Nuclear Physics

1.1. Introduction:

The atom is considered to be the basic building block of all matter. It is the smallest amount of matter that retains the properties of an element. Simple atomic theory tells us that it is composed of smaller particles (that no longer have the same properties as the overall element) and consists of two main components: a nucleus surrounded by an electron cloud. Nuclei sit at the center of any atoms. Therefore, understanding them is of central importance to any discussions of microscopic physics.

1.2. Nuclide Classifications:

The total number of protons in the nucleus of an atom is called the atomic number of the atom and is given the symbol Z. The number of electrons in an electrically neutral atom is the same as the number of protons in the nucleus. The number of neutrons in a nucleus is known as the neutron number and is given the symbol N. The mass number of the nucleus is the total number of nucleons, that is, total number of protons and neutrons in the nucleus. The mass number is given the symbol A and can be found by sum of Z + N = A.

Each of the chemical elements has a unique atomic number because the atoms of different elements contain a different number of protons. The atomic number of an atom identifies the particular element.

Each type of atom that contains a unique combination of protons and neutrons is called a nuclide.

$$\boxed{{}^{A}_{Z}X}$$

Figure 1. Nomenclature for identifying nuclides. X = Symbol of chemical element; A = Mass number; Z = Atomic number

1.3.1. Isotopes

Isotopes are nuclides that have the same atomic number and are therefore the same element, but differ in the number of neutrons. Most elements have a few stable isotopes and several unstable, radioactive isotopes. For example, oxygen has three stable isotopes that can be found in nature (oxygen-16, oxygen-17, and oxygen-18) and eight radioactive isotopes. Another example is hydrogen, which has two stable isotopes (hydrogen-1 and hydrogen-2) and a single radioactive isotope (hydrogen-3).

Different isotopes of the same element have essentially the same chemical properties. The isotopes of hydrogen are unique in that each of them is commonly referred to by a unique name instead of the common chemical element name. Hydrogen-1 is usually referred to as hydrogen. Hydrogen-2 is commonly called deuterium and symbolized ${}_{1}^{2}D$. Hydrogen-3 is commonly called tritium and symbolized ${}_{1}^{3}T$. It is convenient to use the symbols ${}_{1}^{2}H$ and ${}_{1}^{3}H$ for deuterium and tritium, respectively.

1.3.2. Isobars

Isobars are those nuclides that have the same mass number (A), but different numbers of protons and neutrons (Z & N). A special case is, when two isobars have proton and neutron numbers interchanged as in ${}_{Z}^{A}X_{\text{A-Z}}$ and ${}_{Z-1}^{A}Y_{\text{A-Z+1}}$, they are called mirror nuclides (${}_{8}^{15}O_{7}$ and ${}_{7}^{15}O_{8}$)

1.3.3. Isotones

Isotones are those nuclides that have the same number of neutrons (N), but different numbers of protons and mass numbers (Z & A).

1.4. Nuclear Radii and Densities

It is difficult to define exactly the size of an atom because the electron cloud, formed by the electrons moving in their various orbitals, does not have a distinct outer edge. A reasonable measure of atomic size can be the average distance of the outermost electron from the nucleus. Except for a few of the lightest atoms, the average atomic radii are approximately the same for all atoms, about 2×10^{-8} cm. Like the atom, the nucleus does not have a sharp spherical outer boundary.

Experiments have shown that the nucleus is a shaped like a sphere with a radius that depends on the atomic mass number of the atom with the central nuclear charge and/or matter density is nearly the same for all nuclei. Nucleons do not seem to congregate near the center of the nucleus, but instead have a fairly constant distribution out to the surface. Thus, the number of nucleons per unit nuclear volume is roughly constant.

Nucleon density = $\frac{A}{\frac{4}{3}\pi R^3}$

where: R= mean radius of the nucleus; A = atomic mass number

Here, R_0 an elementary radius for a nucleon in the nucleus, a most naïve estimate is given for the nuclear volume $V = 4/3\pi R^3$;

$V = 4/3\pi R_0^3 A$

or $R = R_0 A^{1/3}$

This relation describes the variation of the nuclear radius, with a value of $R_0 \approx 1.2$ fm when deducing a 'charge' distributing radius, and a value of $R_0 \approx 1.4$ fm for the full 'matter' distributing radius.

1.5. Forces in the Nucleus

According to Bohr's 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 both referred to as nucleons. In Bohr's model of the atom faced was accounting for an attractive force to overcome the repulsive force between protons inside the nucleus.

The two classical forces present in the nucleus are

(1) electrostatic forces between charged particles and

(2) gravitational forces between any two objects that have mass.

1.5.1. Gravitational force

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:

$$F_g = \frac{Gm_1m_2}{r^2}$$

where:

F_g = gravitational force (Newton)

m_1 = mass of first body (kilogram)

m_2 = mass of second body (kilogram)

G = gravitational constant (6.67×10^{-11} N-m^2/kg^2)

r = distance between particles (meter)

The equation illustrates that the larger the masses of the objects are or the smaller the distance between the objects is, the greater the gravitational force is. Therefore, 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 for the gravitational force and compare it to the value for 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} Newtons.

1.5.2. Electrostatic force

Coulomb's 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. Coulomb's Law is stated in terms of the following equation.

$$F_e = \frac{KQ_1Q_2}{r^2}$$

where:

F_e = electrostatic force (Newton)

$K = 1/4\pi\varepsilon_0$, electrostatic constant (9.0×10^9 N-m^2/C^2)
Q_1 = charge of first particle (coulomb)
Q_2 = charge of second particle (coulomb)
r = distance between particles (meter)
Using this equation, the electrostatic force between two protons that are separated by a distance of 10^{-20} meters is about 10^{12} Newtons. Comparing this result with the calculation of the gravitational force, (10^{-24} Newton) shows that the gravitational force is so small that one can neglect it.

1.5.3. Nuclear force

If only the electrostatic and gravitational forces existed in the nucleus, it would be impossible to have stable nuclei composed of protons and neutrons. The gravitational forces are much too small to hold the nucleons together compared to the electrostatic forces repelling the protons. Since stable atoms of neutrons and protons do exist in nature, there must be other 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. It acts only between pairs of neutrons, pairs of protons, or a neutron 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^{-15} m).

1.6. Basic nuclear properties:

The basic nuclear properties are discussed below.

1.6.1.Nuclear Mass

Experiments have shown that the mass of a particular atom or isotope is always slightly less than the number of nucleons (sum of the individual neutrons and protons) of which the atom consists. The difference between the atomic mass of the atom and the total number of nucleons (A) in the nucleus is called the mass defect or mass excess (Δm). The mass defect can be expressed in terms of atomic mass units and/or in terms of energy as:
$\Delta m = M\ (Z,N) - Au$
$\Delta m = \{M\ (Z,N) - A\}931.5$ MeV
where: Δm = mass defect (u or MeV); M (Z, N) = mass of nuclide (u); A = mass number.
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. 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.

1.6.2. Nuclear Charge

The charge on the nucleus of an atom; controlled by the number of protons and electrons present in an atom. The effective nuclear charge is the net charge an electron experiences in an atom with multiple electrons. The effective nuclear charge may be approximated by the equation:

$Z_{eff} = Z - S$

Here, Z is the atomic number and S is the number of shielding electrons.

1.6.3. Nuclear Spin

The total angular momentum of a nucleus by the symbol I and it is called nuclear spin. Associated with each nuclear spin is a nuclear magnetic moment which produces magnetic interactions with its environment. The nuclear spins for indivudual protons and neutrons parallel the treatment of electron spin, with spin ½ and an associated magnetic moment.

The rules for determining the net spin of a nuceus as follows. If the number of neutrons and the number of protons are both even, then the nucleus has no spin. If the number of neutrons plus the number of protons is odd, then the nucleus has a half integer spin (i.e. ½, 3/2, 5/2)

1.6.4. Nuclear Magnetic moment

As we know that both, the protons (having an elementary positive charge e) and neutrons (have no charge) are moving inside the nucleus. Consequently, there are charge, mass and current densities. As a result, magnetic dipole and electric quadrupole moment produced. Associated with the nuclear spin is a magnetic moment μ, which can take on any value because it is not quantized. This will provide additional information on the nature of nuclear forces and help in selecting an appropriate nuclear model.

A method known as the magnetic resonance method was developed, and experiment carried out depending essentially on resonance between the precision frequency of the nuclear magnet about a constant magnetic field direction and the frequency of an impressed high-frequency magnetic field. Just like for electrons of the atom, the nuclear magnetic moment of the orbital motion of a proton is expressed in terms of a nuclear magneton μ_N.

$\mu_N = e\hbar/2m_p$

where, m_p is the mass of the proton.

For the intrinsic spin of the nucleus, introduce a nuclear g factor, called gyromagnatic ratio g, to relate the magnetic moment μ of a nucleus to its spin angular momentum I. The nuclear g factor is defined as the ratio of the nuclear magnetic moment, expressed in terms of nuclear magneton, to the spin angular momentum, expressed in units of $\hbar$: $g = \frac{\mu}{I\mu_N}$.

hence

$\mu/g = I\,\mu_N = I\,e\hbar/2m_p$

where $\mu_N = \mu_B/1840 = 0.505\times10^{-23}$ ergs/gauss $= 3.15245\times10^{-14}$ MeV/T

Here, μ_B is the Bohr magneton $= 5.78838\times10^{-11}$ MeV/T.

When a nucleus of magnetic moment μ is in a constant magnetic field B, it will presses about the direction of B with a frequency f given by Larmor's theorem.

$f = \mu B/I\hbar$

The magnetic moment μ of a nucleus can thus be found by measuring Larmor frequency f.

Of very great importance in nuclear physics are the magnetic moments of the proton μ_p, neutron μ_n, and deuteron μ_d, their measured values are:

$\mu_p = 2.792847\ \mu_N$
$\mu_n = -1.913043\ \mu_N$
$\mu_d = 0.857438\ \mu_N$

It is worthwhile to mention the fact that, since the nuclear magnetic moments are only of the order of magnitude of the nuclear magneton (<< Bohr magneton) is, therefore, another strong argument against the existence of electrons inside the nucleus.

1.6.5. Nuclear Size

Nuclear Size is defined by nuclear radius. Nuclear density can be calculated from nuclear size. The emperical relation between charge radius and the mass number A, for heavier nuclei (A>20): $R \sim r.A^{1/3}$ where r is an emperical constant of 1.2-1.5 fm. This gives a charge radius for the gold nucleus (A = 197) of about 7.5 fm.

1.6.7. Nuclear Parity

In addition to their magnetic and electric properties, nuclei have certain properties which are not obviously physical in nature. Among them is the parity. To a good approximation, the wave function of a nucleus may be expressed as the product of a function of the space coordinates and a function depending only on the spin orientation. The motion of a nucleus is said to have even parity if the spatial part of its wave function is unchanged when the space coordinates (x, y, z) are replaced by (-x, -y, -z), or ($r \rightarrow -r$) i.e., reflection of the nucleus. While when reflection changes the sign of the spatial part of the wave function, the motion of the nucleus is said to have odd parity.