Introduction to Basics of Nuclear Force and Terminology

The forces involved in nuclear decay are the forces between fundamental particles in the nucleus of the atom. These forces were discovered after 1900. Before 1900, scientists were only aware of two basic forces, the gravitational force and the electromagnetic force.

Fundamental forces of nature (before 1900):

1.Gravity- Newton discovered that the "source" of the gravitational force was an objects mass. He also discovered that the strength of the force decreased as the inverse of the distance between the objects squared: $F = Gm_1m_2/r^2$, where m_1 stands for the mass of particle 1, m_2 stands for the mass of particle 2, and r is the distance between the particles. The force is infinite in range, and becomes stronger as the objects become closer. Since the gravitational force constant G is relatively weak, to have a substantial gravitational force between two objects one of the objects needs to be very massive. Since the masses of an electron, proton, and neutron are small, the gravitational force between them is negligible and the gravitational force does not play a role in nuclear reactions or decays.

2.Electromagnetic Interaction- The source of the electromagnetic interaction is charge. The electrostatic force law, Coulomb's law, has a similar form as Newton's formula for the gravitational force and is given by: $F = kq_1q_2/r^2$, where q_1 stands for the charge of particle 1, q_2 for the charge on particle 2, and r is the distance between the particles. In this case, the constant k is relatively large and the electromagnetic force between particles in the atom and nucleus is important. The atom consists of protons, neutrons and electrons. Neutrons are neutral in charge, protons are positively charged, and electrons are negatively charged. Thus, the electric interaction is attractive between electrons and protons. The electrical interaction is repulsive between protons and protons, and between electrons and electrons.

In 1912, Rutherford performed a series of important experiments that demonstrated that the atom has a heavy, positively charged nucleus. He directed monoenergetic alpha particles at a thin gold foil, and measured how the alpha particles were scattered. He was surprised by the fact that some of the alpha particles were scattered at large angles, and some even directly backwards from the direction they came. It was known that alpha particles are positively charged. His results could only be understood if the positive charge of the atom were concentrated at the center of the atom. This part of an atom is called the nucleus.

By using alpha particles of different energy, Rutherford was able to measure the size the nucleus for different elements. The size of atoms are of the order of 10^{-10} M, or Angstroms. The size of the nucleus is of the order of 10^{-15} M. 10^{-15} M is defined to be a Fermi (fm). Rutherford also demonstrated that most of the mass is located in the nucleus. From Rutherford's experiments, the picture of the atom is of a small massive positively charged nucleus that is surrounded by light negatively charged electrons. This picture of the atom must have disturbed many people, since it meant that all substances, including ourselves, mainly consist of empty space. We now know that in addition to protons, the nucleus also contains neutrons, and that the constituents of an atom are:

Constituents of Atoms:

particle	charge	mass (Kg)	mc^2 (MeV)
proton	$+e$	1.6726×10^{-27}	939
neutron	0	1.6749×10^{-27}	940
electron	$-e$	9.1×10^{-31}	0.511

where e = 1.6 x 10^{19} Coulombs.

Note that neutrons and protons are around 2000 times more massive than the electron. Rutherford's experiments did more than just determine how the different particles were arranged in the atom. The experiment also demonstrated the existence of a new force. Protons are positive, and neutrons are neutral. The electrical force between the protons is repulsive, and the neutrons experience no electrostatic force. What keeps the protons together? If the electromagnetic force were the only force between the nuclear particles, the protons would repel each other and the nucleus would fly apart. *There must exist another force that makes the protons and neutrons bind together.* This force is called the "strong" force

The strong force does not take on a simple form as does the gravitational and electrostatic force, and its description is beyond the scope of this course. Here, we list some of the main features of the strong interaction:

a)The strong force is very strong, about 1,000,000 times as strong and the electromagnetic force!
b)The strong force is very short range, with the range being around 1 or 2 fm. Note: this is much different than the gravitational or electromagnetic forces, which are infinite in range.

c) The strong force acts between baryons: protons & protons, neutrons & neutrons, protons & neutrons. It does not act between electrons and protons or neutrons and electrons. Neutrons and protons are referred to as *nucleons*.

Experiments, from Rutherford and others, indicate that the radius of nuclei, R, are proportional to the number of nucleons to the 1/3 power:

$$R(fm) = 1.3A^{\frac{1}{3}} \tag{1}$$

Where A = Z + N. Here Z is equal to the number of protons and N is equal to the number of neutrons. This means that the radius cubed is proportional to A. This result suggests that the volume of the nucleus is proportional to the number of nucleons A. A simplistic picture of the nucleus is that the protons and neutrons are packed in the nucleus like hard spheres. Since the strong force has such a short range, the effect of the force only extends a few fm (10^{-15} M) outside the nucleus. In a material, nuclei are separated from each other by more than 10^{-10} M, the distance between atoms. In terms of the strong force, nucleons from one nucleus do not affect nucleons from another nucleus in a material.

Terminology:

To describe a nucleus, we need to specify the number of neutrons and protons that it contains. The following terminology is used to represent a particular nucleus:

$$_Z\textbf{(Chemical Symbol)}^A$$

where Z is the number of protons, and A equals the number of neutrons plus protons. Often the symbol N refers to the number of neutrons. Then A = Z + N. For example the nucleus $_6C^{13}$ contains 6 protons and 7 neutrons. Note: the 6 is redundant, since the chemical symbol C for carbon stands for 6 protons.

Some combinations of neutrons and protons are stable, some are not. We will learn about the different ways that nuclei can decay. For now, we introduce some terms:

Isotopes: Nuclei with the same number of protons (same Z) are called isotopes. The charge of the nucleus determines the chemical properties of the atom. This is because the charge of the nucleus determines how the electrons will distribute themselves in their "shells" and how they will bind with other atoms. This means that isotopes, i.e. nuclei with the same number of protons, have very similar (essentially the same) chemical properties. Examples of isotopes of carbon are $_6C^{12}$, $_6C^{13}$, and $_6C^{14}$. Neutral atoms of these nuclei have 6 electrons, and atoms of these isotopes have the same chemical properties. That is, each of these atoms can combine with two oxygen to form carbon dioxide, etc.

Isobars: Nuclei with the same atomic mass number A (same number of protons + neutrons) are called isobars. Since isobars have different number of protons, they will have different chemical properties. However, since the number of nucleons is the same, Iisobars have similar nuclear properties. Examples of isobars with atomic number 13 are ${}_6C^{13}$ and ${}_7N^{13}$.

Isotones: Nuclei with the same number of neutrons (N) are called isotones.

Isotopes are of particular importance in radiation biology and radiation chemistry. This is because isotopes have the same chemical properties. One can replace a stable nuclei with an isotope that is unstable. The radioactive isotope, radioisotope, will behave chemically the same as the stable one. However, the radioactive isotope will eventually decay, and allow us to trace how the element interacts in the biological and/or chemical system.

Nuclear Reactions:

A nuclear reaction is a reaction between nuclei. For example, two nuclei can collide with each other and form other nuclei. Nuclear reactions can only occur at very high temperatures or in special "high energy" physics laboratories. Since nuclei are positively charged, when two different nuclei come close to each other, they repel each other. So for nuclei to come sufficiently close to interact, they must collide fast enough to overcome the electrical repulsion.

In nuclear reactions, certain quantities are unchanged, i.e. conserved. Some of the quantities conserved in nuclear reactions are: Charge, Atomic Mass Number (A), Lepton number, Angular Momentum. For example, the total charge of the particles before the interaction equals the total charge of the particles after the interaction.

The following are examples of some interesting nuclear reactions:

$$ {}_2He^4 +_7 N^{14} \rightarrow_8 O^{17} +_1 H^1 \tag{2} $$

The above reaction was the first "human-made" nuclear reaction. Rutherford placed an alpha emitter in nitrogen gas, and observed the production of oxygen and hydrogen. An alpha particle is a helium nucleus, ${}_2He^4$. The alpha particle has enough energy to penetrate into the ${}_7N^{14}$ nucleus and cause the reaction. Note that we haven't mentioned anything about the electrons in the helium, nitrogen or oxygen atoms. They are just spectators in the above reaction, and we don't need to consider them. Actually, when the ${}_2He^4$ is emitted it doesn't have any electrons surrounding it. If it were to eventually slow down, it would acquire two electrons and become a neutral helium atom. Also note, that since charge is conserved, the numbers on the bottom are equal on the right and left side of the equation: 2 + 7 = 8 + 1. Also, since atomic mass number is conserved, the top numbers on the left and right sides of the reaction are also conserved: 4 + 14 = 17 + 1.

$${}_0n^1 +_7 N^{14} \rightarrow_6 C^{14} +_1 H^1 \tag{3}$$

The above reaction occurs continually in the atmosphere. Neutrons, ${}_0n^1$, are produced by the sun and enter the earths atmosphere. Some of them can strike a ${}_7N^{14}$ nucleus in the nitrogen in the atmosphere producing "carbon 14", ${}_6C^{14}$. Thus carbon 14 is continually produced in the air. The carbon 14 produced in this manner is used to help scientists determine the age of old fossils. Note that charge and atomic mass number are conserved in the reaction. Since the neutron is neutral, it can penetrate into the ${}_7N^{14}$ nucleus without being repelled away.

$$\begin{aligned}
{}_1H^2 +_1 H^2 &\rightarrow {}_2He^3 +_0 n^1 \quad (4)\\
{}_1H^2 +_1 H^3 &\rightarrow {}_2He^4 +_0 n^1 \quad (5)\\
{}_1H^2 +_2 He^3 &\rightarrow {}_2He^4 +_1 H^1 \quad (6)\\
{}_1H^2 +_1 H^2 &\rightarrow {}_1H^3 +_1 H^1 \quad (7)
\end{aligned}$$

The above reactions take place in the sun. In each case, the nuclei on the left side are positively charged, and need energy to come close enough to cause the nuclear reaction. Since the temperature of the sun is so great, the nuclei have enough energy to overcome the electrical repulsion and undergo the nuclear reaction. When two nuclei come together to form a larger nucleus, it is called fusion.

$${}_0n^1 +_{92} U^{235} \rightarrow Kr + Ba + 3_0n^1 \tag{8}$$

This nuclear reaction was very important historically. A neutron can penetrate the uranium nucleus since it is chargeless. ${}_{92}U^{236}$ is formed, but it is unstable and decays by breaking up into two smaller nuclei and releasing 3 neutrons. This type of decay is called fission, i.e. when a larger nucleus breaks up into two smaller ones. The interesting aspect of the reaction is that three neutrons are produced. Each of the neutrons that are produced can react with another ${}_{92}U^{235}$ nucleus causing another fission reaction. If the concentration of the ${}_{92}U^{235}$ nuclei is great enough, then many such fission reactions can occur rapidly releasing large amounts of energy quickly.

This "chain reaction" is the process in a nuclear bomb. In a nuclear reactor, the fission reaction is controlled and the energy is converted to electricity for domestic and commercial use.

In this course we will mainly study nuclear decays. The same quantities that are conserved in nuclear reactions are also conserved in nuclear decays.