Nuclear Physics

Chapter One

Basic Nuclear Concepts

Research in nuclear physics is an integral part of the search for knowledge and understanding of the world in which we live. All matter is composed of a hierarchy of building blocks.

Living creatures, as well as our inanimate surroundings, are made of molecules, which are in turn made of atoms, whose mass resides almost entirely in the nuclei.

The nuclei are composed of protons and neutrons, which ultimately consist of quarks and gluons.

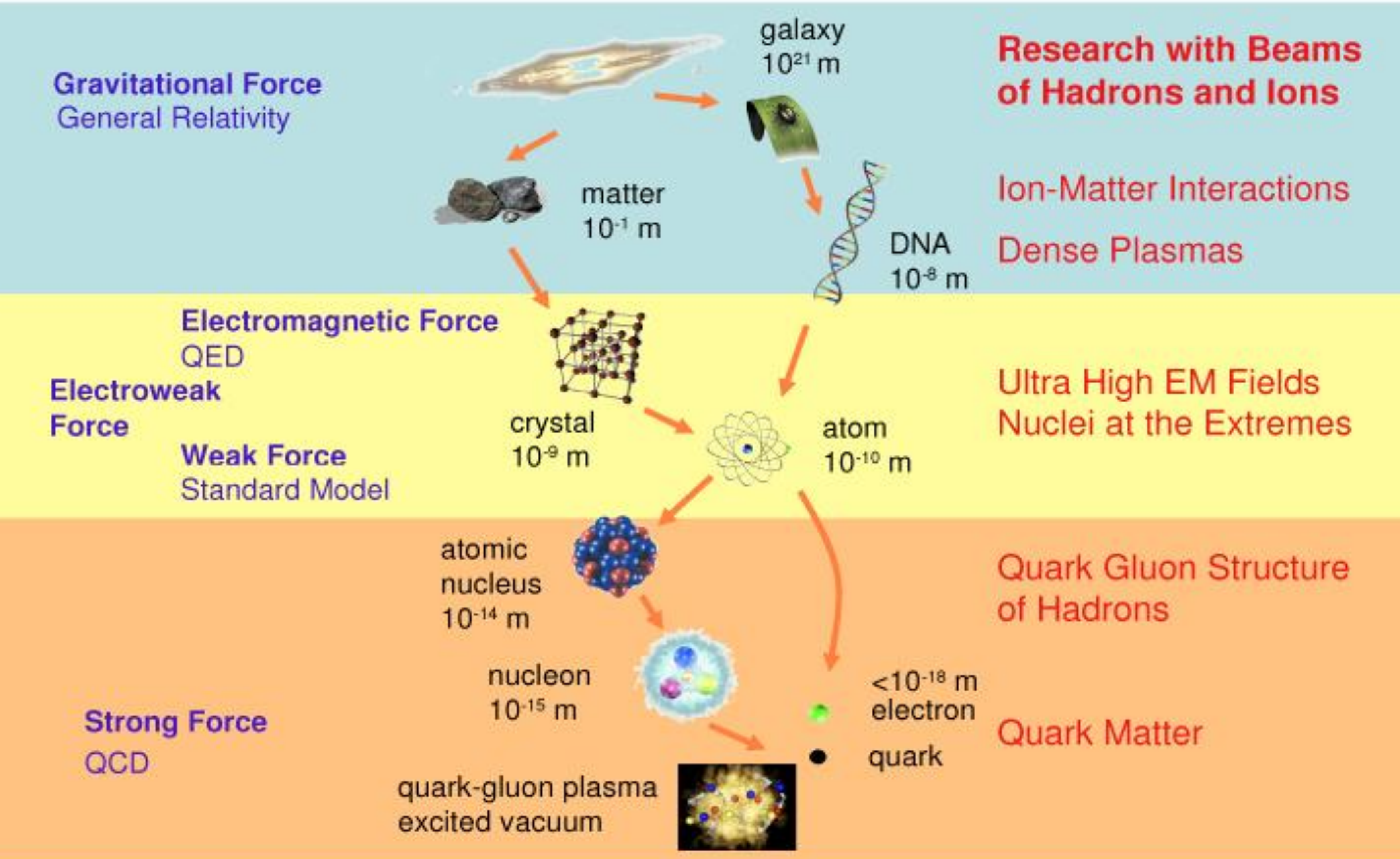
The science of nuclear physics concerns itself with the properties of “nuclear” matter.

Such matter constitutes the massive centers of the atoms that account for 99.9 percent of the world we see about us.

Nuclear matter is within the proton and neutron building blocks of these nuclei, and appears in bulk form in neutron stars and in the matter that arose in the Big Bang.

Nuclear physicists study the structure and properties of such matter in its various forms, from the soup of quarks and gluons present at the birth of our universe to the nuclear reactions in our Sun that make life possible on Earth.

Structure of Matter



1.1 Introduction

A study of nuclear physics centers around two main problems.

First, one hopes to understand the properties of the force which holds the nucleus together.

Second, one attempts to describe the behavior of systems of many particles, such as nuclei are.

These problems are related,

since the properties of a system of many particles are to a large extent determined by the force that binds the particles together.

But other aspects of such a system come about simply because many particles are interacting.

Physicists can discuss many-particle systems only within certain approxi-mations, which are determined by the particular experimental fact they wish to explain.

In the case of nuclei, the approximate descriptions are called ***models.***

Although the historical development of nuclear physics will not be followed, a few of the highlights are presented in Table 1-1.

TABLE 1-1 Some of the highlights in the development of nuclear physics

Discovery of radioactivity (Becquerel)	1896
Rutherford's atomic model	1911
Discovery of isotopes (J. J. Thomson)	1912
Induced nuclear transmutation (Rutherford)	1919
Application of quantum mechanics to radioactivity:	
Alpha decay (Gamow, Gurney, and Condon)	1928
Beta decay (Fermi)	1934
Discovery of neutron (Chadwick)	1932
n-p hypothesis (Heisenberg)	1932
Discovery of positron (Anderson)	1932
Role of mesons in nuclear forces (Yukawa)	1935
Discovery of μ meson (Anderson and Neddermeyer)	1936
Discovery of π meson (Powell)	1946
Nonconservation of parity in beta decay (Lee and Yang)	1956

1-2 BASIC NUCLEAR PROPERTIES

Nuclei have certain time-independent properties such as

mass, size, charge, intrinsic angular momentum (often called *nuclear spin),*

and certain time-dependent properties such as

radioactive decay and artificial transmutations (nuclear reactions).

The nuclei also have excited states, whose energy is usually treated under the first class of properties,

but whose decay is one of the types of radioactive decay.

I-2a Nuclear mass and charge.

Early chemical methods of mass comparison had already brought out the following approximate relation

$$M \approx \text{integer} \times M_H \qquad \textbf{(1-1)}$$

where M = mass of a specific atom
M_H= mass of a hydrogen atom.

The **integer** is now called *mass number* and will be denoted by the symbol *A.*

It was shown by x-ray scattering that the number Z of atomic electrons, and hence the number of positive nuclear charges, was not equal to the mass number *A.*

This made plausible the first hypothesis of nuclear structure, that nuclei consist of *A* protons and *A* — *Z* bound electrons.

The discovery of the neutron (Chadwick, 1932) led Heisenberg (1932) to suggest that protons and neutrons are the fundamental constituents of all nuclei.

The evidence for this is now beyond doubt, but can be understood only on the basis of quantum mechanics.

With the neutron-proton hypothesis we expect the mass of an atom to be

$$M \approx ZM_{\mathrm{H}} + NM_n \qquad \textbf{(1-2)}$$

where Z = number of protons in nucleus (atomic number)
N = number of neutrons in nucleus (neutron number)
M_n = mass of a neutron

The discovery by Thomson (1912) of atomic species with identical chemical properties but different masses (called isotopes) stimulated the development of precise determinations of atomic or nuclear masses.

This specialized branch of nuclear physics, pioneered by Aston (1919), is known as mass spectrometry.

Its importance lies in the fact that a considerable amount of information about nuclear forces and nuclear structure can be obtained from precise mass measurements.

I-2b Nuclear size.

The first detailed model of an atom, going beyond the kinetic theory (solid sphere) model, was proposed by J. J. Thomson (ca.1900) soon after his discovery of atomic electrons.

The electrons were assumed to float among massive positive charges of atomic dimensions ($\simeq 10^{-8}$ cm).

According to this model any high-speed particle could penetrate solid matter only by a diffusion process.

On the other hand, scattering experiments of alpha particles by gold foils (Geiger and Marsden, 1909) showed a much larger amount of back scattering than a diffusion process would allow.

Rutherford noticed that this implied the existence of a very small «10^{-8} cm) atomic nucleus, exerting a simple electrical (coulomb) force on the alpha particle. He deduced the law of scattering.

Later measurements showed that this law is **not obeyed if**:

The alpha-particle kinetic energy is too high.

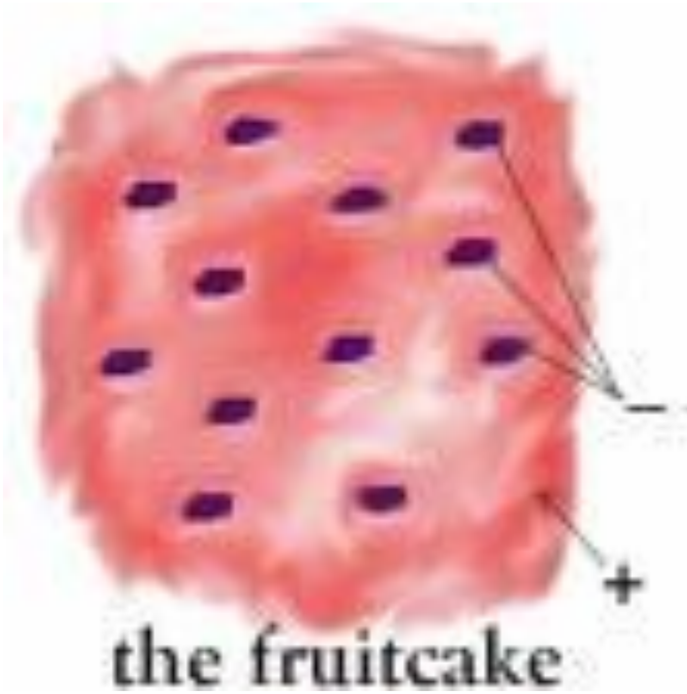
The atomic number of the scatterer is too low.

The critical energy $\mathbf{T_\alpha}$ and corresponding atomic number **Z**, at which the scattering law breaks down, allow a rough estimate of the nuclear radius of the scatterer.

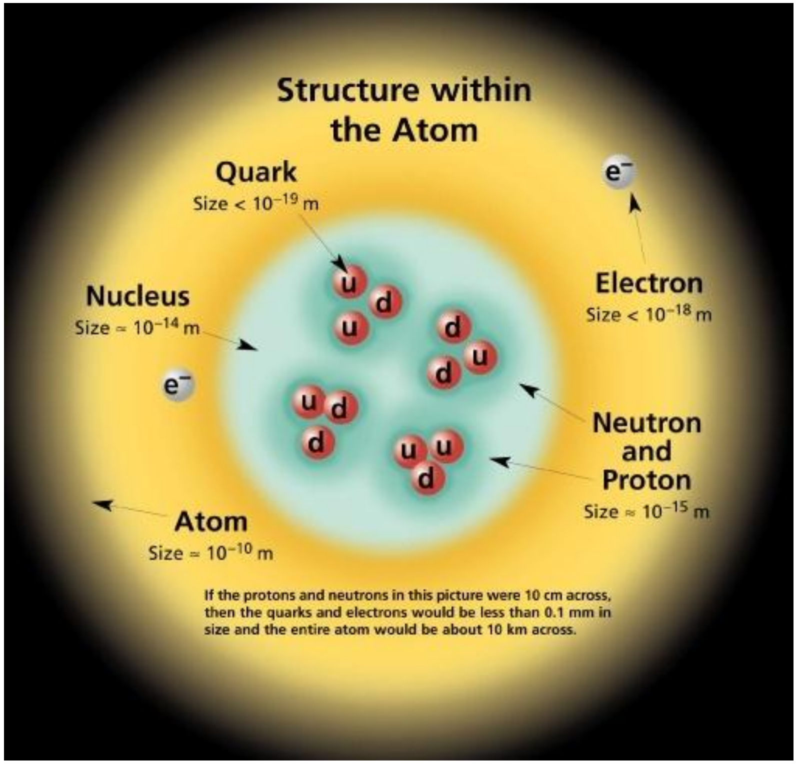
if the distance of separation between the alpha particle and the center of the scatterer becomes smaller than this radius,

nuclear forces come into play which are much stronger than the coulomb force used to derive the scattering law.

Models of Atom

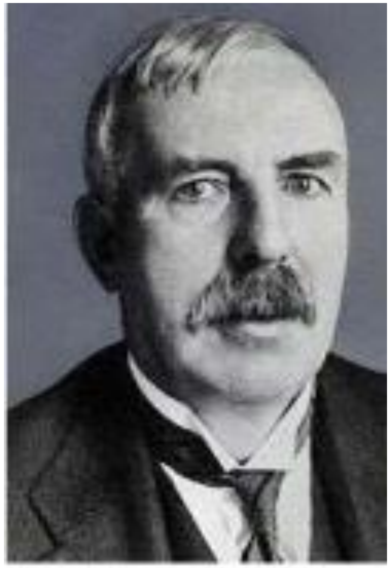


Thomson model of atom

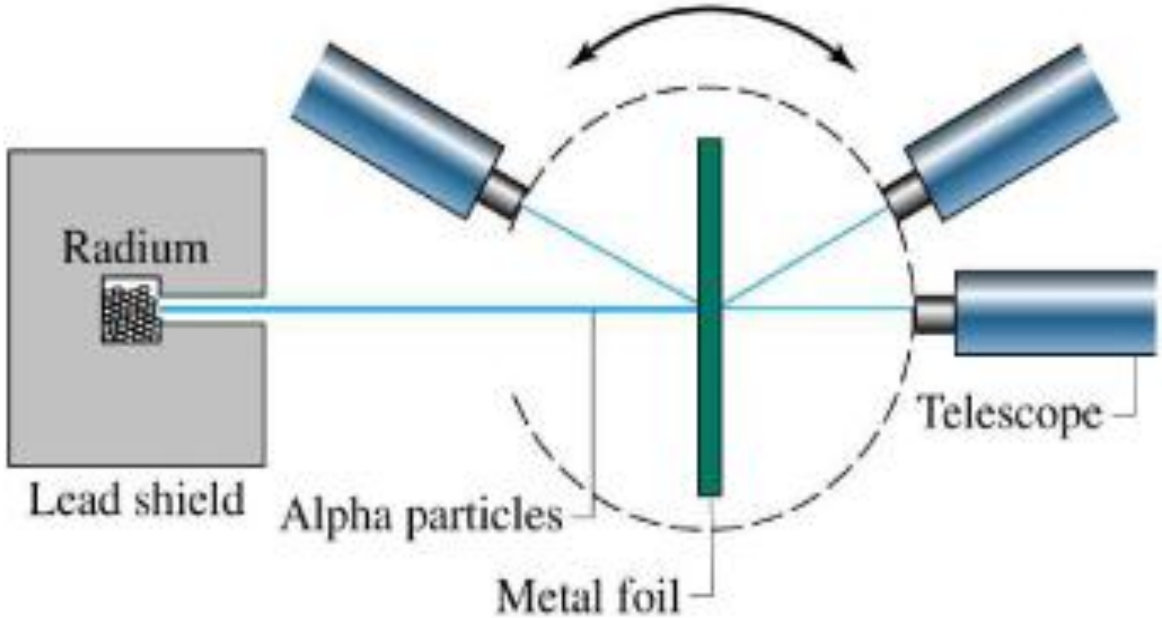


Rutherford model of atom

Rutherford experiment



E. Rutherford



From angular distribution of rescattered α -particles Rutherford concluded existence of positively charged core of atom then called **nucleus** **..\..\B.Sc. Nuclear 2012-2013\Animations\ch 1\Ruther's Alpha Scattering.mp4**

The size of the nucleus was much smaller (10^{-14}m) than size of the atom (10^{-10} m)

When an alpha particle is very distant from a given nucleus, it has only kinetic energy $\mathbf{T_\alpha}$.

It comes closest to the nucleus in a head-on collision.

At that point, the alpha particle has only potential energy if the recoil of the nucleus is neglected.

Hence, by conservation of energy,

$$T_\alpha = \frac{2eZe}{D} \qquad \text{(in electrostatic units)} \qquad \textbf{(1-3)}$$

where $2e$ = charge of the alpha particle (e = 4.80 x 10^{-10} esu)

Ze = charge of the scattering nucleus

D = distance of closest approach

$$D = \frac{2Ze^2}{T_\alpha} \qquad \textbf{(1-4)}$$

For example, alpha particles show deviations from pure coulomb scattering on uranium beyond 25 MeV (1 MeV = 1.60 X 10^{-6} ergs).

In that case

$$D = \frac{2 \times 92 \times (4.8 \times 10^{-10})^2}{25 \times 1.6 \times 10^{-6}}$$

$$\approx 10^{-12}\ \text{cm} = 10\ \text{F} \qquad (1\ \text{F} = 1\ \text{fermi} = 10^{-13}\ \text{cm})$$

More refined experiments, using the scattering of other nuclear particles and of electrons, have shown that the radius at which nuclear effects occur can be written approximately

$$R = R_0 A^{1/3} \qquad \textbf{(1- 5)}$$

where R_o is called the radius constant and has the values

$$R_0 \approx \begin{cases} 1.4\ \text{F} & \text{for nuclear particle scattering on nuclei} \\ 1.2\ \text{F} & \text{for electron scattering on nuclei} \end{cases}$$

The difference between these two values comes about as follows:

In electron scattering we determine the location of the positive (point) charges associated with the protons in the nucleus.

In nuclear-particle scattering we determine the size of the nuclear-force producing region affecting the particle.

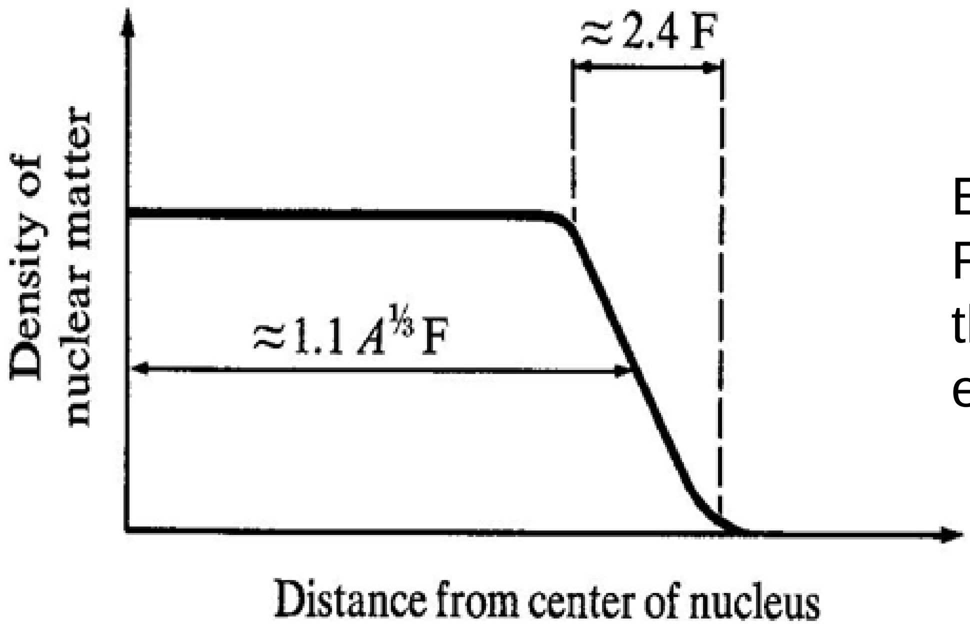
It turns out that the nuclear force extends beyond the region with which charge (or mass) are associated, making the nucleus appear larger than it actually is.

The force extension beyond nuclear matter is about **1 F** and is determined by the range of the nuclear force.

The simple form of Eq. (1 -5) would be obtained if the nucleus were a spherical assembly of **A hard particles**.

In that oversimplified, the volume of the nucleus would be proportional to A and the radius proportional to $A^{1/3}$

Refined electron scattering experiments show that the nuclear density distribution does not have a sharp cutoff at the radius R, but has roughly the shape given in Fig. 1-1.



Equation (1-5) applied to U^{238} gives R = 9 F which compares favorably with the estimate provided by D from expression (1-4).

Figure1-1: Density distribution of nuclear matter in a nucleus.

1-2c Intrinsic angular momentum of a nucleus.

The angular momentum of a nucleus is an important quantity because, as we will see, it restricts the structure of complex nuclei and affects all dynamical nuclear properties.

Like electrons, neutrons and protons have an intrinsic angular momentum **½ ħ**, (ħ is Planck's constant h divided by 2π)

Since angular momentum is a vector, the total angular momentum of a nucleus is the vector sum of the angular momenta of its constituents.

We find, *experimentally*, that complex nuclei have angular momenta equal to **I ħ**,

where For even-A nuclei: **I** is an integer (including zero)

For odd-A nuclei: **I** is an integer (including zero) plus one-half

For example, the nucleus of deuterium H^2 has **I** = 1 and the nucleus of Li^7 has **I** = 3/2

According to the quantum mechanical laws of addition of angular momenta,

any system of P particles can have an angular momentum (about its center of mass) equal to

an integer x $\hbar$ if P is even, and

an integer plus one-half x $\hbar$ if P is odd.

This applies to atomic electrons as well as to nuclear constituents.

Therefore, if the nucleus H^2 were made up of two protons plus one electron (to give Z = 1),

we would expect $I = ½$ or $3/2$.

If, on the other hand, it consists of one proton and one neutron,

we expect $I = 0$ or 1.

The **latter value** is in accord with experiment.

The same reasoning extended to other nuclei shows that nuclei cannot consist of protons and electrons but **must** consist of protons and neutrons.

1-2d Dynamic properties of nuclei.

Like atoms, nuclei can be in excited states of definite energies.

Transitions between excited states occur by emission of electromagnetic radiation (gamma rays) completely analogous to light emission from atoms.

The main difference is that,

whereas atomic states are separated by energies of the order of an electron volt,

the separations between nuclear states are about 10^4 to 10^6 eV.

As a study of atomic spectra, study of gamma-ray spectra leads to nuclear energy states and **nuclear models**.

Nuclei can also be transformed into each other.

Some of the transformations occur spontaneously by the emission of positive or negative electrons (beta rays) or alpha particles.

Other transformations can be induced by nuclear bombardments.

In all cases:

1. conservation of the total number of nucleons,
2. conservation of mass and energy,
3. conservation of linear momentum, and
4. conservation of angular momentum.

have been satisfied.

No contradictions to these conservation laws have been found.

They play an important role in most aspects of nuclear physics.

I-2e Nomenclature

A certain nomenclature has developed based on convenience and tradition.

The important terms are given below.

Nuclide	A specific nuclear species, with a given proton number Z and neutron number N
Isotopes	Nuclides of same Z and different N
Isotones	Nuclides of same N and different Z
Isobars	Nuclides of same mass number A (A = Z + N)
Isomer	Nuclide in an excited state with a measurable half-life .
Nucleon	Neutron or proton

Mesons Particles of mass between the electron mass (m_0) and the proton mass (M_H).

The best-known mesons are **π mesons** ($\cong 270m_0$), which play an important role in nuclear forces, and

μ mesons ($207m_0$) which are important in cosmic-ray phenomena.

Positron Positively charged electron of mass m_0

Photon Quantum of electromagnetic radiation,, commonly apparent as light, x ray, or gamma ray

A given nuclide is specified by a symbol like Li^7, $_3Li^7$, or $_3Li_4^7$.

The letters denote the element.

The right superscript gives the mass number *A*.

The left subscript gives the atomic number Z,

the right subscript the neutron number *N*.

By recent convention the mass number is often given as the left superscript, making the symbol **^7Li, ^7Li, or $^7Li_4$**.

In this book a nucleus in an excited state is denoted by the symbol with a right superscript star, e.g., **Li^{7*}**. ..\..\B.Sc. Nuclear 2012-2013\Animations\ch 1\Isotopes.mp4

Solve the following problems:

Pb. 1

Find the ratio of the nuclear to the atomic density for hydrogen.

Pb. 2

A nucleus with $A = 235$ splits into two new nuclei whose mass numbers are in the ratio $2:1$. Find the radii of the new nuclei.

Pb. 3

The radius of Ge is measured to be twice the radius of ${}^{9}_{4}Be$. From this information, how many nucleons are in Ge?

Pb. 4

Calculate the ratio of the nuclear radius of ${}^{208}_{82}Pb$ to the radius of its innermost electrons as calculated from Bohr theory.