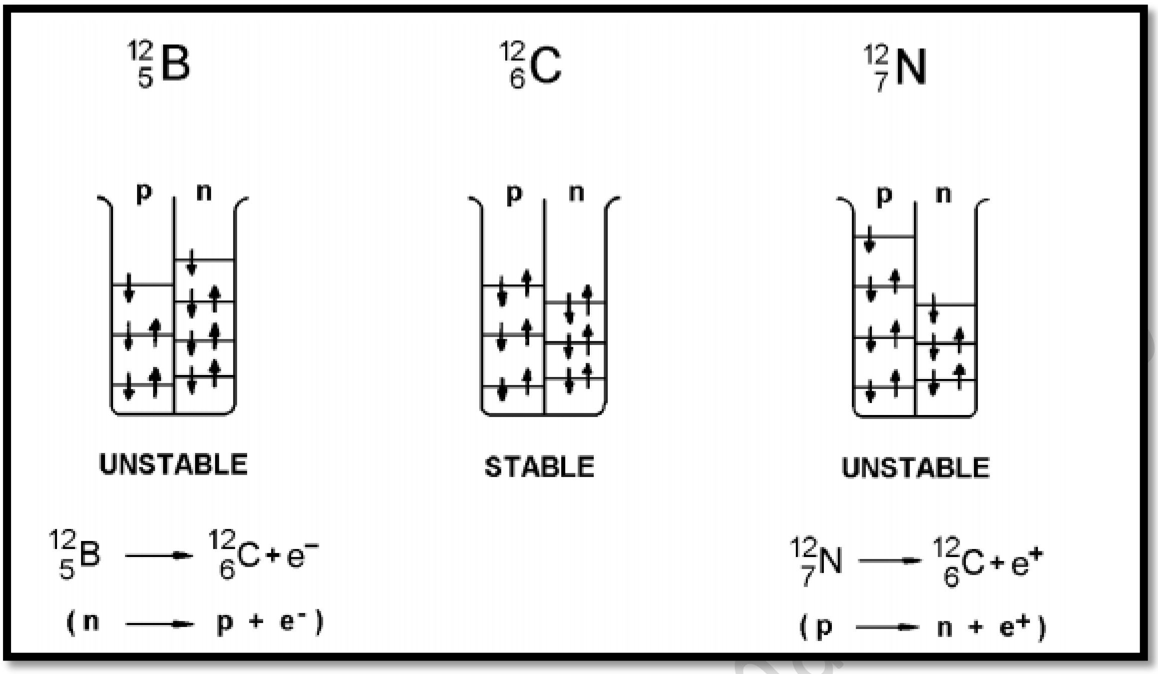
» ~25% are Even-Odd

» Only 4 out of 266 stable nuclides are Odd-Odd! The heaviest stable Odd-Odd nuclide is ^{14}N.



Fig( )

We find the light element stability when number of neutron equal number of proton (N=Z)



Fig( )

Magic Numbers

It has been found that the nuclei with proton number or neutron number equal to certain numbers 2,8,20,28,50,82 and 126 behave in a different manner when compared to other nuclei having neighboring values of Z or N. Hence these numbers are known as magic numbers. these nuclei are more stability

Experimental Evidences for the Existence of Magic Numbers

1- The binding energy of magic numbered nuclei is much larger than the neighboring nuclei. Thus larger energy is required to separate a single nucleon from such nuclei.
2- Number of stable nuclei with a given value of Z and N corresponding to the magic¬ number are much larger than the number of stable nuclei with neighboring values of Z and N. For example, Sn with Z=50 has 10 stable isotopes, Ca with Z=20 has six stable isotopes.

3- Naturally occurring isotopes whose nuclei contain magic numbered Z or N have greater¬ relative abundances. For example, Sr-88 with N=50, Ba-138 with N=82 and Ce-140 with N=82 have relative abundances of 82.56%, 71.66% and 88.48% respectively.

4- Three naturally occurring radioactive series decay to the stable end product Pb with Z=82¬ in three isotopic forms having N=126 for one of them.

5- Nuclei with magic numbers of neutrons or protons have their first excited states at higher energies than in cases of the neighboring nuclei.

6- Electric quadrupole moment of magic numbered nuclei is zero indicating the spherical symmetry of nucleus for closed shells.

7- Energy of alpha or beta particles emitted by magic numbered radioactive nuclei is larger than that from other nuclei.

8- Double Magic Numbers: When both proton number (Z) and neutron number (N) are magic numbers e.g He- 4 , O-16 , Ca-40 , $^{208}_{82}P_{126}$. They show exceptionally high stability.

9- Singly Magic Numbers: When either N or Z are among magic numbers e.g., $^{88}_{38}Sr_{50}$.

Table (*), number of stable nuclei in nature

N	Z	Number of stable nuclei
Even	Even	156
Even	Odd	48
Odd	Even	50
Odd	Odd	5