Nuclear reactions: Factors and Fundamental Forces

Abstract

Nuclear reactions as we know generally are a great source of energy as well as destruction. This research is about physics behind the nuclear reactions and the role of quarks, bosons (fundamental forces), energy, protons, momentum, and lepton (electrons) in nuclear reactions through the Standard Model of Particle Physics. I will try to find out why only some elements are used in nuclear reactions where others are comparatively stable. I will also talk about different types of nuclear reactions and the effects of physical factors like temperature and pressure on them.

Nuclear reactions: Basics Overview

A nuclear reaction is a process in which two nuclei, or a nucleus and an external subatomic particle, collide to produce one or more new nuclei. In such reactions, the composition of the nucleus is changed. These reactions are generally of four types: nuclear fission, nuclear fusion, nuclear decay, and transmutation.

A heavy nucleus is "split" into two (or more) smaller nuclei in fission reactions. A reaction is called nuclear fusion when two (or more) lighter nuclei come together to make a heavy nucleus. Nuclear decay is the process by which an unstable isotope of a particular element spontaneously transforms into a new element by emission of radiation and transmutation is a non-spontaneous process where one element is converted to another by bombarding it with high-energy radiation.

1. $^{235}U + {}^{1}n \rightarrow {}^{141}Ba + {}^{92}Kr + 3\ {}^{1}n$
2. $^{2}H + {}^{3}H \rightarrow {}^{4}He + {}^{1}n$
3. $^{226}Ra \rightarrow {}^{222}Rn + {}^{4}_{2}\alpha$
4. $^{14}N + {}^{4}_{2}\alpha \rightarrow {}^{17}O + {}^{1}H^{+}$

The first nuclear reaction (transmutation) was accomplished by Sir Ernest Rutherford in 1919 when he bombarded nitrogen with alpha particles to get oxygen and a proton. The modern form of nuclear fission was discovered by German scientists Otto Hahn, Lise Meitner, and Fritz Strassmann in the year 1938.

$$^{14}N + {}^{4}He \longrightarrow {}^{17}O + {}^{1}H$$

Huge energy change takes place in these reactions. Kinetic energy may be released in these reactions or kinetic energy may have been absorbed in these reactions. They can be exothermic or endothermic. Energy change in these reactions is the result of the change in mass of the nucleus to conserve total mass energy, as we know that mass is just another form of energy from Einstein’s theory of relativity. Either kinetic energy gets converted into mass or mass gets converted to kinetic energy in these reactions. These energy mass changes can be calculated using the mass-energy equation i.e. $e=mc^2$. If we compare their efficiency with traditional sources of energy, we find that one Kilogram of uranium produces around 8×10^{13} joules of energy, which corresponds to 10^6 kilograms of coal equivalent.

At present we can use only nuclear fission of Uranium and Plutonium in bulk. In such a reaction one neutron is sent toward an atom of Uranium (or Plutonium). This results in the formation of ^{236}U, which is unstable and gets split into lighter atoms, three more neutrons, and a lot of energy. Three neutrons at the product side reinitiate the nuclear fission of three more Uranium atoms and hence the chain continues.

These reactions now are used mainly for three purposes namely as a destructive weapon, as an energy source, and for study. The same Uranium fission (or Plutonium) is used in an Atom bomb. These bombs are so devastating, that even after most countries have them, none of them wants a nuclear war to happen. The Last and first use of them was in 1945 during World War II and it forced Japan to surrender.

The nuclear reaction has been being used in the study for a long knowingly or unknowingly, from the use of alpha radiation (nuclear reaction needed in the emission of alpha particles) in the discovery of the nucleus to the discovery of proton by Rutherford (nitrogen transmutation) and discovery of neutrons by Chadwick. A nuclear reaction is also used as a carbon-14 dating system in history. We should also realize that all the elements-except hydrogen that we see around us today is the result of nuclear reactions only. If not for nuclear reaction everything would have been in the forms of hydrogen, free hadrons, electrons, etc.

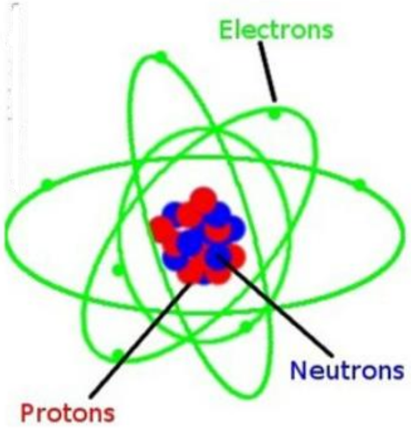
Conservative energy sources are depleting very fast which leads us to fuel scarcity in the future. Nuclear energy is one of the biggest and most advanced energy sources, even if it is very difficult to use. In nuclear power plants, these nuclear reactions are used to heat and evaporate water,r and the vapour is used to rotate the electricity generator hence producing electricity. Nuclear energy can be the future of power sources, which we need to study and understand to use efficiently and safely.

Atomic Nucleus

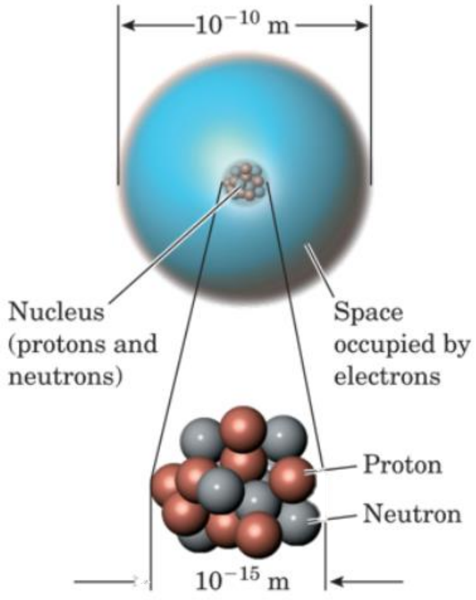
Atoms are the smallest constituent of matter that exhibits the properties of the elements and exists in their Free State. They consist of Protons and Neutrons in the nucleus and Electrons, which revolve around it.

Electrons were discovered by Sir J. J. Thomson in the year 1987. Electrons are the one of most fundamental and stable particles which cannot be divided further. They are part of the first generation of leptons class in the Standard Model of Particle Physics, having the spin of a half. They have a very small mass (around 9.1×10^{31} kilograms or 0.511 MeV/c^2). They are negatively charged particles (-1.6×10^{-19} coulomb) and revolve around the nucleus in their fixed energy states.

Nucleus was discovered by Sir Ernest Rutherford in the year May 1911, when he bombarded a gold foil with alpha particles. In the experiment, he found out that nucleus contains 99.94% of the mass of an atom even if it occupies only 0.01% of its volume. It consists of protons and neutrons, which are collectively also called nucleons. Total nuclear charge is always positive since it consists of protons (which are positively charged). This nuclear charge is responsible for keeping electrons in their stationary states and hence provides stability to the atom.



	Mass (g)	Mass (u)
Proton (p+)	1.67×10^{-24}	1
Neutron (n)	1.67×10^{-24}	1
Electron (e-)	9.07×10^{-28}	1/1836

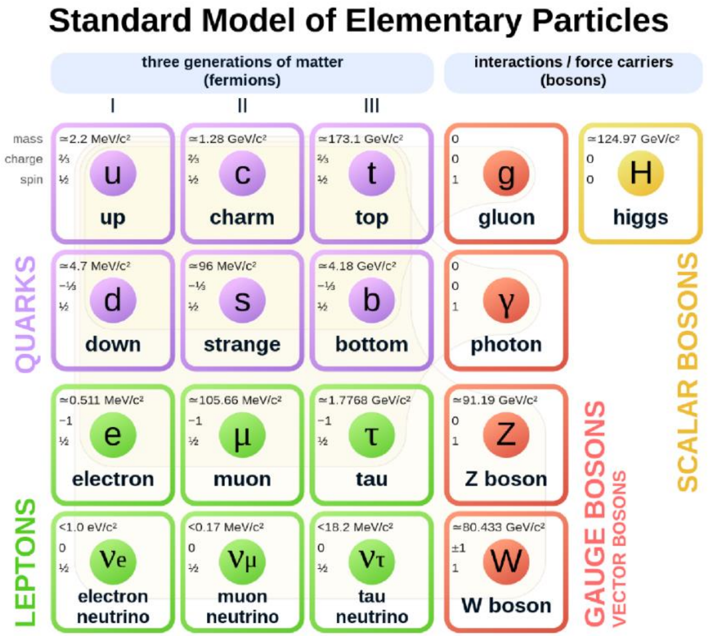


Nucleus consists of protons and neutrons. Protons are positively charged (1.6×10^{-19} coulomb) and in a ground-state atom number of protons is equal to that of electrons. Neutrons on other hand are neutral in charge and provide stability to the nucleus. They kind of create a buffer between electrostatic repulsion between protons. Changes in the number of neutrons result in other isotopes of an atom (element), which can be unstable.

To understand nuclear reactions, we need to know more about the nucleus (properties of protons and neutrons) and forces working at the level through the Standard Model of Particle Physics.

Standard Model of Particle Physics

The standard Model is the most successful grand unified theory in science to explain the basic building blocks of the universe. Standard Model explains fundamental forces and matter using subatomic particles.



Electrons were the first fundamental particles to be discovered in 1897. Throughout the 1950s and 1960s, improvements in particle accelerators and particle detectors led to a bewildering variety of particles found in high-energy experiments. The entire collection of these particles was nicknamed the “particle zoo”. In the 1960s Gell-Mann and Yuval Ne'eman arranged particles in the "Eightfold Way" which could predict new particles, one of them was Ω^-. Famous Ω^- was detected (experimentally) in 1964 which gave rise to the quark model proposed by Murray Gell-Mann himself. The modern form of The Standard Model was developed as a method to combine the fundamental forces. In 1961, Sheldon Glashow combined the electromagnetic and weak interactions giving the name electro-weak force. In 1967 Steven Weinberg and Abdus Salam incorporated the Higgs mechanism into Glashow's electroweak interaction. In the 1970s modern form of the Standard Model was developed finalizing a set of fundamental and exchange particles by combined efforts of scientists all over the world.

The standard model explains 3 of 4 fundamental forces very successfully. It also explains other derived forces like friction etc. It was able to predict the existence of W and Z bosons, which are force carriers of Weak force. The most important thing about it is that speculations of measurements made by the model have been largely correct.

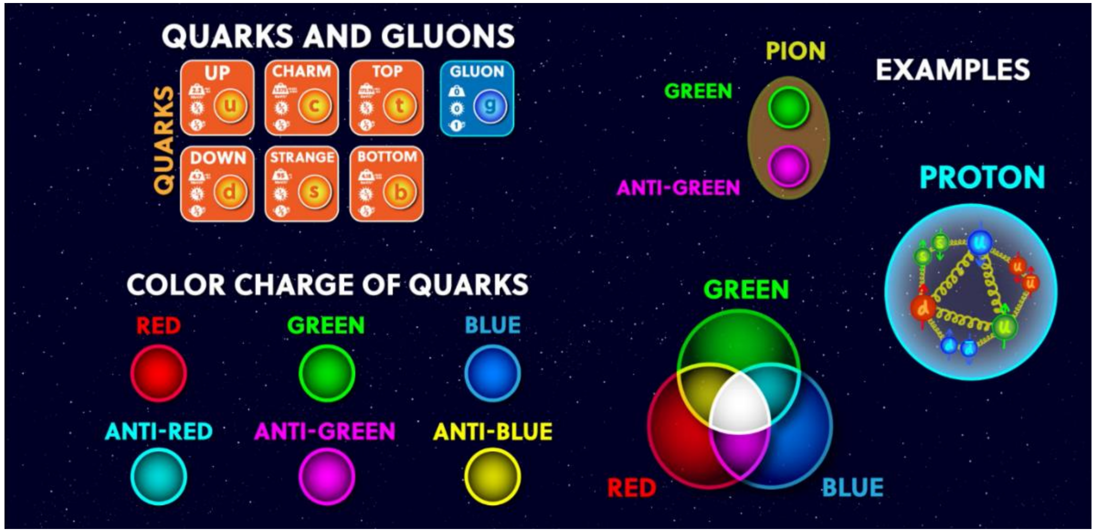
The standard model consists of 17 subatomic particles. They are divided into different groups according to their spin, charge, mass, and stability. 12 of these on right are called fermions. They make up all the matter in the universe and have a spin of one-half. Two categories in this are quarks (makers of nucleons) and leptons (electrons and like).

The other 5 are called bosons, which are also called force carriers or exchange particles. They are responsible for force and Higgs field. They are two types Gauge bosons (force carriers) and Scaler bosons (Higgs field). They all have whole number spin (0 or 1).

Spin, like charge, is one of the fundamental properties of a particle. The spin number of a particle is quantum and represents the Angular Momentum of the particle due to its rotation around its axis in terms of reduced Planck’s constant (which is Planck’s constant divided by 4pi). This infers that electrons have angular momentum equivalent to Planck’s constant divided by 8pi. Another analogy for the spin number of a particle is that it represents the probability of facing the same point after one complete rotation of the particle. For instance, electrons have a spin of one-half, which means that if you want to get the same face of a particle after every two rotations or the probability of finding a certain face of the particle is half in every rotation.

Most of the lengths from here are given in ‘fermi’ which is equivalent to 10^{-15} meters.

Quarks



Quarks are one of the fundamental constituents of matter which have fractional charges of either $\frac{2}{3}$ or $\frac{-1}{3}$ (a relative charge, taking electron as -1) and interact with strong nuclear force. They are only particles, which interact with all the fundamental forces.

The idea of the existence of quarks was given by Gell-Mann and George Zweig separately in the year 1964 to explain strong interaction symmetry. The first experimental proof of them was found in the year 1968 to 1969 when Stanford Linear Accelerator Center conducted deep inelastic collisions. In the experiment, it was found that protons were also made up of smaller point-sized particles. They were named partons, a term coined by Richard Feynman at the time, but now they are recognized as up-and-down quarks.

There are six flavours of quarks namely up, down, strange, charm, top, and bottom. They can be divided into two classes- one with a charge of 2/3, which includes up, strange, and top-quarks. Another class has a charge of -1/3, including down, charm, and bottom quarks.

They are also found in three generations. Only the first generation is stable. Quarks of the other two generations exist only for microseconds and they disintegrate into lighter particles.

Two stable particles are up-quarks and down-quarks. Up quarks have a charge of 2/3 and a mass of about 2.3 MeV/c^2. Down quarks are negatively charged with about 1/3 of the charge of an electron. They are heavier than up-quarks having a mass of about 4.7 MeV/c^2.

Quarks come in 3 colours- red, blue, and green. They are not physical colours because quarks are too small to have any physical colour. It is just an analogy to represent three types of quarks. Three quarks come together to form a hadron such that the final colour is white. Such hadrons are called baryons. Protons and neutrons are also baryons. There is another way hadrons can be formed, by a quark and its antiquark (which has just the opposite colour) coming together. Such hadrons are called pions or pi mesons and they are the carrier of strong interaction between hadrons.

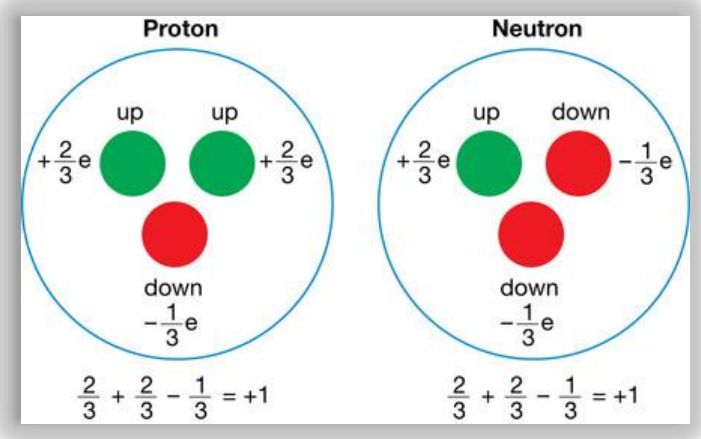
Protons

Protons are hadrons (baryons) made up of three quarks. Two up quarks and a down quark. Understanding the composition helps us in understanding the nature of protons. For instance charge of a proton is such of charges of quarks, of which it is made up. Since the charge of one up quark is 2/3 and the charge of one down quark is -1/3. The total charge of a proton comes out to be positive 1.

$$\left[\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=\frac{3}{3}=1\right]$$

The mass of a proton is the sum of the mass of two up quarks, one down quark, binding energy and kinetic energy of the particles due to their confinement to a small space. Since the mass of the up quarks is 2.3 MeV/c^2 and the mass of the down quark is 4.7 MeV/c^2, these sum up to be 9.3 MeV/c^2. But when we consider and add the mass of gluons and kinetic energy total mass comes out to be around 938.27MeV/c^2 which is about 1.6726×10^{-27} Kilograms. We must keep in mind that the mass of every proton is not fixed, it can change according to the energy present with the quarks even though the change is not very large.

Protons were discovered by Ernest Rutherford in the early 1900s. He discovered them during his research on nuclear reactions. When he sent speeding alpha particles towards Nitrogen atoms, he got oxygen and a proton. He found that it was the same as the nucleus of a hydrogen atom. He also proved that protons are present in all the elements, hence are one of the basic building blocks of atoms.



They are one of the most stable hadrons. They are a very important constituent of an atom. The properties of an atom are decided by the number of protons in its nuclei. Since they are positively charged, they are responsible for the nuclear charge which keeps all the electrons in their specified shells. They are also important in stabilizing neutrons, which are unstable and radioactive.

Neutrons

Neutrons like protons are also baryons, but they are composed of one up quark and two down quarks. The charge of a neutron is 0. Neutrons do not have a charge because the sum of charges of one up and two down quarks is 0.

$$\left[\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = \frac{0}{3} = 0\right]$$

The mass of a neutron is calculated just like protons by considering the mass of quarks, gluons and kinetic energy present. The total mass of a neutron is $939.56\text{MeV}/c^2$ or 1.6749×10^{-27} kilograms, but just like protons, its mass can also differ at different energy.

Neutrons were discovered by James Chadwick in the year 1932 by yet another nuclear reaction. In 1930, Walther Bothe and Herbert Becker found out that when they direct alpha particles towards lithium and beryllium, unusually penetrating radiation is produced. Radiation in the reaction was thought to be gamma radiation, however, this radiation was more penetrating that any usual gamma radiation.

$$^{9}\text{Be} + {}^{4}\text{He}\ (\alpha) \rightarrow {}^{12}\text{C} + {}^{1}\text{n}$$

When James Chadwick heard of this, he aimed the radiation at paraffin wax, studied the scattering of protons and found out that radiation was not gamma but some uncharged particle with mass equal to proton instead. He won Nobel Prize in physics for the discovery of neutrons in 1935.

Neutrons are a very important part of the nucleus. They provide stability to the nucleus. As we know that protons are positively charged, and they repel each other. Even though strong interaction is more powerful than electromagnetism nucleus is help together, neutrons are still very important. They fit themselves in between protons and reduce the strength of electrostatic repulsion. They are also responsible for the additional mass in the nucleus. Neutrons nowadays are also being used for the study of various fields.

Neutrons unlike protons are not very stable. Their average lifetime is around only 15 minutes. A free neutron decays into a proton, an electron and an electron-anti-neutrino. In the nucleus, the proton provides neutron stability. Inside the nucleus when a neutron decays, the produced electron and anti-neutrino fuse with the proton to form other neutrons and produced proton stays the same. Hence the overall composition of the nucleus stays the same.

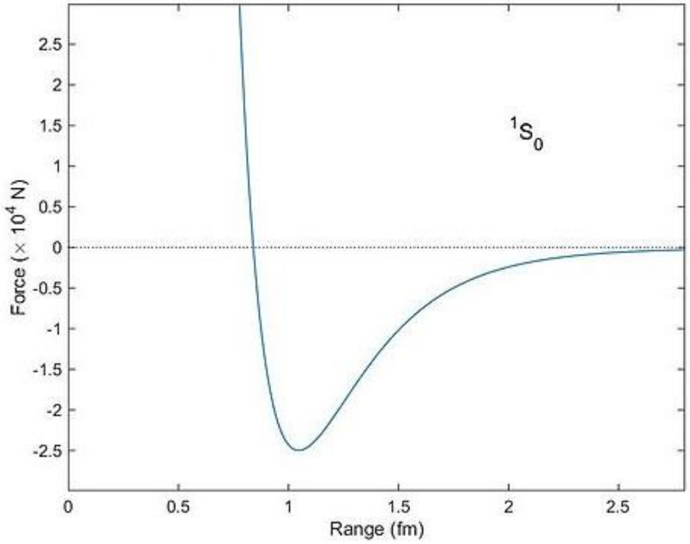
Gauge bosons

Bosons are exchange particles which are responsible for force and the Higgs field. Gauge bosons are bosons which are responsible for force fields. They all have a spin of 1. There are four fundamental forces- strong, weak, electromagnetism and gravity. Only the first three are explained by the standard model. To explain them there are 4 flavours of gauge bosons – gluons, photons, W bosons and Z bosons. Gluons for strong, Photons for electromagnetic and W, and Z for weak interaction. Gravity is explained by Einstein’s theory of general relativity

Gluons: Exchange particles and carriers of Strong force

Gluons are bosons (Gauge) which are responsible for strong field and interaction. They don’t carry any electric charge. They do not interact with weak or electromagnetic forces. They also do not interact with the Higgs field and hence they do not have any mass. They have a spin of 1.

The idea of strong force was given by a Japanese physicist Hideki Yukawa in February 1935, however first direct proof of the existence of gluons was found at DESY laboratory, Germany in the year 1979 through the collision of an electron and an anti-electron.



As protons and neutron make up the nucleus and they are made up of quarks, the electromagnetic force between charged quarks and protons consistently work to break them apart. But we know that even though neutrons are radioactive (the reason being weak interaction), protons are very stable and the same can be said for many of the atomic nuclei. The Strong force is responsible for negating electrostatic repulsion and keeping hadrons together.

Quarks consistently emit and absorb gluons to interact with each other. Gluons also come in different colours and affect particles with colour charge. This colour charge mentioned here is not any physical colour, but a fundamental property of quarks and gluons. Gluons also have a colour charge, hence they interact with the strong field themselves. The strong force is the strongest of the fundamental forces.

Strong is not a linear force, its magnitude increases with distance like tension at first. At distances smaller than 0.7 fermis, it is repulsive. This repulsion prevents quarks from collision and is responsible for the size of hadrons. At a distance of 0.8 fermis, it becomes attractive and it attains its maxima at a distance of 1 fermi. After a distance of 1.2 fermi force again starts to weaken randomly. Its strength drops so fast that at 3.5 fermis it is almost negligible.

Strong interaction behaves again very strangely once 2 quarks come together and form a hadron. The amount of force between two particles keeps on increasing with the distance it reaches a limit distance that is around 1 fermi. After that, it becomes a constant of 10,000 newtons whatever the distance between them. If we try to break them apart, the work done against it forms and ejects two new quarks (in the form of a pion of a quark and an antiquark). That is the reason we still have not found any free quarks yet. Nucleons interact with each other by emitting and absorbing pion (also called pi-mesons) in place of gluons.

W/Z Boson: Weak force carriers

There are two gauge bosons responsible for weak interaction. W and Z bosons with masses around 80 and 91 GeV/c2 respectively. They also like all the bosons have a spin 1. They are no charges on Z bosons, but W bosons can have a charge of either +1 or -1, and hence W bosons themselves are affected by electromagnetic forces. The weak force is the most interactive force of all. All the particles excluding Gluons interact with the weak field including Z and W bosons. Even neutrino, photons and Higgs bosons - that do not interact with strong and electromagnetic force - are affected by weak interaction fields.

The first proposition of weak force was given by Enrico Fermi in the year 1933 to explain beta decay, however, it is better explained by the electro-weak theory given by Sheldon Glashow, Abdus Salam and Steven Weinberg in the 1960s. This theory explains that weak and electromagnetic forces are two aspects of the same force. They also predicted the existence of W and Z bosons, which were discovered later at CERN (European Organization for Nuclear Research) in the year 1983.

The weak force is quite different from all interactions because of its nature. Z and W bosons, because of their big masses, are not very stable. They have a lifetime of under 10^{24} seconds. The weak interaction is the only force that changes the flavour of quarks and leptons, for instance in neutrons, one of the down quarks decays into up quarks and by emitting a virtual W^- boson, which eventually decays into an electron and an antineutrino.

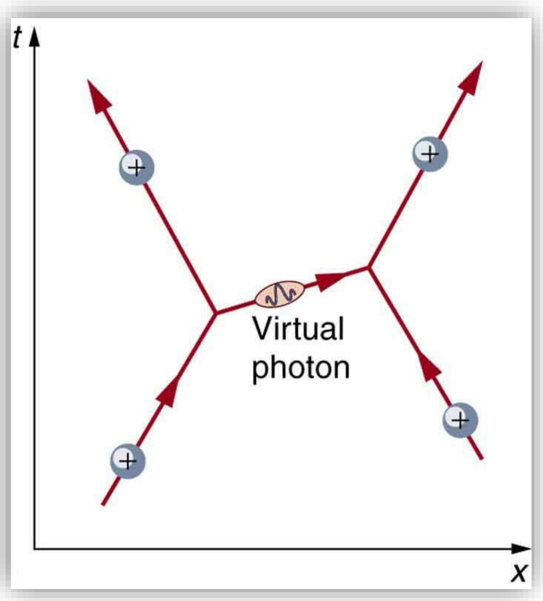
The weak interaction is of two types- charged weak interaction and neutral weak interaction. To understand nuclear reactions we need to understand charged weak interaction only. Charged weak responsible for two types of decay: β^+ decay and β^- decay which is governed by (virtual) W^+ and W^- bosons respectively. In β^- decay negatively charged particles decay into their positively charged flavours by emitting a virtual W^- boson absorbing a W^+ boson. For instance, in the beta decay of neutron a down quarks decay to an up quark and emits a W^- which then decays to an electron, and an anti-neutrino. The resultant up quark comes together with other up and down quarks and forms a proton. Hence we get a high-energy proton, electron, and antineutrino from a neutron. The energy causes the electron moves at a high speed and takes the form of β^- or beta radiation. Protons at the same time have heavier masses and hence move with a lot less speed. The same happens in β^+ decay when a positively charged particle decay into its negatively charged flavours by emitting a virtual W^+ boson.

This can also happen the other way around when flavours are changed by absorbing virtual W^+ boson or W^- boson. This is used in stabilizing the neutrons in the nucleus when a proton accepts an electron and gets converted to a neutron (an up quark of the proton accepts an electron to become a down quark).

The weak force is weaker than both strong and electromagnetic forces. Its range is also lesser than both of them. It is a non-contact force, though its range is restricted to 0.01 to 0.1 fermi. At smaller distances (~ 0.01fermi), it is also as strong as electromagnetic interaction, but with distance, its strength decreases exponentially just like strong interaction.

This force plays the most important role in a nuclear reaction as it is the only force that can change the flavours of fermions. Other than that weak force is only meant to study neutrino and Higgs boson which are the biggest mysteries in particle physics right now.

Electromagnetism and Photons



The electromagnetic interaction is the easiest to understand out of all four fundamental forces. Electromagnetic forces are carried by photons, but they do not carry any charge themselves, and hence do not interact with the electromagnetic field. Photons have a spin of 1. They also do not interact with the Higgs field and are massless.

Photons are quanta of electromagnetic waves such as light and radio waves. They always travel 299792458 meters per second in a vacuum. This results in them having a large momentum and energy. The properties of electromagnetic waves (for instance energy of a photon of that wave) are determined by their frequency. Waves with higher frequency have more energy and are more penetrating like gamma radiation.

Electricity and magnetism were thought to be two completely distinct topics for a very long time. A formula to calculate the strength of the electrostatic force was given by Coulomb. Later Michael Faraday observed that electrically charged particles move they generate a magnetic field and vice-versa. In the 1860s, Maxwell proved that electricity and magnetism can never be separated like two sides of the same coin and that light rays are a type of electromagnetic wave.

Electric charge is a fundamental property of particles. A particle can be positively or negatively charged. Electrically charged particles interact with each other by exchanging virtual photons. Like charges repel and unlike charges attract each other. When these charges are in motion a magnetic field is formed around it. The strength of the magnetic field depends on the magnitude of the magnetic current and its distance from it, however, the electrostatic force is directly proportional to the product of two charges and the inverse of the square of the distance between them.

The force between two charged particles $F = k\frac{q_1 q_2}{d^2}$, where k is the constant for the medium (which is now expressed as $\frac{1}{4\pi\varepsilon}$), q_1 and q_2 are charges and d is the distance between the two of them.

The electromagnetic force is the second most powerful force. We in our daily life interact directly with electromagnetic force only, let it friction, tension, strength of material, light or electric machines. At the atomic level, it is the force responsible for keeping electrons in their specified stationary states and maintaining the volume of matter.

Relation between Forces (Strong vs Weak vs Electromagnetism)

All three types of forces are very different from each other, they get unified into one at high energy with the incorporation of the Higgs mechanism. They are all at their strongest at the atomic level and play a very important role in nuclear reactions.

Here is a table to help us compare the strength of different forces at different distances.

Distance	**Strong force**	**Electrostatic force**	**Weak force**
Inside a quark (at 0.02 fermi approx.)	Does not interact	In terms of 10,000 newtons (both are almost equal)	
0.5 fermi	Repulsive – very much high	921.6 newton	Negligible.
1 fermi	Attractive - 26,000 Newton	230.4 newton	Not effective
2 fermi	Attractive – 2,000 Newton	57.5 newton	Not effective
3 fermi	Attractive – 40 to 50 Newton	25.6 newton	Not effective
5 fermi	Negligible	9.2 newton	Not effective
10 fermi	Not effective	2.3 newton	Not effective
20 fermi	Not effective	0.4 newton	Not effective

As we see the range of electromagnetic is infinite, whereas strong and weak forces have very small ranges. Because of this, when many nucleons are present, at a point strong force due to only 2 or three nucleons is active. In the same situation, at a point, the electromagnetic force of all the nucleons will be active because of their long range. This draws us to the conclusion that there is a fixed limit of the strong force that can work at a point, but electrostatic force just adds with the increase in the number of nucleons, hence as the nucleus gets heavier, the electrostatic force will start dominating strong interaction.

Kinetic energy or Momentum

The only factor that is left is the momentum of nucleons. As we may notice that strong force is too powerful for electromagnetic force or weak force to break protons, but still ^{2}He is not stable. When we confine quarks and nucleons to very small space (in hadrons and nuclei), this confine leads them to have a large amount of momentum and hence kinetic energy. We must realize that individual quarks move and because of the distance between them they have momentum. Most of the mass of nucleons comes from energy because of this motion.

This energy or momentum consistently tries to bring nucleons apart and hence assisted by the electrostatic force of the proton it breaks apart a ^{2}He nucleus. This is the reason that even if strong interaction is very powerful it can not hold many nucleons together. If not for this momentum (or kinetic energy), nucleus fission would have been next to impossible and we would have found many heavy elements.

Nuclear reactions: Factors and conditions which lead to such reactions

As the mass involved in nuclear reactions is very less gravity does not affect nuclear reactions. Weak interaction plays a very important role in nuclear reactions as they are responsible for the instability of neutrons which is the ultimate reason for most nuclear reactions. The role of the weak interaction is fixed in all nuclear reactions, however strong and electromagnetic force work against each other. The electrostatic force between nuclei and protons is always repulsive (and does not interact with neutrons) because of their like charge, hence it always works to break nuclei apart and stops nuclei from coming near to each other (because it has got a longer range, at that distance strong force is negligible). Strong interaction on other hand is attractive between nucleons and always works to keep the nucleus together (because it is stronger than electrostatic force) and attracts nuclei near to each other. When these forces are balanced they create a stable nucleus. There are largely seven situations such that these forces are unbalanced and a nuclear reaction happens.

1. Normally nuclei are at distance in terms of angstroms (10^{-10} meters), the strong force is not effective and electrostatic force keeps nuclei away because of its long range. When In the sun or at high pressure and temperature, nuclei like hydrogen come near to each other (by increasing pressure), even though both of the forces get stronger, the increase in the magnitude of the strong force is much higher than that of electrostatic force. Then due to their kinetic energy (due to temperature), they move very swiftly in random directions and collide. At the time of collision strong force becomes stronger than electrostatic force (because they are very near to each other at the time of collision), and nuclei merge to make a heavier nucleus. Such reactions are called nuclear fusion.

   To get the temperature at which fusion occurs, we will first calculate the minimum velocity needed to bring nuclei together against electrostatic force.

   The formula to calculate the velocity needed is $\sqrt{\frac{kQq}{rm}}$, which implies that the needed velocity increases with the increase in charge or the number of protons or atom numbers. It also proves that heavier isotopes of atoms are more likely to show nuclear fusion as less velocity is needed as the mass and radius of the nucleus increase. From here we can imply that ^{2}H or ^{3}H will need a lower temperature to show nuclear fusion as they have less charge and greater mass (and radius).

   Note: Here temperature should be very high to make nuclei collide and high pressure increases the possibility of a collision, but the real work of binding them together and making one nucleus is done by the strong interaction. Without gluons (carriers of strong force) and nuclei would have just collided and bounced back.

      1. $^{2}H + ^{3}H \rightarrow ^{4}He + ^{1}n$

      2. $^{1}H + ^{1}H \rightarrow ^{2}He$

2. The same fusion of nuclei can be done differently. When alpha radiation (or any other very light nuclei) is directed towards another light stationary sample of nuclei (heavier than first) with a great speed (so that it can bypass electrostatic force), they also collide but here part of the alpha particle (or any other nuclei) merges with the sample nuclei and rest is ejected as radiation. They are different from fusion because here major nucleons of the resultant atom come from sample nuclei, whereas radiation only changes the number of nucleons (or only protons) in its nuclei and hence its properties. That is the reason these reactions are called transmutation reactions. Here density of sample nuclei should be more to increase the frequency of collisions where the velocity needed (or energy) of radiation again depends on the charge and mass of nuclei as in nuclear fusion.

    1. ${}^{14}N + {}^{4}{}_{2}\alpha \rightarrow {}^{17}O + {}^{1}H^{+}$
    2. ${}^{9}Be + {}^{4}{}_{2}\alpha \rightarrow {}^{12}C + {}^{1}n$

3. This situation usually comes after the fusion of two light proton-efficient nuclei (mostly hydrogen). When in a nucleus there are more protons than the neutron, and protons have a lot of energy with them, most of the time nuclei just split (protons break away from the nucleus) because of repulsion between positive charges and kinetic energy contained by nucleons. Sometimes (once in every million) Due to increased mass (because of high energy), usually stable protons decay. Weak force breaks an up quark of proton (with its increased mass due to high energy) into a down quark, a positron and a neutrino. Hence proton is converted to a neutron to balance electromagnetism and kinetic energy and a positron is ejected with high speed. This process is called positron emission. This process can be considered a distorted form of nuclear decay.

    1. ${}^{2}He \rightarrow {}^{2}H + {}^{0}e^{1}$

    Note- ${}^{3}He$ (helium) and ${}^{1}H$ are the only nuclei that are stable with more protons than neutrons in them.

4. When there are more protons than neutrons in any nucleus, and there are low energy electrons around, one of the electrons is attracted towards by positive charge (of protons in the nucleus) and falls into the nucleus. When electrons come very near (less than 0.01fermi) to protons in the nucleus, weak force using electron changes an up quark and electron to a down quark and a neutrino, hence the proton is converted to neutron. This process is called ‘electron capture’ and is a type of transmutation reaction only.

    Note: Electromagnetic interaction cannot change the flavour of fermions, hence without weak interaction electrons would have collided and then bounced back. Strong interaction cannot hold them together because it does not affect leptons (electrons and others).

1. $^{106}Ag + {}^{0}e^{-1} \rightarrow {}^{106}Pd$

5. When the number of neutrons in the nucleus becomes so high that protons can no longer stabilize them (by electron capture), neutron decays to proton and release electron. Weak interaction converts a down quark of neutron to an up quark, an electron and an antineutrino. Since sufficient protons are not present in the nucleus, electrons are ejected as beta radiation and the atomic number reduces by one. This reaction is very useful in the study of old historical things, as we use it in the carbon-14 dating system. This reaction is also a type of nuclear decay only.

   Note- it is not necessary that if neutrons are more than protons, the nucleus will be unstable only. The number of needed neutron to protons ratio increases with heavier elements. It is 1 in elements up to 20 atomic numbers and after that, it slowly raises to 1.6.

   1. $^{14}C \rightarrow {}^{14}N + {}^{0}e^{-1}$

6. This situation is for radioactive elements. When atoms become very heavy the number of nucleons in them is more than 208, and the nucleus becomes permanently unstable. In this case, reducing neutrons results in electromagnetic repulsion in protons and if we increase neutrons there will not be sufficient protons to balance the radioactivity of neutrons. Here neutrons change to protons and electrons, which increases the repulsion between the nucleons and nuclei releases alpha radiation (^{4}He-2 protons and 2 neutrons) and becomes lighter to balance it. Heavier nuclei go through multiple decays till they reach stable nuclei.

   1. $^{226}Ra \rightarrow {}^{222}Rn + {}^{4}_{2}\alpha$

7. There are special cases of the last one where if you add a (or more) neutrons to heavier nuclei like uranium or plutonium, the nucleus becomes very unstable due to the increased number of nucleons (electromagnetic repulsion between protons and radioactivity of neutrons). The force of repulsion becomes so high in such cases that the nucleus breaks into 2 or lighter nuclei (heavier than ^{4}He) instead of releasing multiple helium nuclei. This process is called nuclear fission. In this situation, extra neutrons are also released, as lighter atoms needed neutrons to proton ratio to balance forces in lesser than that of heavier atoms. These extra neutrons restart fission and hence make nuclear fission difficult to control.

   1. $^{235}U + {}^{1}n \rightarrow {}^{141}Ba + {}^{92}Kr + 3\,{}^{1}n$

Nuclear reactions as a source of energy

We know that due to mass defects during nuclear reactions, a huge energy change takes place, but not all nuclear reactions are feasible. Right now we can only perform nuclear fission of Plutonium or uranium (or thorium by converting it to uranium) in bulk to use as energy sources. Other sources have their flaws like most transmutation reactions need continuous bombardment of alpha particles. Energy change in a nuclear decay reaction is not very large and also they radiate high-speed particles, which makes them very dangerous to perform.

The nuclear fission of one uranium atom yields around 194 MeV energy, which makes it around 8 $\times 10^{13}$ joules of energy per kilogram. Nuclear power plants run on uranium fission. A few neutrons are directed towards the source uranium, which initiates the reaction. After every fission of uranium, 3 more neutrons are emitted, which again reinitiates the nuclear fission other 3 uranium atoms and hence this reaction goes on.

- $^{235}U + {}^{1}_{0}n \rightarrow {}^{141}Ba + {}^{92}Kr + 3\,{}^{1}n$

As you might observe the reaction will go uncontrollable after some time left unchecked. In energy fission, 1 neutron is used and 3 released, which makes the reaction go 3 three times faster after everyone until all the fuel is consumed. To overcome this problem hard water and boron plates are used to observe extra neutrons and keep the reaction under control.

The energy exchanged from these reactions (in form of heat) is used to boil water. When water vapour rises from these boilers it turns the turbine of electricity generators. Hence these power plants are also called 'Thermal power plants'.

There is one more alternative for these power plants, which is still being tried and tested i.e. using nuclear (hydrogen) fission as an energy source. We know the whole of the universe runs on fusion energy. In a hydrogen fusion of two nuclei around 18 MeV energy is produced. It might seem less in comparison to nuclear fission, but there is also a mass factor. The mass used in fission is around 60 times that of a hydrogen fusion reaction. If we find out the calorific value it comes to be in the order of 7×10^{14} depending upon the type of fusion performed.

- $^{2}H + {}^{3}H \rightarrow {}^{4}He + {}^{1}n$
- $^{1}H + {}^{1}H \rightarrow {}^{2}He$
- $^{2}H + {}^{2}H \rightarrow {}^{3}He + {}^{1}n$

In nuclear fusion (that can be used as a fuel) 2 deuterium with or without a neutron collide at high temperature and pressure so that their nuclei fuse and produce a lot of energy. Since very less neutrons are produced in these reactions than used, fusion reactions are controlled directly by temperature, pressure and amount of fuel provided. These reactions produce no harmful radiation and are easily controllable and hence are more profitable than nuclear fission. Scientists are trying to perform these reactions in bulk, but they do have their problem i.e. very high temperatures and pressure are required to perform such reactions in bulk.

If these reactions are made possible in near future, they will be an even better option for energy sources than nuclear fission. The amount of uranium (and such metals) on earth which can be feasibly mined is also not much, whereas we can always get more hydrogen than we need by electrolysis of water.

Conclusion

We try to conclude the complete research in a few postulates we can say:

- Nuclear reactions are of 4 types basically- fission, fusion, transmutation, and nuclear decay.
- Quarks, leptons and their different flavours are very important for nuclear reactions.
- Strong, electromagnetic and weak interactions work unified or against each other to promote or prevent nuclear reactions. Their role can be different in different cases.
- The strong force is responsible for the size of hadrons and keeping them together. Electromagnetic force for size, state, and structure of matter. It is the force we directly and mostly interact with. The weak forces, even though weakest and with the smallest range, are responsible for changing the flavours of fermions and are very crucial. They are the backbone of all nuclear reactions.
- Kinetic energy and momentum of particles (quarks, hadrons and leptons) also play a very important role in nuclear reactions and stability.
- Protons and neutrons complement each other in the nucleus and when they are in the correct combination, they form stable nuclei. Neutrons create a decreased force of repulsion between protons but are unstable (radioactive), whereas protons stabilize neutrons by absorbing their decay-but they repel each other because of their positive charge.
- Light elements with fewer protons are better choices for nuclear fusion, whereas heavier elements tend to show nuclear fission instead.
- Nuclei with an unbalanced ratio of protons and neutrons absorb or release radiation to stabilize themselves.
- A huge energy exchange takes place in a nuclear reaction as compensation for the mass defect that occurs after these reactions. This change in energy can be understood and calculated by the mass-energy equation of Albert Einstein i.e. $E=mc^2$.
- Pressure and temperature do not directly affect the nuclear reaction, but they can definitely change the rate of collisions and hence rate the reaction itself.
- Nuclear fusion is an energy source of the future because of its efficiency, and the control that we have over them, they are free from pollution and we can ample hydrogen from the electrolysis of water very easily.
- Nuclear reactions are very important and can be of great use if we understand them and use them judiciously.

Mysteries and Anomalies

At the time we know a lot about nuclear reactions yet there is a lot of it that is only predicted are not known. Of them I have listed below:

- The standard model is the most accepted and accurate theory to explain the working of the universe, but it is still a theory that can also be wrong.
- Many parts of the standard model are explained by the presence of virtual particles.
- We do not know the involvement of neutrinos in nuclear reactions other than being emitted and annihilated.
- We do not know whether up-quarks can decay ever or not and if they can what will be its resultants and their life.
- We do not have an exact method to calculate the magnitude of the strong and weak forces.
- Gluons, W and Z bosons are also vector bosons then why force carried by them is not linear and conservative?
- How can we predict mass defect or energy exchange without experiments?

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