Nuclear Physics

Sreeja Laksmi
Assistant Professor
Department of Physics
MES Keveeyam College, Valanchery

Nuclear Physics

- The Nucleus
- Binding Energy
- Radioactivity
- Half-life
- Biological Effects of Radiation
- Induced Nuclear Reactions
- Fission and Fusion

Nuclear Structure

The atomic nucleus is composed of neutrons and protons. These particles are called **nucleons**.

The atom’s **atomic number** (Z) gives the number of protons in its nucleus. It is the atomic number that determines an atom’s identity.

The **nucleon number** or **mass number** is A = Z+N, where N is the number of neutrons.

Masses of atoms are sometimes give in terms of atomic mass units. $1u = 1.660539 \times 10^{-27}$ kg.

For an atomic nucleus

$$m \propto A$$

$$V \propto A.$$

This implies the density of an atomic nucleus is independent of A.

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

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

As an equality $r = r_0 A^{1/3}$

where $r_0 = 1.2\times10^{-15}$ m = 1.2 fm

Binding Energy

A nucleus is held together by the **strong nuclear force**. This force only acts over distances of a few fermis.

The **binding energy** (E_B) of a nucleus is the energy that must be supplied to separate it into individual protons and neutrons.

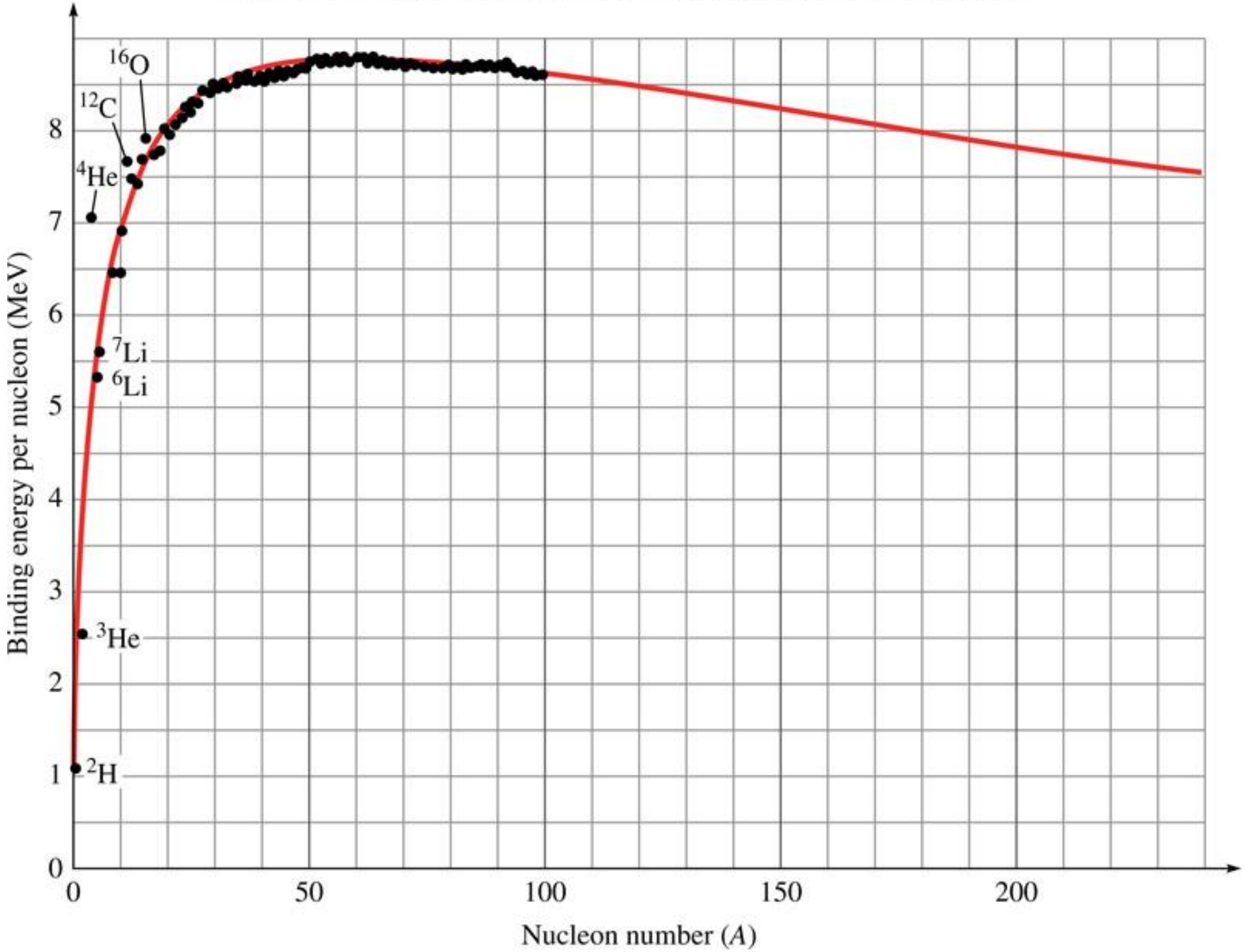
E_B = Total energy of Z protons and N neutrons – total energy of nucleus.

Total energy of Z protons and N neutrons = (mass of Z protons and N neutrons)c^2.

Total energy of nucleus = (mass of nucleus)c^2.

These can be used to define the **mass defect** Δm = (mass of Z protons and N neutrons) – (mass of nucleus) so that

$$E_B = \Delta m c^2.$$


16O
12C
4He
7Li
6Li
3He
2H
Binding energy per nucleon (MeV)
0
1
2
3
4
5
6
7
8
0
50
100
150
200
Nucleon number (A)

Radioactivity

Some nuclei are unstable and decay. These nuclei are **radioactive**. A nucleus can emit an alpha ray, beta ray, or a gamma ray during its decay.

Alpha rays have been identified as helium nuclei.

The reaction for alpha decay is

$$^{A}_{Z}P \rightarrow {}^{A-4}_{Z-2}D + {}^{4}_{2}\alpha$$

Parent nucleus

Daughter nucleus

Alpha particle

Example (text problem 29.29): Show that the spontaneous alpha decay of ^{19}O is not possible.

The reaction is $^{19}_{8}\mathrm{O} \rightarrow ^{15}_{6}\mathrm{C} + ^{4}_{2}\alpha.$

The mass of the products (including electrons) is 19.01320250u.

The mass of ^{19}O is 19.0035787u.

The mass of the products is larger than the reactant, so this reaction cannot occur spontaneously.

Sreeja Laksmi

Beta rays have been identified as either electrons (β^-) or positrons (β^+).

The reaction for beta-minus decay is

$$ {}_{Z}^{A}P \rightarrow {}_{Z+1}^{A}D + {}_{-1}^{0}e + {}_{0}^{0}\bar{\nu}. $$

The reaction for beta-plus decay is

$$ {}_{Z}^{A}P \rightarrow {}_{Z-1}^{A}D + {}_{+1}^{0}e + {}_{0}^{0}\nu. $$

During beta-minus decays, a neutron is converted into a proton.

$$^{1}_{0}\mathrm{n} \rightarrow ^{1}_{1}\mathrm{p} + ^{0}_{-1}\mathrm{e} + ^{0}_{0}\overline{\nu}$$

During beta-plus decays, a proton is converted into a neutron.

$$^{1}_{1}\mathrm{p} \rightarrow ^{1}_{0}\mathrm{n} + ^{0}_{+1}\mathrm{e} + ^{0}_{0}\nu$$

During inverse beta decay (**electron capture**) a proton in a nucleus captures an electron. The reaction is

$$ {}^{0}_{-1}\mathrm{e} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{0}\nu . $$

Half-Lives

The **half-life** of a sample of unstable nuclei is the time it takes for one-half of the sample to decay. The decay process is quantum mechanical and is based on probability.

Each radioactive nucleus has a probability per second that it will decay, called the **decay constant.**

$$\text{decay constant} = \lambda = \frac{\text{probability of decay}}{\text{unit time}}$$

The number of nuclei that decay in a short time interval is

$$\Delta N = -N\lambda\Delta t.$$

There are statistical fluctuations in the number of decays that occur. These fluctuations are of order $\sqrt{|N|}$.

The **decay rate** or **activity** is the number of radioactive decays that occur in a sample per unit time.

$$R = \frac{\text{number of decays}}{\text{unit time}} = -\frac{\Delta N}{\Delta t} = \lambda N$$

The unit of activity is the bequerel. 1 Bq = 1 decay/sec. Another common unit is the curie. 1 Ci = 3.7×10^{10} Bq.

The number of nuclei remaining in a sample having N_0 nuclei at t = 0 is

$$N(t) = N_0 e^{-t/\tau}.$$

$\tau = \dfrac{1}{\lambda}$ is the **mean lifetime** of a nucleus.

Note: the above expression for N(t) is a way to determine the number of remaining nuclei only. It does not tell us which nuclei have decayed.

It is common to write the expressions for N(t) and R(t) in terms of half-life ($T_{1/2}$).

$$T_{1/2} = \tau \ln 2 \qquad N(t) = N_0\left(2^{-t/T_{1/2}}\right) = N_0\left(\frac{1}{2}\right)^{t/T_{1/2}}$$

Biological Effects of Radiation

The **absorbed dose** of ionizing radiation is the amount of radiation energy absorbed per unit mass of tissue. Ionizing radiation is radiation with enough energy to ionize an atom or molecule.

The SI unit of absorbed dose is the Gray. 1 Gy = 1 J/kg. Another common unit is the rad (radiation absorbed dose). 1 rad = 0.01 Gy.