Nuclear and Particle Physics

General properties of nuclei

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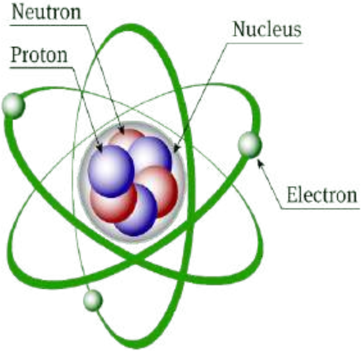
General properties of nuclei

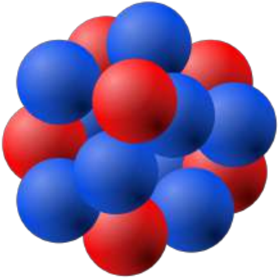
- There are only three fundamental atomic particle electron, proton and neutron. After the discovery of the neutrons by Chadwick in 1932, it was proposed that nuclei are composed of protons and neutrons, which are collectively called nucleons. The neutron carries mass slightly greater than that of the proton, but unlike proton which is positively charged, a neutron is electrically neutral. A species of atom characterized by the constituents of its nucleus is called a nuclide.
- The important static properties of the nuclei include their electric charge, mass, binding energy , size , shape, angular momentum, magnetic dipole moment, electric quadruploe moment, statistics, parity and iso-spin.

The Atom



- Atom is a neutral system
- Atomic excitations $\sim 1 - 10^5 eV$.
- Caused by transitions between electronic states.

The Atomic nucleus



- Nuclear excitations $\sim 10^5 - 10^8 eV$.
- Caused by transitions between nuclear states.

Protons and Neutrons

In fact, protons and neutrons are so similar, they can be classified as the same object; The Nucleon

Nucleons are quantum mechanical objects:

- They are spin 1/2 Fermions
- Radius $r \sim 1 \times 10^{-15}$ (1 fermi)
- Charge
  - p $\rightarrow +$e
  - n$\rightarrow$ 0
- Mass
  - $p \rightarrow 938.27 MeV/c^2$
  - $n \rightarrow 939.56 MeV/c^2$

Nuclear Mass

- The atomic nuclei are made up of two different types elementary particles, protons and neutrons. The sum of the number of neutrons (N) and protons (Z) inside the nucleus is known as its mass number A, so that $A = N + Z$. Z is equal to the atomic number of the element in the periodic table. A nucleus of an atom X of atomic number Z and mass number A is written as ${}^A_Z X$.
- The nuclear mass M_{nuc} is obtained from the atomic mass M by subtracting the masses of the Z orbital electrons from the atomic mass. $M_{nuc} = M - Zm_e$. The nuclei of atoms are very strongly bound. If we want to break up a nucleus of Z protons and N neutrons completely so that they are all separated from one another, a certain minimum amount of energy is to be supplied to the nucleus. This energy is known as the binding energy of the nucleus.
- It has been observed that the mass of a nucleus is always less than the sum of the individual masses of the protons and the neutrons, which constitute it. This difference is a measure of the nuclear binding energy which holds the nucleus together, is known as the mass defect Δm.

Nuclear Mass and binding energy

- The nuclear binding energy is given by $E_B = \Delta mc^2$, where c is the speed of light. Let M_p be the rest mass of a proton, M_n is that of proton and M_N is the rest mass of the nucleus; Z and A are the atomic and mass numbers of the nucleus.
- $$E_B = [ZM_p + (A - Z)M_n - M_n]\, c^2$$
- Thus the average binding energy per nucleon is

$$\epsilon = E_B/A \tag{1}$$

Nuclear Mass and binding energy

Most of the nuclei have an average binding energy per nucleon of $7.5 - 8.9 Mev$. The elements with low A values have their ϵ values less than 7 Mev, the important exception being He^4, C^{12} etc nuclei which have their A values integral values of 4. Again ϵ is maximum for those elements which have $A \sim 50$ (for those elements which be in the middle of the periodic table) ϵ assumes a value $8Mev$. For elements with high atomic and mass number mainly for radioactive isotopes ϵ is less than $8Mev$ which implies that these elements are unstable.

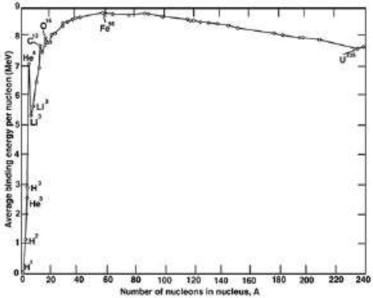


Figure: *N versus Z plot for stable nuclei*

Size

- Nuclear size is defined by nuclear radius, also called rms (root mean square) charge radius.
- It can be measured by the scattering of electrons by the nucleus.
- Generally, the nucleus is modeled as a sphere of positive charge for the interpretation of electron scattering experiments.
- Experimental evidences also show that the distribution of nuclear matter density ρ_m is also approximately constant. Since nuclear mass is almost linearly proportinal to mass number A, this means that $\rho_m \sim A/V = constant$, i.e., the nuclear volume $V \propto A$.

- Assume a spherical shape of the nucleus with a radius R, we then get

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

$$R \propto A^{1/3}$$

so that

$$R = r_0 A^{1/3}$$

where r_0 is a constant, known as the nuclear radius parameter. This nuclear radius is the radius of the nuclear mass distribution.

Isotopes, Isotones and Isobars

- Isotope

Nuclei with the same number of protons (Z), but a different number of neutrons (N) and a different mass (A).

- Isotone

Nuclei with the same number of neutrons (N), but a different number of protons (Z) and a different mass (A).

- Isobar

Nuclei with the same number of nucleon (A), but a different number of protons (Z) and neutrons (N).

Exercise:

- Find the density of $^{12}_{C}6$ nucleus.
- The binding energy of the neon isotope $^{20}_{Ne}10$ is 160.647 MeV. Find its atomic mass.

Books Suggested:

- Concept of Modern Physics, Arthur Beiser
- Atomic and Nuclear Physics, Vol II; S. N. Ghosal
- Nuclear Physics, Theory and Experiment; R. R. Roy & B. P. Nigam
- Atomic and Nuclear Physics, An Introduction; T.A. Littlefield & N. Thorley
- Image courtesy: Wikipedia