

The Nuclear Forces and Nuclear Radiation

Nuclear Forces

In the Bohr model of the atom, **the nucleus consists of positively-charged protons and electrically neutral neutrons**. Since both protons and neutrons exist in the nucleus, they are both referred to as **nucleons**. One problem that the Bohr model of the atom presented was accounting for an attractive force to overcome the repulsive force between protons.

Two forces present in the nucleus, they are :

1. **Gravitational forces** between any two objects that have mass
2. **Electrostatic forces** between charged particles.

It is possible to calculate the magnitude of the gravitational force and electrostatic force based upon principles from classical physics.

- ❖ **Newton stated** that the **gravitational force** between two bodies **is directly proportional to the masses of the two bodies** and **inversely proportional to the square of the distance** between the bodies. This relationship is shown in the equation below:

$$F_g = \frac{G m_1 m_2}{r^2}$$

Where: F_g = gravitational force (newton), m_1 = mass of the first body (kilograms)

m_2 = mass of the second body (kilograms), G = gravitational constant ($6.67 \cdot 10^{-11} \text{ N.m}^2/\text{kg}^2$)

r = distance between particles (meters)

This equation illustrates the larger the masses of the objects or the smaller the distance between the objects the greater the gravitational force. So even though **the masses of nucleons are very small, the fact that the distance between nucleons is extremely short** may make the gravitational force significant.

It is necessary to calculate the value of gravitational force and compare it to the value for other forces to determine the significance of the gravitational force and compare it to the value of other forces to determine the significance of the gravitational force in the nucleus.

The gravitational force between two protons that are separated by a distance of 10^{-20} meters is about 10^{-24} newton.

- ❖ **Coulombs Law** can be used to calculate the force between two protons. **The electrostatic force** is directly **proportional to the electrical charges of the two particles** and **inversely proportional to the square of the distance between the particles**. Coulombs Law is stated as the following equation.

$$F_e = \frac{K Q_1 Q_2}{r^2}$$

Where

F_e = electrostatic force (newton), K = electrostatic constant ($9.0 \cdot 10^9 \text{ N.m}^2/\text{C}^2$)

Q_1 = charge of first particle (coulombs) , Q_2 = charge of second particle (coulombs)

r = distance between particles (meters)

Using this equation, **the electrostatic force** between two protons that are separated by a distance of **10^{-20} meters** is about **10^{12} newton**. Comparing this result with the calculation of the **gravitational force (10^{-24} newton)** shows that the gravitational force is so small that it can be neglected.

- **If only the electrostatic and gravitational forces existed in the nucleus, then it would be impossible to have stable nuclei composed of protons and neutrons.**
- The gravitational forces are too small to hold the nucleons together compared to the electrostatic forces repelling the protons.
- **Since stable atoms of neutrons and protons do exist, there must be another attractive force acting within the nucleus.** This force is called the **nuclear force**.
- **The nuclear force: Is a strong attractive force that is independent of charge.**

The Properties of Nuclear Force

- **It acts equally only between pairs of neutrons, pairs of protons, or a neutrons and a proton.**
- **The nuclear force has a very short range; it acts only over distances approximately equal to the diameter of the nucleus (10^{-13}) cm.**
- **The attractive nuclear force between all nucleons drops off with distance much faster than the repulsive electrostatic force between protons.**

Table – 2 : Forces Acting in the Nucleus

Force	Interaction	Range
Gravitational	Very weak attractive force between all nucleons	Relatively long
Electrostatic	Strong repulsive force between like charged particles (protons)	Relatively long
Nuclear Force	Strong attractive force between all nucleons	Extremely short

- **In the stable atoms, the attractive and repulsive forces in the nucleus are in balance.**
- **If the forces do not balance, the atom cannot be stable, and the nucleus will emit radiation in an attempt to achieve a more stable configuration.**

Mass defect

Careful measurements have shown that the mass of a particular atom is always slightly less than the sum of the masses of the individual neutrons, protons, and electrons of which the atom consists.

The mass defect (Δm):

The difference between the mass of the atom and the sum of the masses of its parts .

- **The mass defect can be calculated using equation (1).**
- **In calculating the mass defect it is important to use the full accuracy of mass measurements because the difference in mass is small compared to the mass of the atom. (تعليق)**
- Rounding off the masses of atoms and particles to three or four significant digits prior to the calculation will result in a calculated mass defect of zero.

$$\Delta m = [Z (m_p+m_e) + (A-Z) m_n]- m_{\text{atom}} \quad \dots\dots\dots (1)$$

Where, Δm = mass defect (amu) , m_p = mass of a proton (1.007277)
 m_n = mass of neutron (1.008665) , m_e = mass of electron (0.00054859)
 m_{atom} = mass of nuclide ${}^A_Z X$ (amu) , Z = atomic number (number of proton)
 A = mass number (number of nucleons)

Example:

Calculate the mass defect for lithium -7. The mass of lithium-7 is 7.016003 amu.

Solution:

$$\Delta m = [Z (m_p+m_e) + (A-Z) m_n]- m_{\text{atom}}$$

$$\Delta m = [3(1.007826 \text{ amu}) + (7-3) 1.008665 \text{ amu}] - 7.016003 \text{ amu}$$

$$\Delta m = 0.0421335 \text{ amu}$$

Binding energy

Why there is a mass defect?

It is due to the conversion of mass to binding energy when the nucleus is formed. (تعليق)

Binding energy : Is the amount of energy that must be supplied to a nucleus to completely separate its nuclear particle (nucleons).

It can also be understood as the amount of energy that would be released if the nucleus was formed from the separate particle.

Binding energy is the energy equivalent of the mass defect.

Since the mass defect was converted to binding energy (BE) when the nucleus was formed.

- It is possible to **calculate the binding energy using** a conversion factor derived by the mass-energy relationship from Einstein Theory of relativity.
- Einstein's famous equation relating mass and energy **$E=mc^2$** where c is the velocity of light ($c=2.998 \times 10^8 \text{ m/sec}$). The energy equivalent of 1 amu can be determined by inserting this quantity of mass into Einstein's equation and applying conversion factors.

$$E = m c^2$$

$$\begin{aligned}
&= 1 \text{ amu} \left(\frac{1.6606 \times 10^{-27} \text{ kg}}{1 \text{ amu}} \right) \left(2.998 \times 10^8 \frac{\text{m}}{\text{sec}} \right)^2 \\
&= 1.4924 \times 10^{-10} \text{ J} \left(\frac{1 \text{ MeV}}{1.6022 \times 10^{-13} \text{ J}} \right) \\
&= 931.5 \text{ MeV}
\end{aligned}$$

Conversion Factors:

$$\begin{aligned}
1 \text{ amu} &= 1.6606 \times 10^{-27} \text{ kg} \\
1 \text{ newton} &= 1 \text{ kg-m/sec}^2 \\
1 \text{ joule} &= 1 \text{ newton-meter} \\
1 \text{ MeV} &= 1.6022 \times 10^{-13} \text{ joules}
\end{aligned}$$

Since 1 amu is equivalent to 931.5 MeV of energy, the binding energy can be calculated using Equation (1-2).

$$\text{B.E.} = \Delta m \left(\frac{931.5 \text{ MeV}}{1 \text{ amu}} \right) \tag{1-2}$$

Example:

Calculate the mass defect and binding energy for uranium-235. One uranium-235 atom has a mass of 235.043924 amu.

Solution:

Step 1: Calculate the mass defect using Equation (1-1).

$$\begin{aligned}
\Delta m &= [Z (m_p + m_e) + (A - Z) m_n] - m_{\text{atom}} \\
\Delta m &= [92 (1.007826 \text{ amu}) + (235 - 92) 1.008665 \text{ amu}] - 235.043924 \text{ amu} \\
\Delta m &= 1.91517 \text{ amu}
\end{aligned}$$

Step 2: Use the mass defect and Equation (1-2) to calculate the binding energy.

$$\begin{aligned}
\text{B.E.} &= \Delta m \left(\frac{931.5 \text{ MeV}}{1 \text{ amu}} \right) \\
&= 1.91517 \text{ amu} \left(\frac{931.5 \text{ MeV}}{1 \text{ amu}} \right) \\
&= 1784 \text{ MeV}
\end{aligned}$$

Energy Levels of the Nucleus

- ❖ **The nucleons (proton + neutron) in the nucleus of an atom**, like the electrons that circle the nucleus, exist in shells that **correspond to energy state**.
- ❖ **There is a state of lowest energy shells of the nucleus** are less defined and less understood than those of the electron.
- ❖ There is a state of lowest energy (the ground state) and discrete possible excited states for a nucleus. **Where the discrete energy states for the electrons of an atom are measured in eV or keV, the energy levels of the nucleus are considerably greater and typically measured in MeV.**
- ❖ **A nucleus that is in the excited state** will not remain at that energy level for an indefinite period. Like the electrons in the excited atom, **the nucleons in an excited nucleus will transition towards their lowest energy configuration and in doing so emit a discrete bundle of electromagnetic radiation called a gamma ray (γ -ray)** are their energy levels and whether they are emitted from the electron shell or from the nucleus.
- ❖ **The ground state and the excited states of a nucleus** can be depicted **in a nuclear energy-level diagram**. The nuclear energy-level diagram consists of a stack of horizontal bar, one bar for each of the excited states of the nucleus.
- ❖ The vertical distance between the bar representing excited state and the bar representing the ground state is proportional to the energy level of the excited state with respect to the ground state. **This difference in the energy between the ground state and the excited state is called the excitation energy of the excited state.** The ground state of a nuclide has **zero** excitation energy. The bars for the excited states are labeled with their respective energy levels. Figure 1 is the energy levels diagram for nickel-60 agram

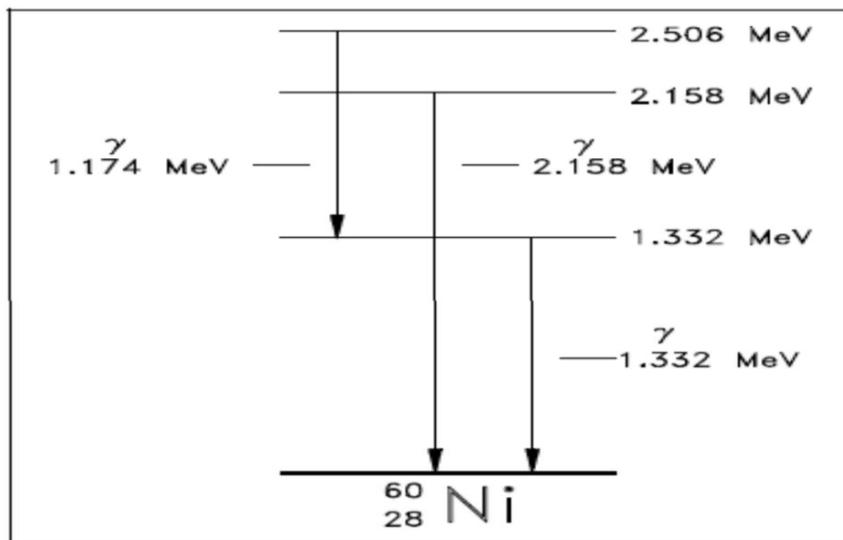


Figure – 1 : Energy Levels Diagram of Nickel – 60

Radioactivity :

In 1896, Becquerel accidentally discovered that crystal of uranium salt emitted rays that were similar to x-ray in that they were highly penetrating, could effect and darken a photographic plate and ionize gases even though the plate is covered to exclude light. This process of spontaneous emission of radiation by uranium was soon to be called radioactivity.

Radioactivity : Is the process where an unstable atomic nucleus spontaneously emits energy and particles to become more stable.

Subsequent experiments by other scientists showed that other substances were more powerfully radioactive. The most significant early investigations of this type were conducted by Marie and Pierre Curie (1859–1906). After several years of careful and laborious chemical separation processes, the Curies reported the discovery of two previously unknown elements, both radioactive, named polonium and radium. Additional experiments, including Rutherford's famous work on alpha-particle scattering, suggested that radioactivity is the result of the decay, or disintegration, of unstable nuclei.

Three types of radioactive decay occur in radioactive substances:

- ❖ alpha (α) decay, in which the emitted particles are ${}^4\text{He}$ nuclei;
- ❖ beta (β) decay, in which the emitted particles are either electrons or positrons;
- ❖ gamma (γ) decay, in which the emitted particles are high-energy photons.

A positron is a particle like the electron in all respects except that the positron has a charge of $+e$. (The positron is the antiparticle of the electron). The symbol e^- is used to designate an electron, and e^+ designates a positron.

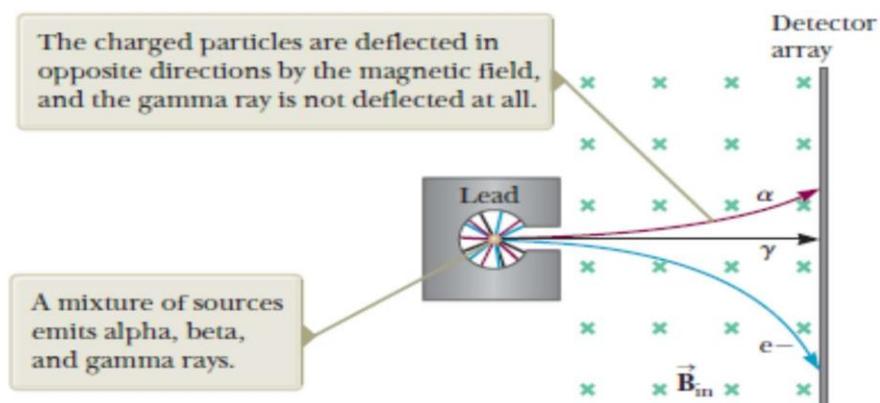


Figure 2 The radiation from radioactive sources can be separated into three components by using a magnetic field to deflect the charged particles. The detector array at the right records the events.

We can distinguish among these three forms of radiation by using the scheme described in figure 2. The radiation from radioactive samples that emit all three types of particles is directed

into a region in which there is a magnetic field.

- ❖ **The radiation beam splits into three components**, two bending in opposite directions and the third experiencing no change in direction.
- ❖ This simple observation shows that **the radiation of the undeflected beam carries no charge (the gamma ray), the component deflected upward corresponds to positively charged particles (alpha particles), and the component deflected downward corresponds to negatively charged particles (e^-)**. If the beam includes a positron (e^+), it is deflected upward like the alpha particle, but it follows a different trajectory due to its smaller mass.

Penetrating power of nuclear radiation

Penetration Power :The ability of the radiation to pass through matter.

The three types of **nuclear radiation** have quite different penetrating powers.

- **Alpha particles** barely penetrate a sheet of paper,
- **Beta particles** can penetrate a few millimeters of aluminum,
- **Gamma rays** can penetrate several centimeters of lead.

