

University of Al-Anbar  
College of Applied Sciences-Heet  
Biophysics Department  
Modern Physics-Fourth Stage

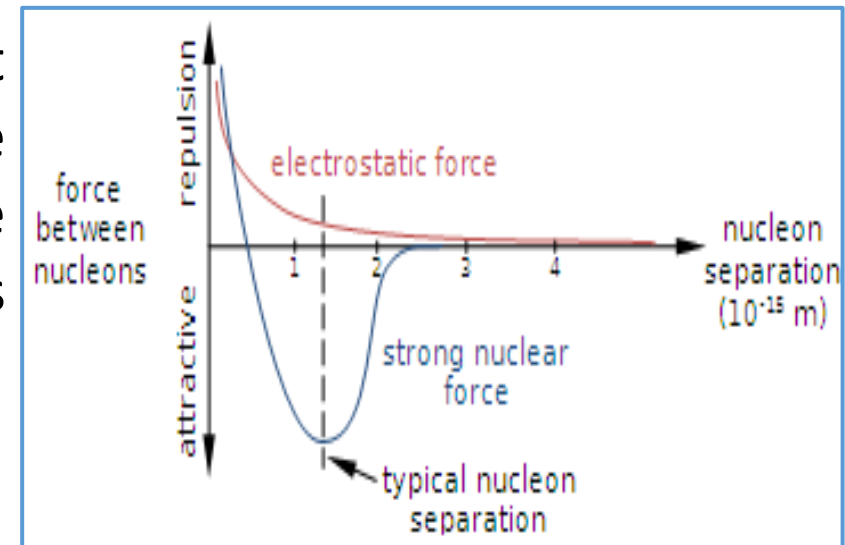
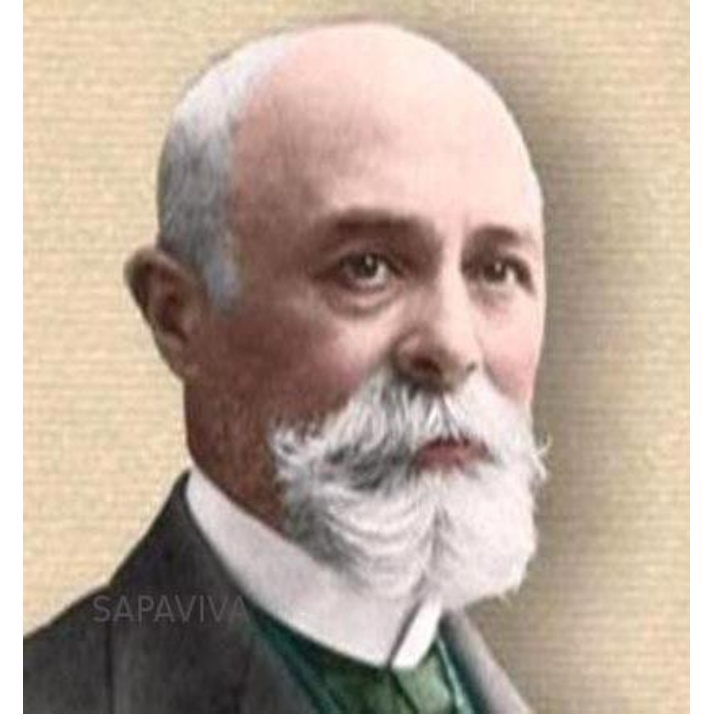
# Nuclear Physics

## Lecture Four

*Dr. Nabeel F. Lattoofi*

# Introduction

- The year 1896 marks the birth of nuclear physics when French physicist **Antoine-Henri Becquerel** (1852–1908) discovered radioactivity in uranium compounds.
- **Ernest Rutherford** showed that the radiation emitted from radioactive substances is of three types **alpha, beta, and gamma rays** classified according to the nature of their electric charge and their ability to penetrate matter and ionize air.
- After alpha-particle scattering experiments, subsequent studies revealed the presence of a new type of force, the **short-range nuclear force**, which is predominant at particle separation distances less than approximately  $10^{-14}$  m and is zero for large distances.



# Some Properties of Nuclei

All nuclei are composed of two types of particles: protons and neutrons

## 1- Charge and Mass

The proton carries a single positive charge  $e$ , equal in magnitude to the charge  $-e$  on the electron ( $e = 1.6 \times 10^{-19}$  C).

The proton is approximately **1 836** times as massive as the electron, and the masses of the proton and the neutron are almost equal.

The atomic mass unit  **$u$**  is defined in such a way that the mass of one atom of the isotope  $^{12}\text{C}$  is exactly  $12u$ , where ( $1\ u = 1.660539 \times 10^{-27}$  kg) which is equal to the proton or neutron mass.

## Isotope Symbols

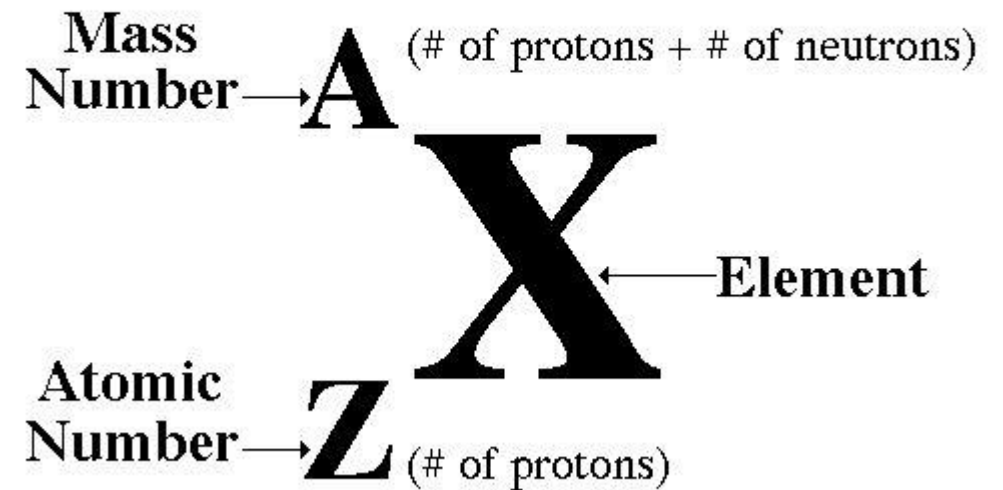


Table 44.1 Masses of Selected Particles in Various Units

Particle	kg	Mass u	MeV/ $c^2$
Proton	$1.672\ 62 \times 10^{-27}$	1.007 276	938.27
Neutron	$1.674\ 93 \times 10^{-27}$	1.008 665	939.57
Electron ( $\beta$ particle)	$9.109\ 38 \times 10^{-31}$	$5.485\ 79 \times 10^{-4}$	0.510 999
$^1_1\text{H}$ atom	$1.673\ 53 \times 10^{-27}$	1.007 825	938.783
$^4_2\text{He}$ nucleus ( $\alpha$ particle)	$6.644\ 66 \times 10^{-27}$	4.001 506	3 727.38
$^4_2\text{He}$ atom	$6.646\ 48 \times 10^{-27}$	4.002 603	3 728.40
$^{12}_6\text{C}$ atom	$1.992\ 65 \times 10^{-27}$	12.000 000	11 177.9

How six protons and six neutrons, each having a mass larger than 1 u, can be combined with six electrons to form a carbon-12 atom having a mass of exactly 12 u? The bound system of  $^{12}\text{C}$  has a lower rest energy than that of six separate protons and six separate neutrons. According to Equation ( $E = mc^2$ ), this lower rest energy corresponds to a smaller mass for the bound system. The difference in mass accounts for the binding energy when the particles are combined to form the nucleus.

$$E_R = mc^2 = (1.660\,539 \times 10^{-27} \text{ kg})(2.997\,92 \times 10^8 \text{ m/s})^2 = 931.494 \text{ MeV}$$

### Example 44.1 The Atomic Mass Unit

Use Avogadro's number to show that  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ .

#### SOLUTION

**Conceptualize** From the definition of the mole given in Section 19.5, we know that exactly 12 g (= 1 mol) of  $^{12}\text{C}$  contains Avogadro's number of atoms.

**Categorize** We evaluate the atomic mass unit that was introduced in this section, so we categorize this example as a substitution problem.

Find the mass  $m$  of one  $^{12}\text{C}$  atom:

$$m = \frac{0.012 \text{ kg}}{6.02 \times 10^{23} \text{ atoms}} = 1.99 \times 10^{-26} \text{ kg}$$

Because one atom of  $^{12}\text{C}$  is defined to have a mass of 12.0 u, divide by 12.0 to find the mass equivalent to 1 u:

$$1 \text{ u} = \frac{1.99 \times 10^{-26} \text{ kg}}{12.0} = 1.66 \times 10^{-27} \text{ kg}$$

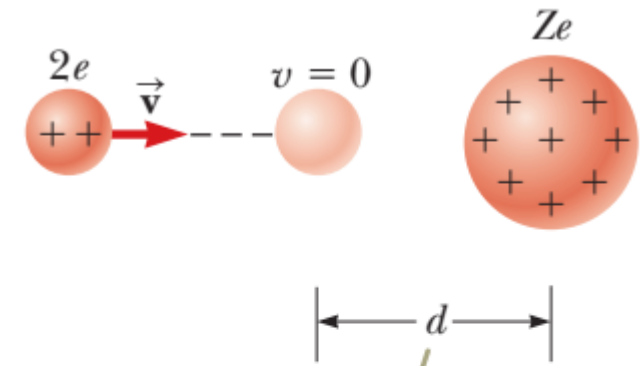
## 2- The Size and Structure of Nuclei

Rutherford used, in scattering experiment, the isolated system (energy) analysis model to find an expression for the separation distance  $d$  at which an alpha particle approaching a nucleus head-on is turned around by Coulomb repulsion.

$$\Delta K + \Delta U = 0$$

$$(0 - \frac{1}{2}mv^2) + \left(k_e \frac{q_1 q_2}{d} - 0\right) = 0$$

$$d = 2k_e \frac{q_1 q_2}{mv^2} = 2k_e \frac{(2e)(Ze)}{mv^2} = 4k_e \frac{Ze^2}{mv^2}$$



Because of the Coulomb repulsion between the charges of the same sign, the alpha particle approaches to a distance  $d$  from the nucleus, called the distance of closest approach.

Rutherford found that the alpha particles approached nuclei to within  $3.2 \times 10^{-14}$  m. Rutherford concluded that the positive charge in an atom is concentrated in a small sphere, which he called the nucleus, whose radius is no greater than approximately  $10^{-14}$  m (  $1 \text{ fm} \equiv 10^{-15} \text{ m}$  )



### 3- the volume and density

In the early 1920s, it was known that the nucleus of an atom contains  $Z$  protons and has a mass nearly equivalent to that of  $A$  protons, where on average  $A \sim 2Z$  for lighter nuclei ( $Z \leq 20$ ) and  $A > 2Z$  for heavier nuclei.

To account for the nuclear mass, Rutherford proposed that each nucleus must also contain  $A-Z$  neutral particles that he called neutrons. In 1932, British physicist James Chadwick discovered the neutron.

➤ Other experiments have shown that most nuclei are approximately spherical and have an average radius given by

$$r = aA^{1/3}$$

where  $a = 1.2 \times 10^{-15} \text{ fm}$

Because the volume of a sphere is proportional to the cube of its radius, it follows that the volume of a nucleus (assumed to be spherical) is directly proportional to  $A$ , the total number of nucleons. This proportionality suggests that all nuclei have nearly the same density. When nucleons combine to form a nucleus, they combine as though they were tightly packed spheres.

**Example 44.2****The Volume and Density of a Nucleus**

Consider a nucleus of mass number  $A$ .

**(A)** Find an approximate expression for the mass of the nucleus.

*continued*

**Analyze** The mass of the proton is approximately equal to that of the neutron. Therefore, if the mass of one of these particles is  $m$ , the mass of the nucleus is approximately  $Am$ .

**(B)** Find an expression for the volume of this nucleus in terms of  $A$ .

**SOLUTION**

Assume the nucleus is spherical and use Equation 44.1:

$$(1) \quad V_{\text{nucleus}} = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi a^3 A$$

**(C)** Find a numerical value for the density of this nucleus.

**SOLUTION**

Use Equation 1.1 and substitute Equation (1):

$$\rho = \frac{m_{\text{nucleus}}}{V_{\text{nucleus}}} = \frac{Am}{\frac{4}{3}\pi a^3 A} = \frac{3m}{4\pi a^3}$$

Substitute numerical values:

$$\rho = \frac{3(1.67 \times 10^{-27} \text{ kg})}{4\pi(1.2 \times 10^{-15} \text{ m})^3} = 2.3 \times 10^{17} \text{ kg/m}^3$$

**Finalize** The nuclear density is approximately  $2.3 \times 10^{14}$  times the density of water ( $\rho_{\text{water}} = 1.0 \times 10^3 \text{ kg/m}^3$ ).

**WHAT IF?** What if the Earth could be compressed until it had this density? How large would it be?

**Answer** Because this density is so large, we predict that an Earth of this density would be very small.

Use Equation 1.1 and the mass of the Earth to find the volume of the compressed Earth:

$$V = \frac{M_E}{\rho} = \frac{5.97 \times 10^{24} \text{ kg}}{2.3 \times 10^{17} \text{ kg/m}^3} = 2.6 \times 10^7 \text{ m}^3$$

From this volume, find the radius:

$$V = \frac{4}{3}\pi r^3 \rightarrow r = \left(\frac{3V}{4\pi}\right)^{1/3} = \left[\frac{3(2.6 \times 10^7 \text{ m}^3)}{4\pi}\right]^{1/3}$$

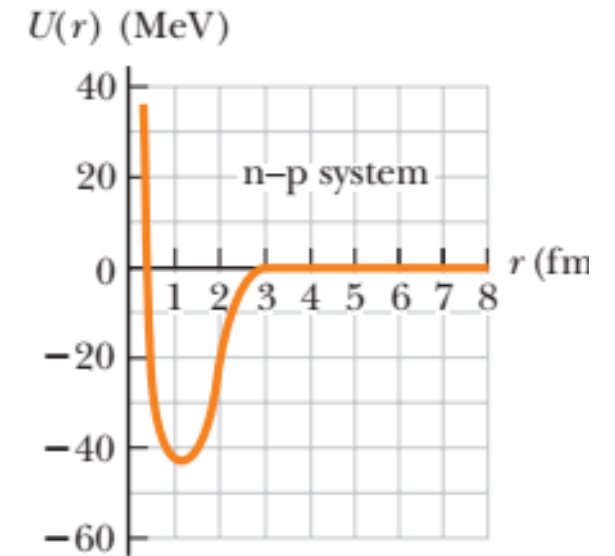
$$r = 1.8 \times 10^2 \text{ m}$$

An Earth of this radius is indeed a small Earth!

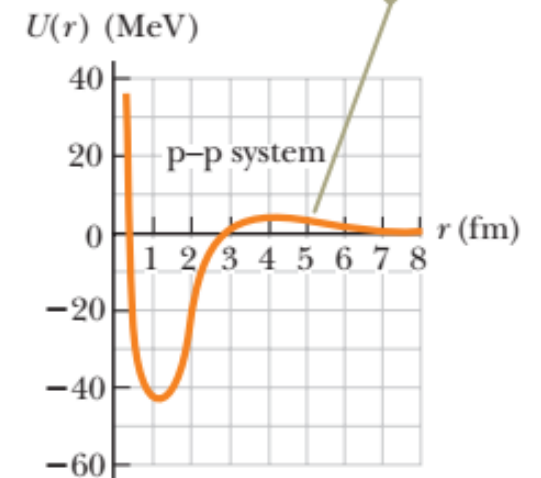
## 4-Nuclear Stability

- The nuclear force is a very short range (about 2 fm) attractive force that acts between all nuclear particles. The protons attract each other by means of the nuclear force, and, at the same time, they repel each other through the Coulomb force.

The nuclear force is independent of charge. The depth of the n–p potential energy well is 40 to 50 MeV, and there is a strong repulsive component that prevents the nucleons from approaching much closer than 0.4 fm

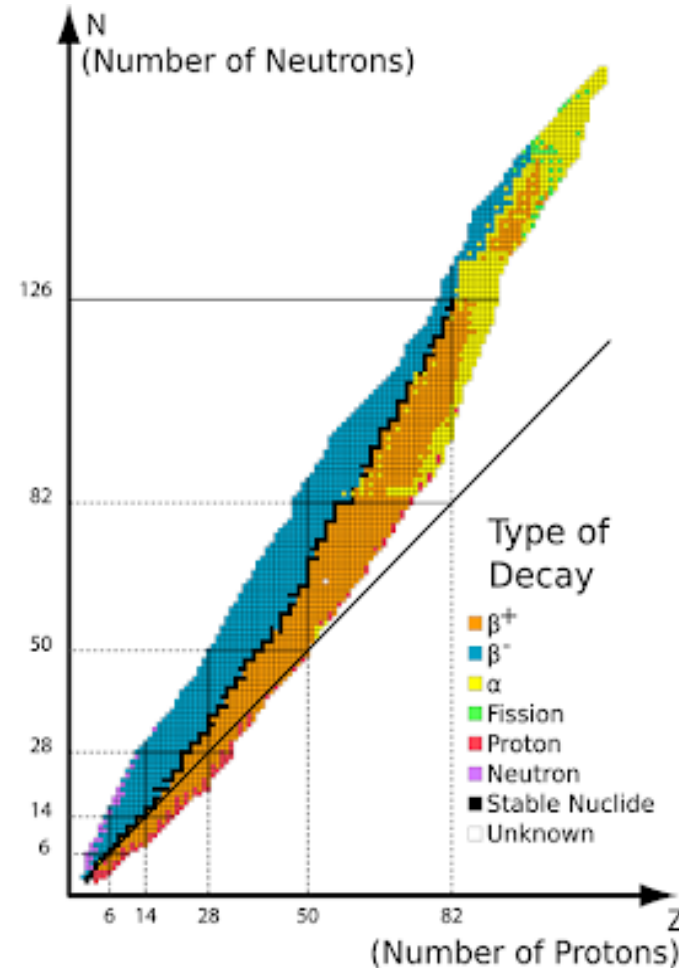


The difference in the two curves is due to the large Coulomb repulsion in the case of the proton–proton interaction.





- The existence of the nuclear force results in approximately **270 stable nuclei**; hundreds of other nuclei have been observed, but they are unstable.  $N = Z$  for light nuclei. Also notice that in heavy stable nuclei, the number of neutrons exceeds the number of protons: **above  $Z=20$ , the line of stability deviates upward from the line representing  $N = Z$ ?**
- Eventually, the repulsive Coulomb forces between protons cannot be compensated by the addition of more neutrons. This point occurs at  $Z=83$ , meaning that elements that contain more than 83 protons do not have stable nuclei.



## Nuclear Stability

Decay will occur in such a way as to return a nucleus to the band (line) of stability.

The most stable nuclide is Iron-56

If  $Z > 83$ , the nuclide is radioactive

**THANK YOU**  
**FOR YOUR ATTENTION**

# Reference

