Lecture1
Basic Properties of Nucleus

1. Nucleus's Ingredients

Nucleus of an atom consists of **protons** and **neutrons**, each of which is called a **nucleon**. Symbolizes to nucleus $^{A}_{Z}X_{N}$,

Where:

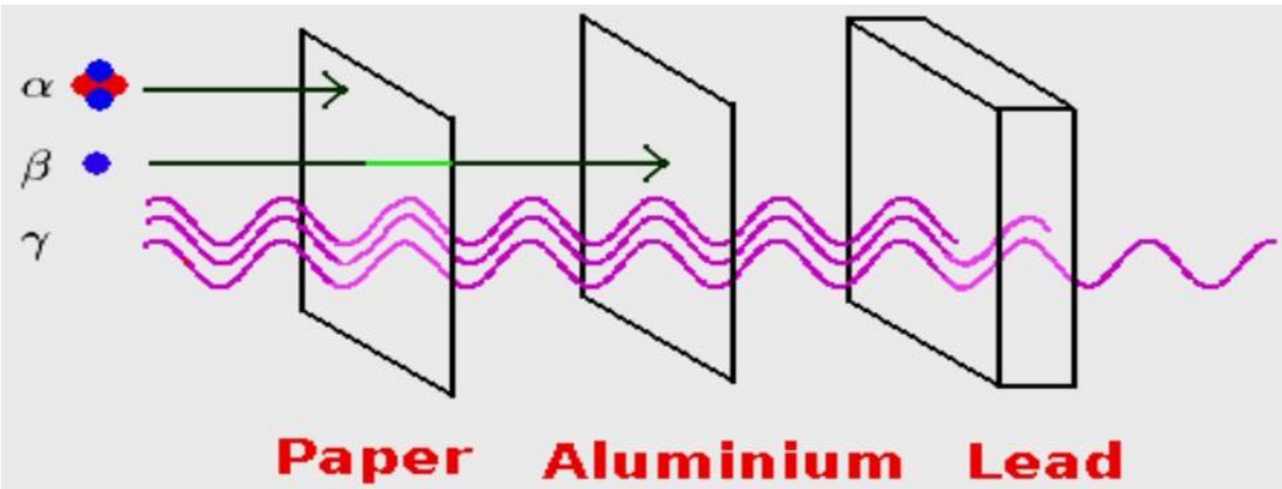
- ***X*** is an element.
- ***Z*** is atomic number (represents the number of protons inside a nucleus and also, equals to the number of electrons of the atom).
- ***N*** is the number of neutrons in a nucleus).
- ***A*** is the mass number (represents the **summation** of the number of **protons** and **neutrons** in a nucleus).

Some particular sequences of nuclei have special names:

- ***Isotopes***: have same charge ***Z***, but different ***N***, for instance $^{238}_{92}U$ and $^{235}_{92}U$. and also, $^{1}_{1}H_0$, $^{2}_{1}H_1$, $^{3}_{1}H_2$. There are more than 400 stable isotopes.
- ***Isotones:*** have the same ***N***, but different ***Z***, for instance $^{14}C_8$ and $^{16}O_8$. And also, $^{64}_{28}Ni_{36}$, $^{66}_{30}Zn_{36}$, $^{65}_{29}Cu_{36}$
- ***Isobars***: have the same mass number ***A***, such as ^{3}He and ^{3}H. and also, $^{50}_{24}Cr$, $^{50}_{23}V$, $^{50}_{22}Ti$

2. Alpha & Beta particles and Gamma Ray

Alpha particle (α) composed of two **protons** and two **neutrons** and, denoted for it $^4_2He_2$. Its energy is **large** and **dangerous** with the body, as it is **absorbed completely** by the body and has little **permeability**, i.e., **large absorption**. It is **positively** charged, so it is affected by the electric and magnetic field and can be stopped by a sheet of paper.



Beta particles *(β)* have **mass** and **charge** and are affected by electric and magnetic fields. It is an **electron** β^- or a **positron** β^+. It has a **permeability** greater than that of alpha particles, i.e., its **absorption is less**. A positron has the same mass as an electron with a positive charge and can be stopped by an aluminum plate.

What is the difference between an electron and a beta particle?

Gamma ray (γ) is an **electromagnetic radiation** (photons or quantities of energy). Gamma ray is emitted after emitting beta or alpha. It is **not affected** by the electric and magnetic fields because it is not charged. It has **a high permeability**, that is, **low absorption** and can be stopped using a lead shield.

3. Fundamental properties of nuclei

The basic properties of the nucleus divided into two classes. Time- independent properties such as **mass**, **charge**, **volume**, **density** and **angular momentum**. And time-dependent properties such as natural radioactive decay or nuclear reaction.

a) Nuclear mass and charge:

Since the nucleus is composed of **protons** (P) and **neutrons** (N), its mass is approximately equal to

$$M \cong ZM_P + NM_N$$

Where:

- **M** is nucleus mass measured in units (**amu**) "atomic mass unit" **1amu = 931.14Mev**
- M_P and M_N are the proton and neutron mass respectively.

As for the charge, it is equal to the charge of the protons Z, since the charge is equal to the charge (+1e), so the charge represents (+Ze).

b) The nucleus volume

The size of the nucleus is approximately $\mathbf{10^{-12}}$ cm and it is much smaller than the size of an atom $\mathbf{10^{-8}}$ cm, while the size of an atom is almost constant according to the size of the nucleus and the number of nucleons present in it. Where many experiments were conducted to measure the size of the nucleus, and one of these experiments are the scattering experiments. To calculate the **nucleus size** (***V***), should be calculate the **nucleus radius** (***R***).

Suppose that the nucleus has a spherical shape, so the sphere size (***V***) is equal to:

$$V = \frac{4\pi}{3} R^3 \qquad \text{AND} \qquad V = \frac{m}{\rho}$$

$$\frac{MA}{\rho} = \frac{4\pi}{3} R^3 \Longrightarrow R^3 = \frac{3MA}{4\pi\rho}$$

After calculating $R^3 = \frac{3M}{4\pi\rho}$, it was about between (**1.2 and 1.4**) fm (f=10^{-15}m). So, the **nucleus radius** equal to $R^3 = 1.2\, A^{1/3}$ with (**fermi units**).

c) Density

It can also be calculated by calculating **(mass / volume)**, so the nuclear density is approximately equal to **10^4** gm/cm.

d) Angular momentum

The scientist Pauli proposed the hypothesis that "the **nucleus of an atom has nuclear spin** (***i***) **which results from the intrinsic spin of nucleons (protons and neutrons)**". Where the spin of angular momentum (**I**) is:

$$I = \sqrt{i(i+1)}\ \hbar$$

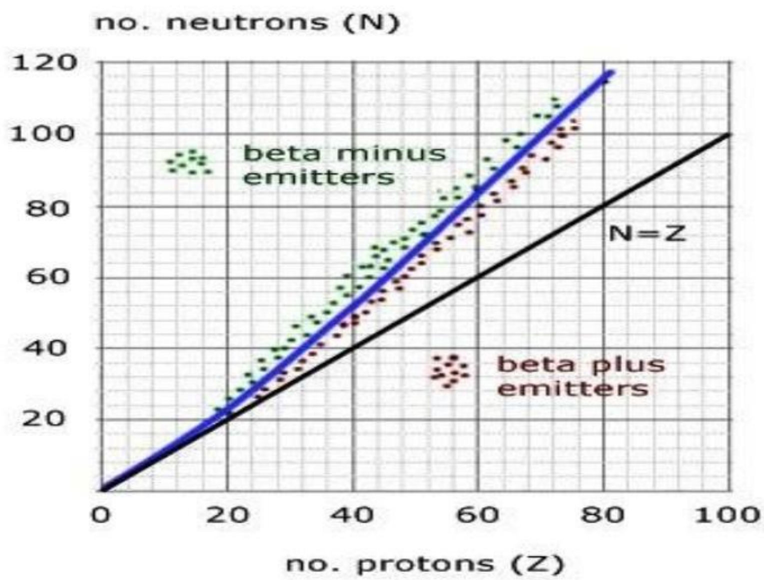
$(\hbar = \frac{h}{2\pi})$ *where* ***h*** *is plank constant* $6.626 * 10^{-34}\ m^2 kg/sec$

i is real number or multiples of half singles.

- ☒ If **Z** of an element is **odd** or **even** and **A** is **odd**, ***i*** is one of the multiples of half singles.
- ☒ If **Z** of an element is **odd** and **A** is **even**, ***i*** is **zero** or **real number**.

4. Nucleus stability

The **stability** of the nuclei **changes** with the change of the **Z** and **N** values, as shown in the figure below.



It appears from the figure that the number of protons is equal to the number of neutrons in the **stable nuclei**. In the light nuclei the nuclei clustered around the theoretical line of stable nuclei, which represents Z=N. As for the heavy nuclei, the nuclei grouping is above the theoretical line.

We note that the abundance of stable nuclei is when the nuclei are even-even, meaning the protons are an even number, as well as neutrons more than the individual nuclei - even or odd - odd.

This results from the nature of the **nuclear forces** that lead to a stronger bonding between pairs of similar nuclei present in the same state. This is why the alpha particle is so strong and unique. The state of high stability and high abundance of nuclei occurs in a special way when **N** and **Z** are **equal** to the integer numbers **2, 4, 20, 28, 50, 82, 126** and these numbers are called **Magic numbers**.

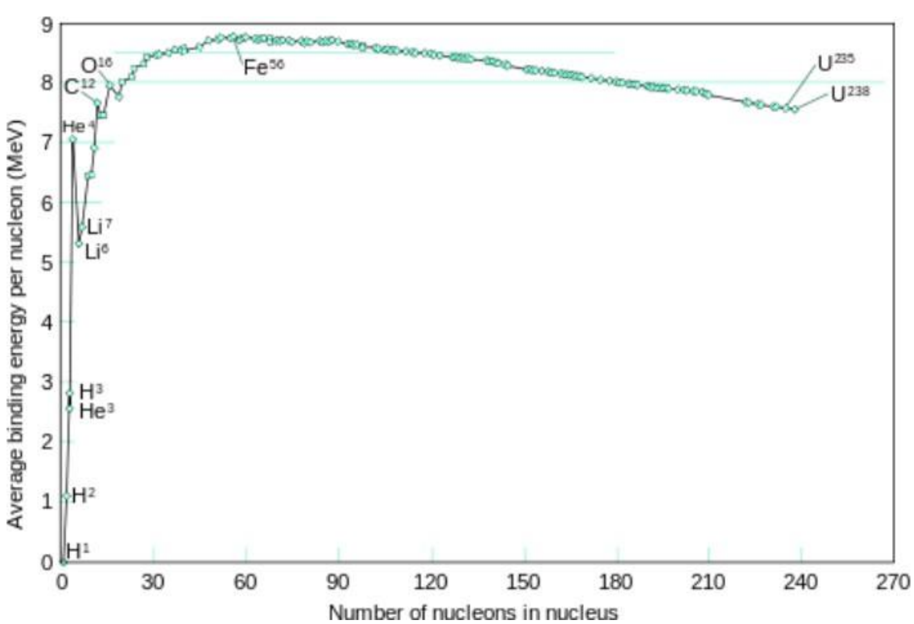
5. Nuclear Binding Energy

The difference between the nuclear mass and the sum of the nucleon's masses called the total binding energy of the nucleus, and is symbolized by $\boldsymbol{B_{tota}(A, Z)}$. It is defined as (the work required to disassemble the nucleus into its components, or it is the energy released when assembling nuclei Individually with each other.) and, the nuclear binding energy is calculated from the following equation:

$$B\,(A, Z) = [\,Zm_p + Nm_n - M(A, Z)]\,c^2$$

The total binding energy depends directly on the mass and atomic number as shown in the figure below, and this indicates that its value changes from one nucleus to another and the rate of nuclear binding energy, which is defined as: the work required to separate a neutron or one proton from the nucleus, can be calculated through the following equation:

$$B_{\,(average)} = \frac{Btotal}{A}$$



Example1

Calculate the total binding energy B_{total} and the rate binding energy $B_{average}$ for the nucleons of the atom nucleus of $^{16}_{8}\mathbf{O}$?

Note that: $m_p = 1.00759\ (amu), m_n = 1.00899\ (amu)\ and\ M(A, Z) = 16\ (amu)$.

$$B\ (A, Z) = [Zm_p + Nm_n - M\ (A, Z)]\ c^2$$

$$B\ (A, Z) = [8(1.00759) + 8(1.00899) - 16.000]\ c^2$$

$$= 0.137\ C^2\ (amu) \times 931.14\ Mev/amu.\ C^2 = 127.57\ Mev$$

$$B_{(average)} = \frac{Btotal}{A}$$

$$B_{(average)} = \frac{127.5}{16} = 7.97\ Mev/\ Nucleon$$

<u>Example1 (H.W)</u>

Calculate the total binding energy B_{total} and the rate binding energy $B_{average}$ for

the nucleons of the atom nucleus of $^{3}_{2}\mathbf{H}$? Note that: $M(A, Z) = 3(amu)$

6. Nuclear Separation Energy

The work needed to separate a single proton, neutron, or alpha particle from the nucleus of an atom. The nuclear separation energy can be calculated for neutrons, protons, and α-particles.

$S_p = [M(A-1, Z-1) + M_p - M(A, Z)]\,c^2$

$S_n = [M(A-1, Z) + M_n - M(A, Z)]\,c^2$

$S_\alpha = [M(A-4, Z-2) + M_\alpha - M(A, Z)]\,c^2$

Also, the separation equations can be written in terms of the total binding energy as follows:

$$S_n = B_{total}(A, Z) - B_{total}(A-1, Z)$$

$$S_p = B_{total}(A, Z) - B_{total}(A-1, Z-1)$$

$$S\alpha = B_{total}(A, Z) - B_{total}(A-4, Z-2) - B_{total}(4, 2)$$

7. Nuclear Force

There are many known fundamental forces that exist in nature, such as the force of attraction, electromagnetic forces, and weak forces, in addition to these forces. There is another very important force, which is the **nuclear force**, which is responsible for linking the components of the nucleus together. This force has properties as shown below:

- The nuclear force is a strong attraction force between the nucleons, i.e. between (a proton and a proton, a neutron and a neutron or a proton and a neutron) and this force maintains the stability of the nucleus. In the heavy nuclei, we note that the nuclear force is greater than the force of the columbic repulsion between the protons.
