Nuclear Chemistry (PART1)

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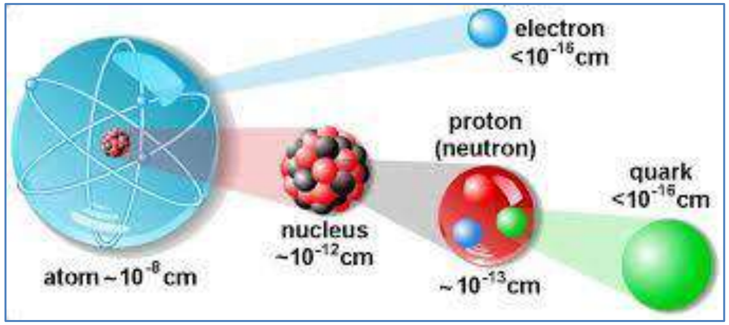
Atomic nucleus



- The **atomic nucleus** is the small, dense region consisting of protons and neutrons at the center of an atom, discovered in 1911 by Ernest Rutherford (father of nuclear physics).

- After the discovery of the neutron in 1932, models for a nucleus were developed by Dmitri Ivanenko and Werner Heisenberg.

- An atom is composed of a positively-charged nucleus, with a cloud of negatively-charged electrons surrounding it, bound together by electrostatic force.

- Almost all of the mass of an atom is located in the nucleus, with a very small contribution from the electron cloud. Protons and neutrons are bound together to form a nucleus by the nuclear force.

- It is believed that protons and neutrons are the constituent particles of the nucleus.

- This nuclear constituent particles are called nucleons which follow the Fermi-Dirac statistics.

- The nucleus contains Z protons (atomic number) and N neutrons to give the

  Mass number $A(= Z + N)$

- Z is the fundamental property of an element.

- For a particular value of Z, because of different numbers of N, the Isotopes appear.

- The neutron – proton ratio and their oddness and evenness are very much important in determining the stability of the nucleus.

N.B – In the proton – neutron model, it is believed that they are continiously changing one into another.
Thus, within the nucleus, it is not appropriate to define a particle either as a proton or as a neutron. They are really indistinguishable within the nucleus due to the exchange phenomena.
That is why, within the nucleus, the constuent particles are referred to as nucleons, and they can be characterised as protons or neutrons when they emerge from the nucleus.

FERMIONS

Follow Fermi-Dirac statistics

- A **fermion** is any particle that has an odd half-integer (like 1/2, 3/2, and so forth) spin. And follow Fermi-Dirac statistics. Examples are electrons, protons and neutrons etc.
- Fermions are characterised with half-integer spin quantum number.
- They obey Pauli Exclusion principle and consequently only a single fermion particle can occupy a given quantum state.

BOSONS

Follow Bose-Einstein statistics

- A **boson** is any particle that has an Zero or even integer (like 0, 1, 2 etc) spin. And follow Bose-Einstein statistics. Examples are meson, photons, Helium etc.
- Bosons are characterised with zero or integer spin quantum number.
- They do not obey Pauli Exclusion principle and any number of Boson can pile up in a given quantum state. This assembly is called Bose-Einstein Condensate (BEC)*

Mirror nuclei -

- **Definition** - Nuclei, where the number of protons of element one (Z_1) equals the number of neutrons of element two (N_2) and the number of protons of element two (Z_2) equals the number of neutrons in element one (N_1), such that the mass number is the same ($A = N_1 + Z_1 = N_2 + Z_2$). Thus the mirror nuclei are isobaric.
  As that $Z_1 = N_2$ and $Z_2 = N_1$, $A = N_1 + N_2 = Z_1 + Z_2$. By making the substitution $Z_1 = Z$ and $Z_2 = Z - 1$, the mass number can be rewritten in the form $2Z - 1$.

- **Examples of mirror nuclei** -
  - ^{3}H and ^{3}He: $J^{\pi} = 1/2^{+}$
  - ^{14}C and ^{14}O: $J^{\pi} = 0^{+}$
  - ^{15}N and ^{15}O: $J^{\pi} = 1/2^{-}$
  - ^{24}Na and ^{24}Al: $J^{\pi} = 4^{+}$
  - ^{24m}Na and ^{24m}Al: $J^{\pi} = 1^{+}$

- Pairs of mirror nuclei have the same spin and parity. If we constrain to odd number of nucleons ($A=Z+N$) then we find mirror nuclei that differ from one another by exchanging a proton by a neutron.
- The nuclear force depends on the number of nucleons irrespective of their charge.
  After allowing the electronic repulsive force between the protons, the nuclear forces in the interactions, (n - n), (n - p), (p - p) are equal.
  In a particular set of mirror nuclei the number of nucleons in each nuclide is the same and consequently the binding energy between them only differes due to the additional Coulombic repulsive energy..

- **Exceptions** - In 2020 Strontium-73 and bromine-73 were found to not behave as expected.[3]

NUCLEAR STABILITY

- Nuclear stability means that the nucleus of an element is stable and thus it does not decay spontaneously emitting any kind of radioactivity.

- Those nuclei with the highest binding energy per nucleon are the most **stable** with respect to destructive **nuclear** reactions.

- Among the ≈9,000 nuclei expected to exist, and the ≈3,000 presently known, only 195 are stable against spontaneous decay.

Oddo—Harkins rule Rule states that the cosmic abundance of elements with an even atomic number is greater than that of adjacent elements with an odd atomic number.

Table 5.3.1.1. Abundance distribution of stable nuclides *(illustrations of Harkins' rule).*

Composition of nucleus			No. of stable nuclides	Abundance, % in the earth's crust	Examples
Neutrons (N)	Protons (Z)	$A = Z + N$			
(i) Even	Even	Even	~ 162	~ 85	${}^{4}_{2}He$, ${}^{16}_{8}O$, ${}^{28}_{14}Si$, ${}^{40}_{20}Ca$, ${}^{56}_{26}Fe$, ${}^{208}_{82}Pb$
(ii) Even	Odd	Odd	~ 52	~ 13	${}^{27}_{13}Al$, ${}^{23}_{11}Na$, ${}^{39}_{19}K$
(iii) Odd	Even	Odd	~ 50	~ 2	${}^{17}_{8}O$, ${}^{25}_{12}Mg$
(iv) Odd	Odd	Even	~ 4*	0	${}^{2}_{1}H$, ${}^{6}_{3}Li$, ${}^{10}_{5}B$, ${}^{14}_{7}N$

Ref. – A. K. Das, Volume 1