Introduction to Nuclear Physics

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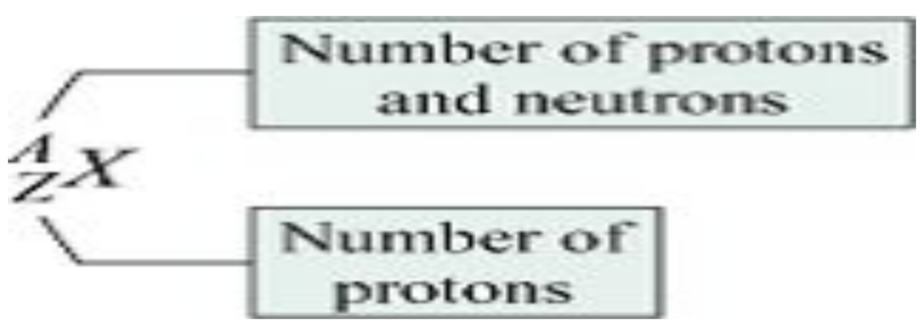
Nuclear Structure

Atoms consist of electrons in orbit about a central nucleus. As we have seen later, the electron orbits are quantized in nature and have interesting characteristics which distinguishing the properties of all elements. **Little has been said about the nucleus.** However, the nucleus is subject of our study and our interest, which we will deal them in detail.

The nucleus of an atom consists of **neutrons and protons**, collectively referred to as ***nucleons***.

The **proton,** has a mass 1835 times mass of electron and carry positive charge

The ***neutron***, carries no electric charge and has a mass slightly larger than that of a proton

- Any nucleus is specified by its atomic number (Z)(no. of protons) and its mass number (A)(total no. of nucleons=no. of protons + no. of neutrons).
- As an example Uranium element has
- A=238 and Z=92
- Then, the no. of neutrons N =A – Z= 238 -92 = 146
- In general, for an element whose chemical symbol is *X*, the symbol for the nucleus is
- 

Materials are classified into :

1. Stable	2. Unstable
Not Change with time	Change with time
Natural	Natural - Artificial

- (*nucleon* is always used to refer to either a proton or a neutron).
- The symbol we use to represent nuclei is ${}_{Z}^{A}X$, where X represents the chemical symbol for the element. For example, ${}_{13}^{27}Al$ has the mass number 27 and the atomic number 13; therefore, it contains 13 protons and 14 neutrons.

Some Properties of Nuclei

- All nuclei are composed of two types of particles: neutrons and protons. The only exception is the hydrogen nucleus, For describe the nucleus, we make use of the following quantities:
- • **Atomic number *Z***, which equals the number of protons in the nucleus.
- • **Neutron number *N***, which equals the number of neutrons in the nucleus.
- • **Mass number *A***, which equals the number of nucleons in the nucleus

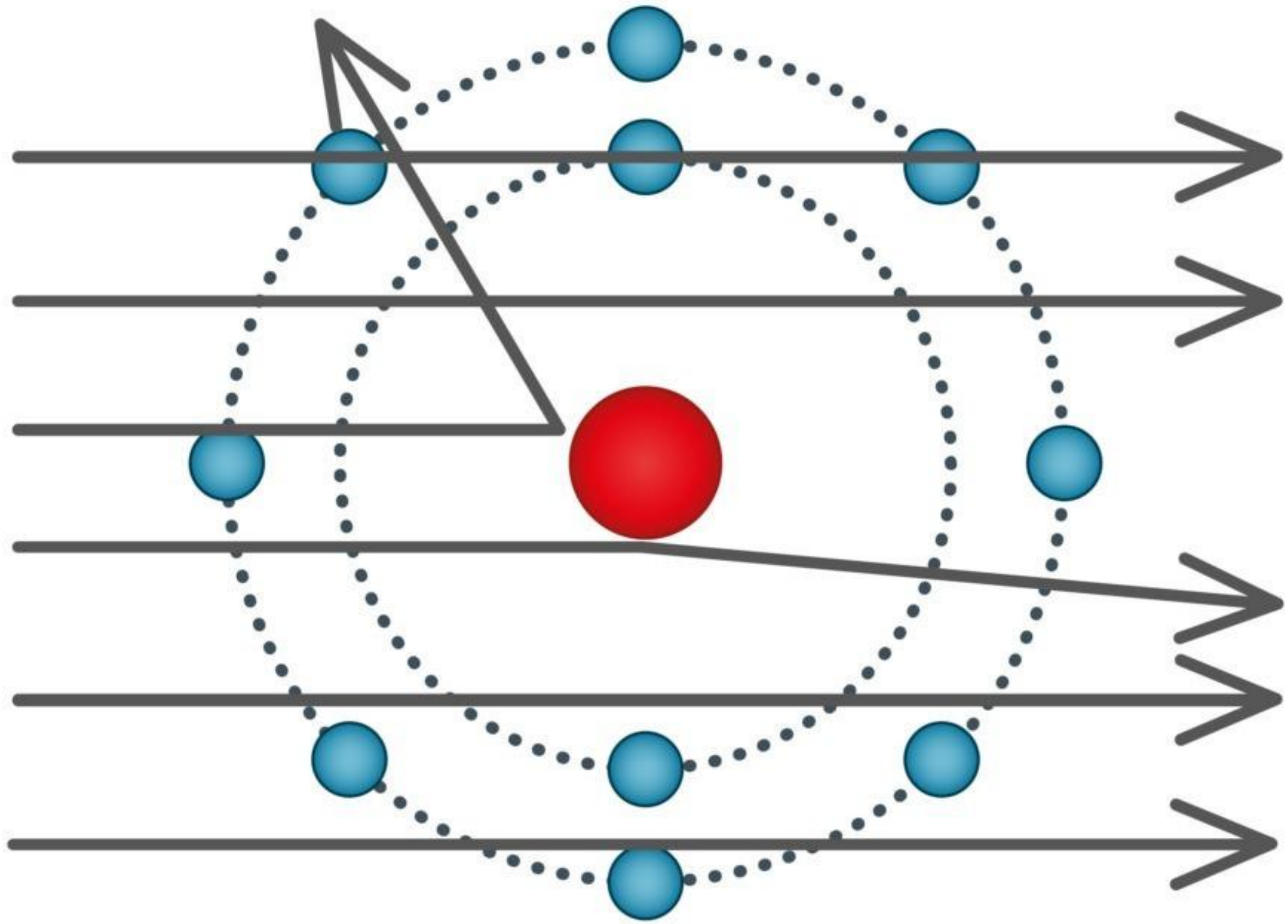
Furthermore, a survey of the stable nuclei reveals that even-even nuclei are the ones most abundant in nature. This again lends support to the strong-pairing hypothesis, namely that pairing of .nucleons leads to nuclear stability

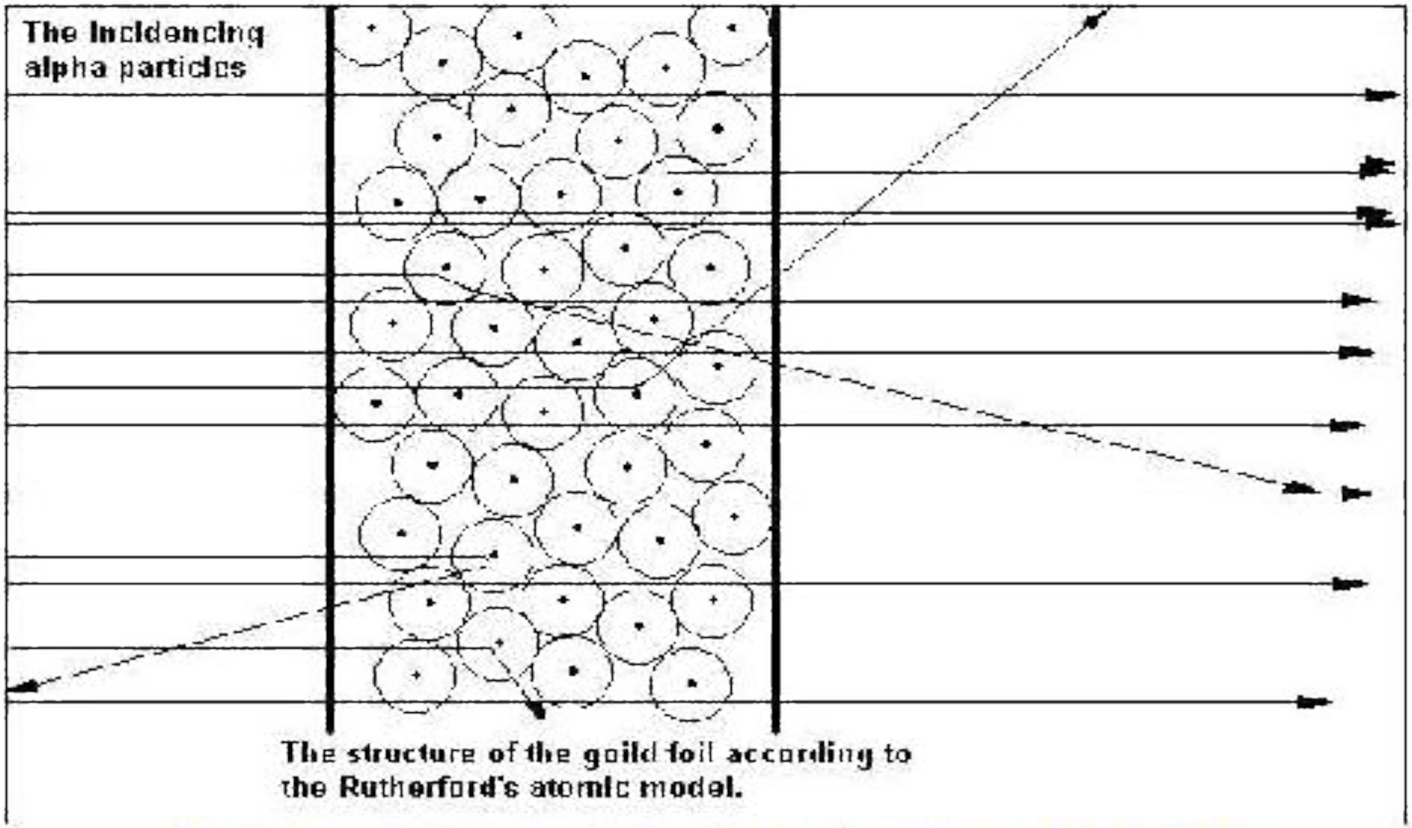
N	Z	Number of Stable Nuclei
Even	Even	156
Even	Odd	48
Odd	Even	50
Odd	Odd	5

Rutherford's experiment

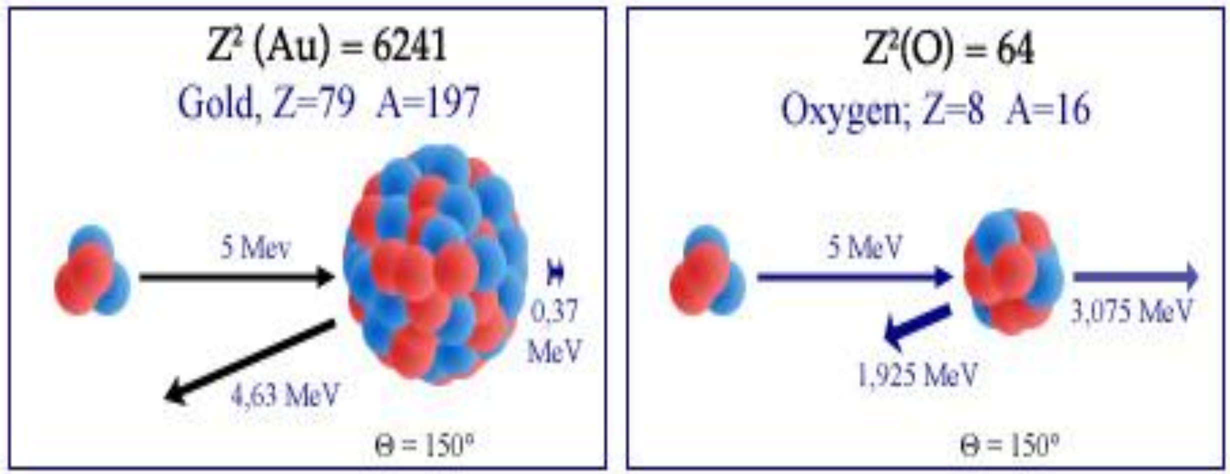
Principle of **Rutherford's experiment**. By bombarding a very thin **gold foil** with alpha particles, **Rutherford**, observed that a small fraction (1 in 8000) of these particles were deflected at large angle as if it bounced off a heavy obstacle , which is the nucleus.

Rutherford's Model





The alpha particles propagated on the atomic nucleuses of the gold foil.



Alpha backscattering on nucleus

Rutherford observed the backward bounce of some alpha particles as projectiles sent on the atoms of a thin gold foil. He interpreted this rebound as the "backscatter" of a light nucleus (alpha particle) on the heavy nucleus of a gold atom. Because of the mass ratio (A = 4 versus A = 197), the alpha particle bouncing off (on the left figure) at 150 °, loses only a small portion of its energy. On the contrary, in the case of a collision (on the right) with a lighter nucleus as oxygen (A = 16), the alpha loses most of its energy in aid of oxygen propelled .forward

The Size of Nuclei

Rutherford found an expression for how close an alpha particle moving directly toward the nucleus can come to the nucleus before being turned around by Coulomb repulsion. In such a head-on collision, the kinetic energy of the incoming alpha particle must be converted completely to electrical potential energy when the particle stops at the point of closest approach and turns around .

- If we equate the initial kinetic energy of the alpha particle to the maximum electrical potential energy of the system (alpha particle plus target nucleus), we have

$$\frac{1}{2} m v^2 = k_e \frac{q_1 q_2}{r} = k_e \frac{2e\, Ze}{d}$$

where *d* is the distance of closest approach. Solving for *d*, we get

$$d = \frac{4 k_e Z e^2}{m v^2}$$

From this expression,

Rutherford found that alpha particles approached to within 3.2 x 10^{-14} m of a nucleus when the foil was made of gold.

Thus, the radius of the gold nucleus must be less than this value. For silver atoms, the distance of closest approach was 2x 10^{-14} m. From these results, Rutherford concluded that the positive charge in an atom **is oncentrated in a small sphere, which he called the nucleus, with radius no greater than about 10^{-14} m**. Because such small lengths are common in nuclear physics, a convenient unit of length is the *femtometer* fm ,

sometimes called the **Fermi** and defined as

$$1\ Fm = 10^{-15}\ m$$

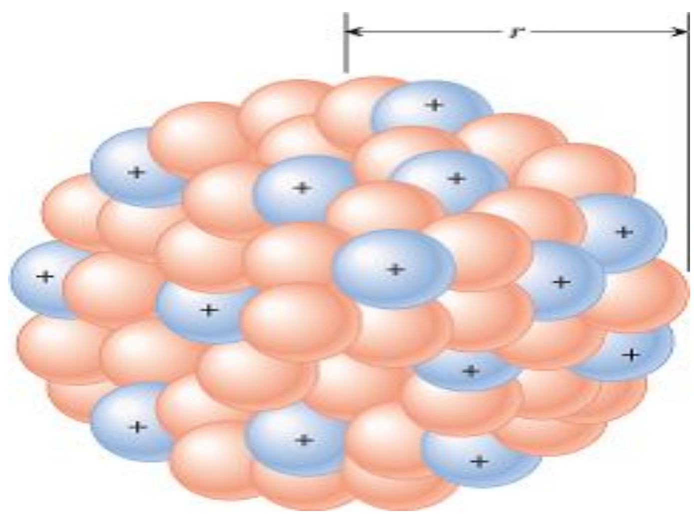
Calculation of Nuclear Radius

The nuclear radius (R) is considered to be one of the basic quantities that any model must predict. For stable nuclei the nuclear radius is roughly proportional to the cube root of the mass number (A) of the nucleus, and particularly in nuclei containing many nucleons, as they arrange in more spherical configurations:

Most nuclei are approximately spherical and have an average radius given by

$$R = r_0 A^{1/3} \qquad (1)$$

R = nuclear radius in meters (m), r0 = is the radius of a nucleon approx 1.2 fm, A = number of nucleons [or atomic mass number, or Z + N]



where *A* is the total number of nucleons and r_0 is a constant equal to 1.2×10^{-15} m. Because the volume of a sphere is proportional to the cube of its radius, it follows from Equation 1, that **the volume of a nucleus (assumed to be spherical) is directly proportional to *A*, the total number of nucleons.** This relationship then suggests that **all nuclei have nearly the same density**. Nucleons combine to form a nucleus *as though* they were tightly packed spheres

- It is well known that lead and oxygen contain different atoms and that the density of solid lead is much greater than that of gaseous oxygen. We now decide whether the density of the *nucleus* in a lead atom is greater than, approximately equal to, or less than that in an oxygen atom.
- **Reasoning and Solution** We know that density is mass divided by volume.
- The total mass *M* of a nucleus is approximately equal to the number of nucleons *A* times the mass $M = A\ m_o$,
- The values of *A* are different for lead and oxygen atoms, however.

The volume *V* of the nucleus is approximately spherical and has a radius *R*, so that

$$V = 4/3\ \pi\ R^{3}.$$

But R^3 is proportional to the number of nucleons *A*, Therefore, the volume *V* is also proportional to *A*. Thus, for example the mass lead nucleus $M_{lead} = m_o A$, where m_o is the mass of the nucleon inside the nucleus, but $V = 4/3\ \pi\ R^3 = 4/3\ \pi\ A\ r^3$

when the total mass *M* is divided by the volume *V*, the factor of *A* appears in both the numerator and denominator and is eliminated algebraically

from the result, no matter what the value of *A* is. i.e nucleus density $\rho = {m_o}/{\frac{4}{3}\pi r_o^3}$

$$\rho = \frac{3m_o}{4\pi r_o^3}$$

We find, then, that ***the density of the nucleus in a lead atom is approximately the same as it is in an oxygen atom.*** In general, the nuclear density has nearly the same value in all atoms.

The stable nucleus with the largest number of Protons (Z = 83) is that of bismuth, $^{209}Bi_{83}$ which contains 126 neutrons. All nuclei with more than 83 protons (e.g., uranium Z = 92) are unstable and spontaneously break apart or rearrange their internal structures as time passes.

This spontaneous disintegration or rearrangement of internal structure is called ***radioactivity***.

Two positive charges that are as close together as they are in a nucleus repel one another with a very strong electrostatic force. **What, then, keeps the nucleus from flying apart?** Clearly, **some kind of attractive force must hold the nucleus together,** since many kinds of naturally occurring atoms contain stable nuclei.

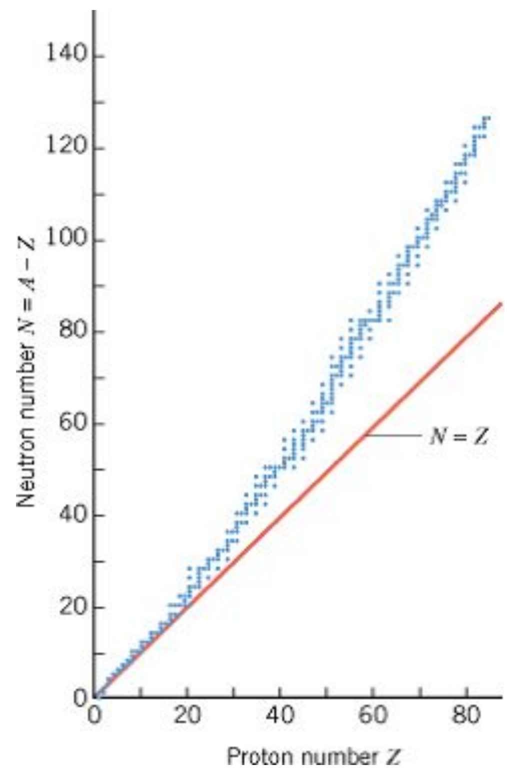
so a different type of force must hold the nucleus together.

This force is the ***strong nuclear force*** and is one of only four fundamental forces that have been discovered, fundamental in the sense that all forces in nature can be explained in terms of these four forces. The gravitational force is also one of these forces, as is the electroweak force

Many features of the strong nuclear force are well known. For example, **it is almost independent of electric charge.** At a given separation distance, nearly the same nuclear **force of attraction** exists between two protons, between two neutrons, or between a proton and a neutron. **The range of action of the strong nuclear force is extremely short,** with the force of attraction being very strong when two nucleons are as close as 10^{-15}m and essentially zero at larger distances.

- The limited range of action of the strong nuclear force plays an important role in the stability of the nucleus. For a nucleus to be stable, the electrostatic repulsion between the protons must be balanced by the attraction between the nucleons due to the strong nuclear force. But one proton repels all other protons within the nucleus, since the electrostatic force has such a long range of action.
- In contrast, a proton or a neutron attracts only its nearest neighbors via the strong nuclear force.

As in Fig. shows a plot of *N* versus *Z* for naturally occurring elements that have stable nuclei. For reference, the plot also includes the straight line that represents the condition A=Z. With few exceptions, the points representing stable nuclei fall above this reference line, reflecting the fact that the number of neutrons becomes greater than the number of protons as the atomic number *Z* increases.



140
120
100
80
60
40
20
0
0
20
40
60
80
Neutron number N = A − Z
Proton number Z
N = Z

As more and more protons occur in a nucleus, there comes a point when a balance of repulsive and attractive forces cannot be achieved by an increased number of neutrons. Eventually, the limited range of action of the strong nuclear force prevents extra neutrons from balancing the long-range electric repulsion of extra protons. The stable nucleus with the largest number of protons (Z=83) is that of bismuth, which contains 126 neutrons.

All nuclei with more than 83 protons (e.g., uranium, Z=92) are unstable and spontaneously break apart or rearrange their internal structures as time passes. This spontaneous disintegration or rearrangement of internal structure is called ***radioactivity***, first discovered in 1896 by the French physicist Henri Becquerel (1852–1908). Next section will discusses radioactivity in greater detail.

Isotopes

The isotopes of an element have the same *Z* value, but different *N* and *A* values. The natural abundances of isotopes can differ substantially. For example $^{11}_{6}C$, $^{12}_{6}C$, $^{13}_{6}C$,and $^{14}_{6}C$, and are four isotopes of carbon .

The natural abundance of the isotope $^{12}_{6}C$ is about 98.9%, whereas that of the isotope $^{13}_{6}C$ is only about 1.1%.

Even the simplest element, hydrogen has isotopes: $^{1}_{1}H$ hydrogen; $^{2}_{1}H$ deuterium; and $^{3}_{1}H$ tritium.

- Some isotopes don't occur naturally, but can be produced in the laboratory through nuclear reactions.
- **Isotones:**
- Nuclei with the same N and different Z are called **isotones**,
- **Isobars**:
- nuclides with the same mass number A are called isobars.

The basic properties of the atom constituents can be summarized as follows:

	charge	Mass (u)	Spin (h)	Magnetic moment(J /T)
Proton		1.007276	1/2	
Neutron	0	1.008665	1/2	
electron	-e	0.000549	1/2	

Spin: Each of the atomic constituents has spin ½ h and is an example of what is named Fermions.

- **Magnetic moment:**
- associated with the spin is a magnetic dipole moment. Compared with the magnetic moment of the electron, nuclear moments are very small. However , they obey an important role in the theory of nuclear structure. Although the neutron is uncharged it has a magnetic moment. This due to elementary structure of neutron (Quarks, charged components).

Charge and Mass

The proton carries a single positive charge e = 1.602 177 33 x 10^{-19} C, the electron carries a single negative charge $-e$, and the neutron is electrically neutral.

Because the neutron has no charge, it's difficult to detect.

The proton is about 1836 times as massive as the electron, and the masses of the proton and the neutron are almost equal (Table 1).

Table 1

Particle	Kg.	u	MeV/C^2
Proton	1.6726×10^{-27}	1.007 276	938.28
Neutron	1.6750×10^{-27}	1.008 665	939.57
Electron	9.109×10^{-31}	5.486×10^{-4}	0.511

- it is convenient to define the **unified mass unit** u in such a way that the mass of one atom of the isotope ^{12}C is exactly 12 u, where 1 u = 1.660 559 x 10^{-27} kg. The proton and neutron each have a mass of about 1 u, and the electron has a mass that is only a small fraction of an atomic mass unit.

Because the rest energy of a particle is given by $E_R = mc^2$, it is often convenient to express the particle's mass in terms of its energy equivalent.

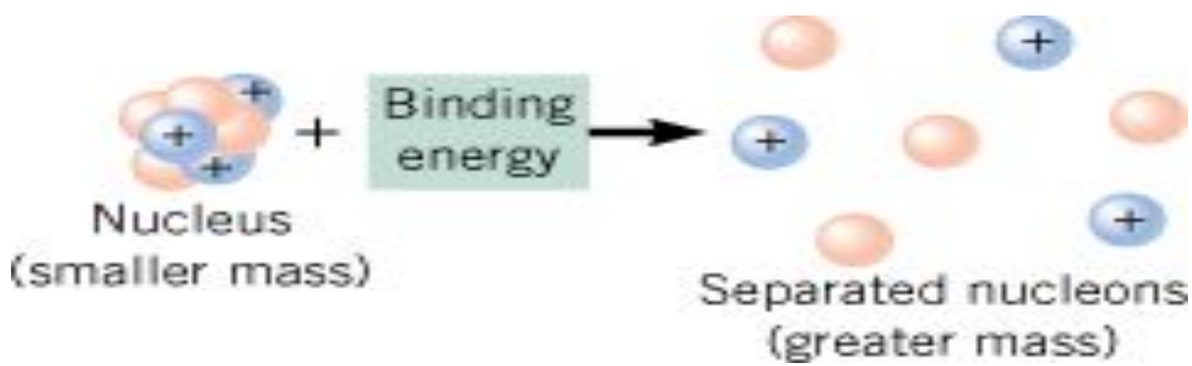
For one atomic mass unit, we have an energy equivalent of

$E_R = mc^2 = (1.660\ 559 \times 10^{-27}\ \text{kg})\ (2.997\ 92 \times 10^{8}\ \text{m/s})^2$

- $= 1.492\ 431 \times 10^{-10}$ J = **931.494 MeV**

The Mass Defect of the Nucleus and Nuclear Binding Energy

Because of the strong nuclear force, the nucleons in a stable nucleus are held tightly together. Therefore, energy is required to separate a stable nucleus into its constituent protons and neutrons. The more stable the nucleus is, the greater the amount of energy needed to break it apart. The required energy is called the ***binding energy*** of the nucleus.



- *Energy, called the binding energy, must be supplied to break the nucleus apart into its constituent protons and neutrons. Each of the separated nucleons is at rest and out of the range of the forces of the other nucleons.*
- Using, Einstein's theory of special relativity, energy and mass are equivalent. the binding energy of a nucleus can be determined from the mass defect according to Equation
- **Binding energy = (mass defect) c^2**
- **$= \Delta m . c^2$**

- It would be found that the **total mass of the atom is less than the sum of the masses of the individual protons and neutrons.**
- This slight difference in mass is known as the *mass defect*, (pronounced "delta")
- and can be computed for each nuclide, using the following equation.

- $\Delta = (Z)(Mp) + (Z)(Me) + (A\text{-}Z)(Mn) - Ma$
- where:
- Δ = mass defect
- *Z* = atomic number, *Mp* = mass of a proton (1.00728 amu)
- *Me* = mass of a electron (0.000548 amu), *A* = mass number
- *Mn* = mass of a neutron (1.00867 amu), |
- *Ma* = atomic mass of the nucleus

- The binding energy of a nucleus is also defined as the energy required to separate it into its constituent neutrons and protons. The mass of an atom is therefore less than the mass of its constituents . this is written as

$$m(A,Z) = Zm_p + Nm_n - \frac{B.E.}{C^2} \qquad 1.1$$

Or as:

$$\frac{B.E.}{C^2} = Zm_p + Nm_n - m(A,Z) \qquad 1.2$$

- To see how the nuclear binding energy varies from nucleus to nucleus, it is necessary to compare the binding energy for each nucleus per-nucleon. The graph in Figure 31-5 shows a plot in which the binding energy divided by the nucleon number *A* is plotted against the nucleon number itself. In the graph, the peak for the ^{4}He isotope of helium indicates that its nucleus is particularly stable. The binding energy per nucleon increases rapidly for nuclei with small masses and reaches a maximum of approximately 8.7 MeV/ nucleon for a nucleon number of about A =60.

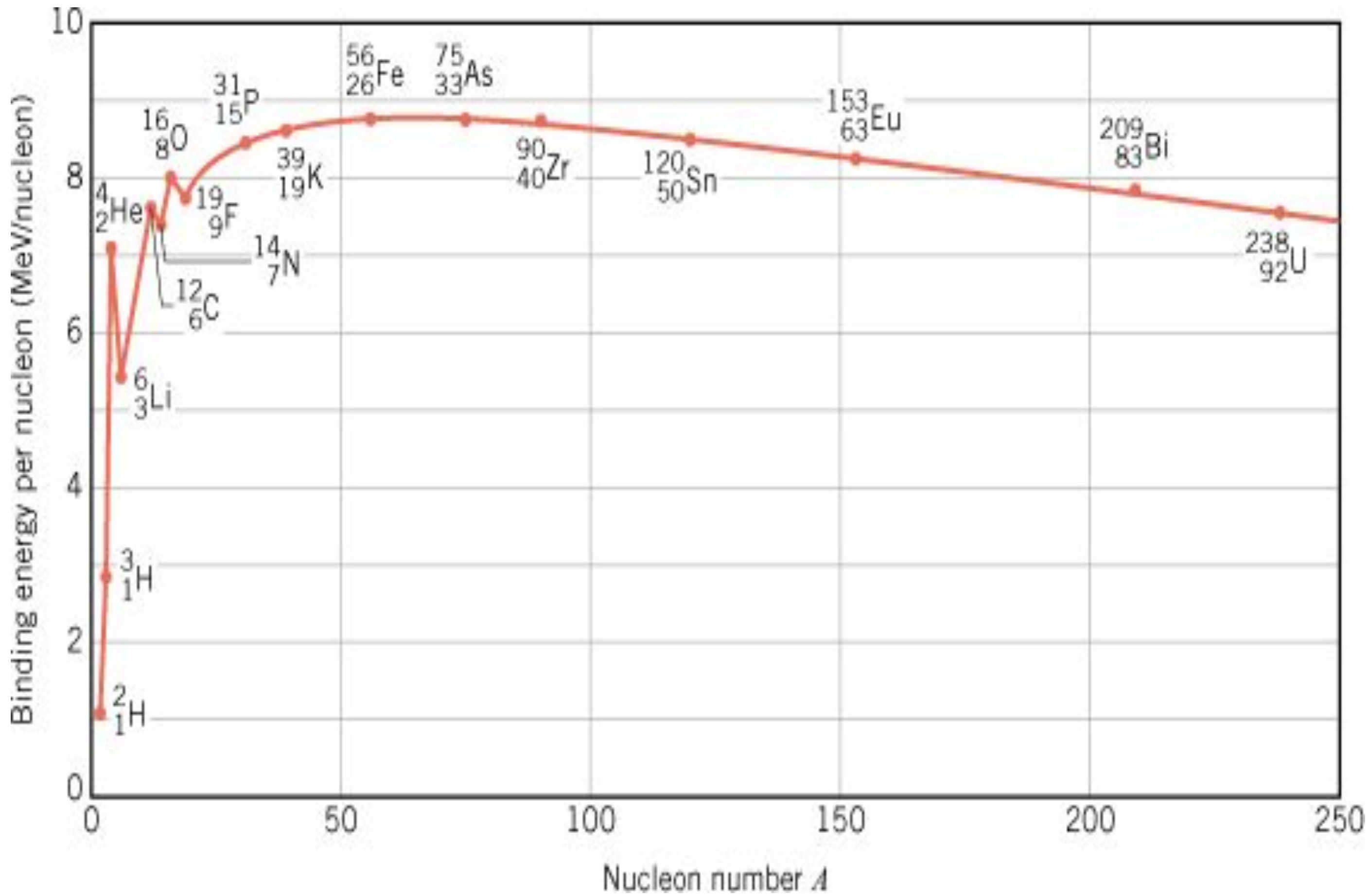
For greater nucleon numbers, the binding energy per nucleon decreases gradually.

Eventually, the binding energy per nucleon decreases enough so there is insufficient binding energy to hold the nucleus together

Nuclei more massive than the ^{209}Be nucleus of bismuth are unstable and hence radioactive.

- For example, consider an isotope of Lithium, Li:
- $A = 7$, $Z = 3$, $M = 7.01600$ amu
- Therefore:
- $\Delta = (3)(1.00728) + (3)(0.00055) + (7-3)(1.00867) - (7.01600)$
- $\Delta = (3.02184) + (0.00165) + (4.03468) - (7.01600)$
- $\Delta = (7.05817) - (7.01600)$
- $\Delta = 0.04217$ amu
- the binding energy of a nucleus can be determined from the mass defect according to the equation B.E. = $\Delta \times c^2$, where c is the velocity of light.

plot of binding energy per nucleon versus the nucleon number



Nucleon states in a nucleus

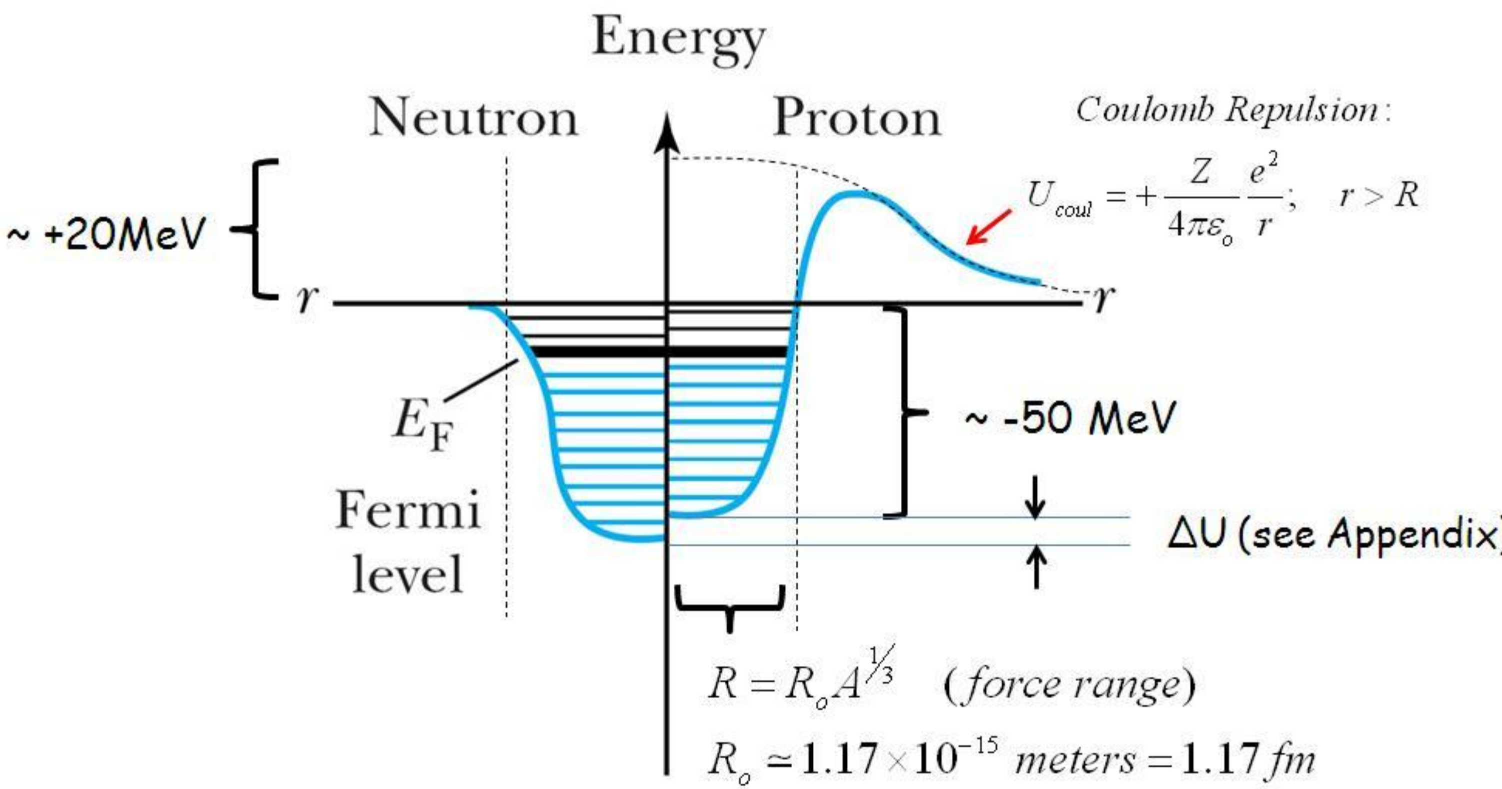
- It can be shown in the first approximation that a nucleon in the nucleus experiences an average attractive energy due to the strong nuclear interaction with its neighbors.
- Outside the nucleus the proton experiences the electric force

$$V_e = \frac{Ze^2}{4\pi\epsilon_o r}$$

- It is what prevents low energy charged nuclei coming into contact with each other and initiating nuclear reactions.

From scattering data infer a nuclear potential well U(r)

(values appropriate for middle mass nucleus: A~120)



The STRONG NUCLEAR FORCE that binds nuclei is always *attractive* and therefore produces a POTENTIAL ENERGY "WELL". The nucleons "fall" into this well when they are sufficiently close to each other.

- A model of nucleus is to consider that neutron and proton exist inside nuclei in certain allowed energy levels within the average potential well.

- The simplest example is that of a particle in one dimensional box, with size a centered at x=0. Solving this problem leads to the energy is

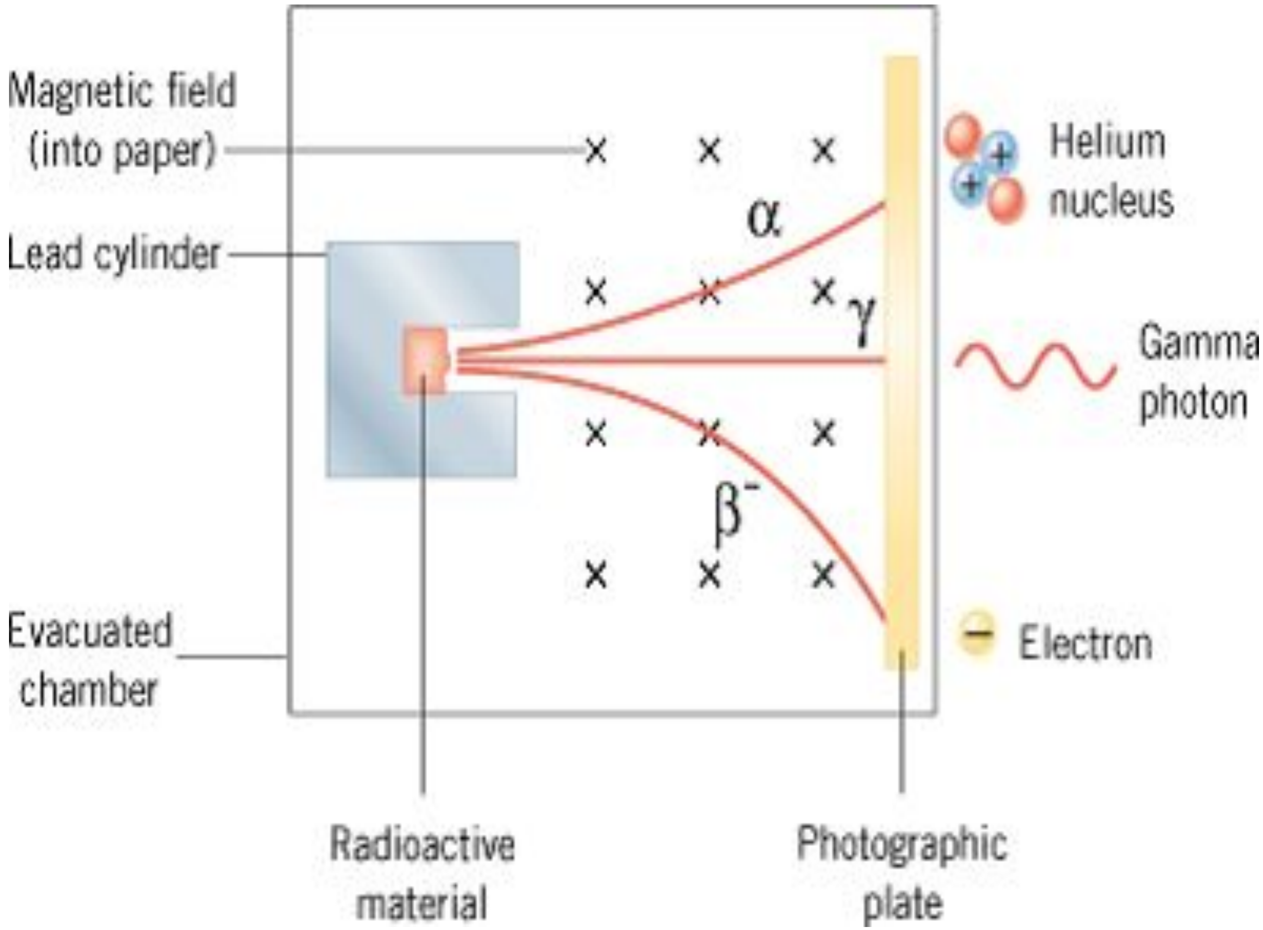
- $E_x = \frac{h^2}{8\,m\,a^2} n^2$, n =1, 2, 3,

- There are discreet levels of the particle in the box.

Radioactivity

- When an unstable or radioactive nucleus disintegrates spontaneously, certain kinds of particles and/or high energy photons are released. These particles and photons are collectively called "rays." Three kinds of rays are produced by naturally occurring radioactivity: α rays, β rays and γ rays. They are named according to the first three letters of the Greek alphabet, alpha (α), beta (β), and gamma (γ),

α and β rays are deflected by a magnetic field



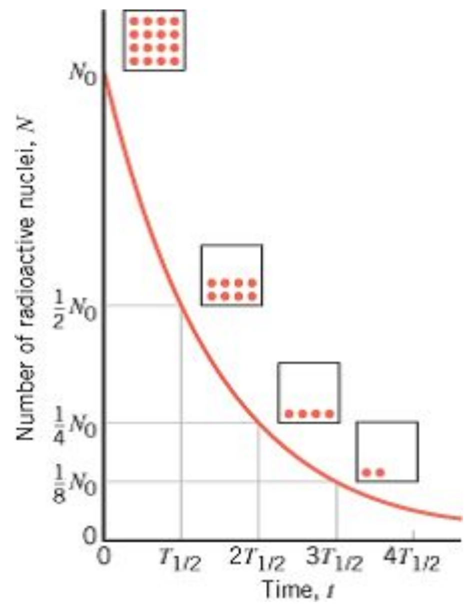
- ***Alpha particles (α)*** (+ve charge, helium nuclei He).
- ***Beta particles (β)*** (-ve charge, electrons).
- ***Gamma ray (γ)*** (photons whose energies are usually greater than X-ray).

Radioactive Decay Law

- At time t=0, if there are (N_o) nuclei, then at a later time (t). The number of nuclei remaining is determined by: $N = N_o e^{-\lambda t}$:
- λ is called the decay constant (Sec^{-1}).
- **Decay constant**, λ, specifies the probability of a certain radioactive decay mode. It is independent of space and time, but is specific to the particular nucleus.
- **The decay constant gives the fraction of nuclei decaying per second**.

Half-life (τ)

- It is the time required for half the nuclei present to decay (its unit sec).
- Then, when $t=\tau$, $N=N_o/2$
- $$N = N_o e^{-\lambda t}$$
- $$\frac{N_0}{2} = N_o e^{-\lambda \tau}$$
- $$\text{Ln } 2 = \lambda \tau$$
- $$\lambda = \frac{0.693}{\tau}$$



N_0
Number of radioactive nuclei, N
$\frac{1}{2}N_0$
$\frac{1}{4}N_0$
$\frac{1}{8}N_0$
0
0
$T_{1/2}$
$2T_{1/2}$
$3T_{1/2}$
$4T_{1/2}$
Time, t

- The ***activity*** of a radioactive sample is the number of disintegrations per second that occur. Each time a disintegration occurs, the number *N* of radioactive nuclei decreases. As a result, the activity can be obtained by dividing ΔN , the change in the number of nuclei, by Δt , the time interval during which the change takes place; the average activity over the time interval is the magnitude of , $\Delta N/\Delta t$.

- Since the decay of any individual nucleus is completely random, the number of disintegrations per second that occurs in a sample is proportional to the number of radioactive nuclei present, so that
  - $$\frac{dN}{dt} = -\lambda N$$
- The SI unit for activity is the *Becquerel* (Bq); one Becquerel equals one disintegration per second.
- Activity is also measured in terms of a unit called the *curie* (Ci), Historically, the curie was chosen as a unit because it is roughly the activity of one gram of pure radium. In terms of Becquerel's,
  - **$1\,Ci = 3.7 \times 10^{10}\,Bq$**

- **Example:**
- Iodine 131 is used in the treatment of thyroid (الغدة الدرقية) disorders.
- Its half-life is 8.1days. If a patient ingests a small quantity of I^{131}. What fraction (N/N_o) remains after 60 days.

Problems

- After 24 hours the radioactivity of a nuclide is one-eighth times its original level. What is its half-life ?

- Suppose there are 100,000 radioactive atoms in a sample of material. How many would be left after one half-life has elapsed? Two half-lives? Three half-lives?

- Suppose there are 3×10^7 radon atoms **(τ=3.83 days**) trapped in a basement. (a) How many radon atoms remain after 31 days? Find the activity (b) just after the basement is sealed against further entry of radon and (c) 31 days later.

- **Alpha Decay**
- The nucleus may emit a fast, massive particle that contains two protons and two neutrons. These particles were called “alpha rays,” but they have since been found to be identical to the nuclei of He atoms. Even today, such nuclei when produced in nuclear processes are called **alpha particles**. Since the nucleus loses two protons in alpha decay, the resulting nucleus (“daughter”) has a lower atomic number than before and thus belongs to a different chemical element. Its mass number is reduced by four. An example is the radioactive decay of radium.

$$^{226}_{88}Ra \;\text{------}\; ^{222}_{86}Rn + \, ^{4}_{2}He .$$

- **Beta Decay**
- The nucleus may emit a fast electron. Since there is reason to believe that electrons cannot be confined in the nucleus, a neutron within the nucleus appears to create and immediately emit the electron. Neutrons isolated outside of atomic nuclei always decay by beta emission after a short time. The neutrons become protons, emitting energy and negative charge in the form of fast electrons
- 14 14 0
- C N + e .+ antineutrino
- 6 7 -1

- **Gamma Decay**
- Gamma decay is most like the emission of light by atomic electrons. Alpha and beta decay usually leave the particles of the "daughter" nucleus in excited states. The daughter nucleus can move to lower-energy states by emitting a photon. However, nuclear states usually involve greater energy changes than electron states in atoms, so the resulting photons from nuclei have higher energy than those emitted by atoms. These high-energy photons are called **gamma rays**.