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INSTITUTE OF SCIENCE AND TECHNOLOGY

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SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

UNIT – I - NUCLEAR STRUCTURE – SPHA5401

An Overview

Central to these studies is the concept of nuclear shell structure, in which protons and neutrons occupy quantized energy levels within a potential generated by their interactions with all of the other nucleons.

Nuclear magnetic moment

The nuclear magnetic moment is the magnetic moment of an atomic nucleus and arises from the spin of the protons and neutrons. It is mainly a magnetic dipole moment; the quadrupole moment does cause some small shifts in the hyperfine structure as well. All nuclei that have nonzero spin also possess a nonzero magnetic moment and vice versa, although the connection between the two quantities is not straightforward or easy to calculate. The nuclear magnetic moment varies from isotope to isotope of an element. For a nucleus of which the numbers of protons and of neutrons are both even in its ground state (i.e. lowest energy state), the nuclear spin and magnetic moment are both always zero. In cases with odd numbers of either or both protons and neutrons, the nucleus often has nonzero spin and magnetic moment. The nuclear magnetic moment is not sum of nucleon magnetic moments, this property being assigned to the tensorial character of the nuclear force, such as in the case of the most simple nucleus where both proton and neutron appear, namely deuterium nucleus, deuteron.

Nuclear Radius

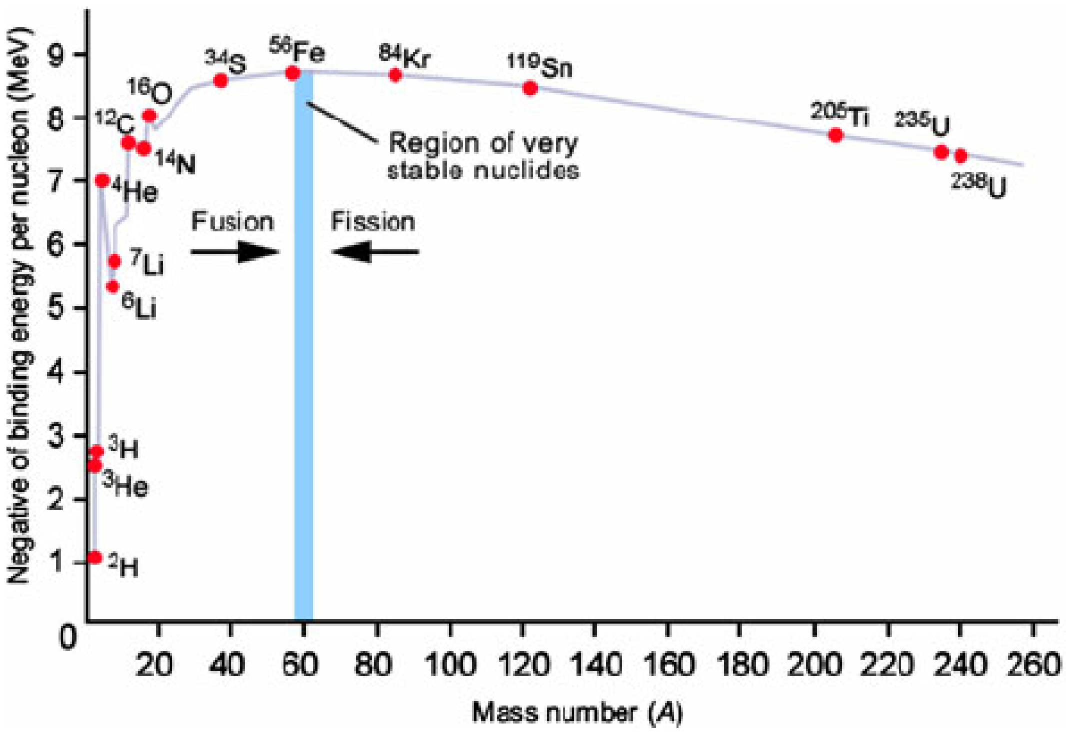
The **nucleus** of an atom has no sharply **defined** boundaries and, although it can be considered spherical in form, care must be taken when speaking of its '**radius**'. ... The **nuclear radius**, R, can be **defined** as the distance from the centre to the point where the density has decreased to half its original value.

Binding Energy

Nuclear binding energy is the **energy** required to split a nucleus of an atom into its components. The **mass defect** of a nucleus represents the **mass** of the **energy binding** the nucleus, and is the difference between the **mass** of a nucleus and the sum of the **masses** of the nucleons of which it is composed. Einstein's famous equation relates energy and mass: $E = mc^2$ You can use that to prove that a mass of 1 u is equivalent to an energy of 931.5 MeV. Something should strike you as strange about the table above. The carbon-12 atom has a mass of 12.000 u, and yet it contains 12 objects (6 protons and 6 neutrons) that each have a mass greater than 1.000 u, not to mention a small contribution from the 6 electrons.

This is true for all nuclei, that the mass of the nucleus is a little less than the mass of the individual neutrons, protons, and electrons. This missing mass is known as the mass defect, and represents the binding energy of the nucleus. The binding energy is the energy you would need to put in to split the nucleus into individual protons and neutrons. To find the binding energy, add the masses of the individual protons, neutrons, and electrons, subtract the mass of the atom, and convert that mass difference to energy. For carbon-12 this gives:

Mass defect = Dm = 6 * 1.008664 u + 6 * 1.007276 u + 6 * 0.00054858 u - 12.000 u = 0.098931 u
The binding energy in the carbon-12 atom is therefore 0.098931 u * 931.5 MeV/u = 92.15 MeV.



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Models of Nucleus

Liquid Drop Model

Scattering experiments suggest that nuclei have approximately constant density, so that the nuclear radius can be calculated by using that density as if the nucleus were a drop of a uniform liquid. A liquid drop model of the nucleus would take into account the fact that the forces on the nucleons on the surface are different from those on nucleons on the interior where they are completely surrounded by other attracting nucleons. This is something similar to taking account of surface tension as a contributor to the energy of a tiny liquid drop. The volume of the liquid drop is proportional to the mass number A, and the surface would then be proportional to the two-thirds power of A.

The first step toward a liquid drop model of the nucleus would then be to postulate a volume term and a surface term in the form:

$$E_b \approx \underset{\text{Volume term}}{C_1 A} \quad \underset{\text{Surface term}}{- C_2 A^{2/3}}$$

$$C_1 = 15.75 MeV, \quad C_2 = 17.8 MeV$$

This simple model in fact gives a reasonable approximation of the variation of nuclear binding energy with mass number when the constants have the values

$$\Delta E_b^{Coulomb} \approx \frac{-(0.711 MeV)Z^2}{A^{1/3}}$$

Another contribution to the binding energy would be the coulomb repulsion of the protons, so there should be a negative term proportional to the square of the atomic number Z :

$$\Delta E_b^{Pauli} \approx \frac{-(23.7 MeV)(A-2Z)^2}{A}$$

The Pauli principle favors nuclei in which A=2Z, so the empirical model of binding energy contains a term of the form

Discussion of Pauli contribution

The Pauli principle also favors nuclear configurations with even numbers of neutrons and protons. In the liquid drop model, this is included by using the even-odd nucleus as a reference and adding a correction term which is positive for even-even nuclei and negative for odd-odd nuclei. This strategy for modeling the nuclear binding energy is attributed to Weizsaecker and called the Weizsaecker formula.

The Weizacker Formula

The Weizsaecker formula is an empirically refined form of the liquid drop model for the binding energy of nuclei. It is also referred to as the "semi-empirical mass formula" and the "Bethe-Weizsaecker formula". Expressed in terms of the mass number A and the atomic number Z for an even-odd nucleus, the Weizsaecker formula is

$$E_b^{even-odd} \approx \underset{\text{Volume term}}{(15.75 MeV)A} - \underset{\text{Surface term}}{(17.8 MeV)A^{2/3}} - \underset{\text{Coulomb term}}{\frac{(0.711 MeV)Z^2}{A^{1/3}}} - \underset{\text{Pauli term}}{\frac{(23.7 MeV)(A-2Z)^2}{A}}$$

Using the even-odd as a reference, there are then correction terms for even-even and odd-odd nuclei, the even-even groupings of protons and neutrons bing favored in stability

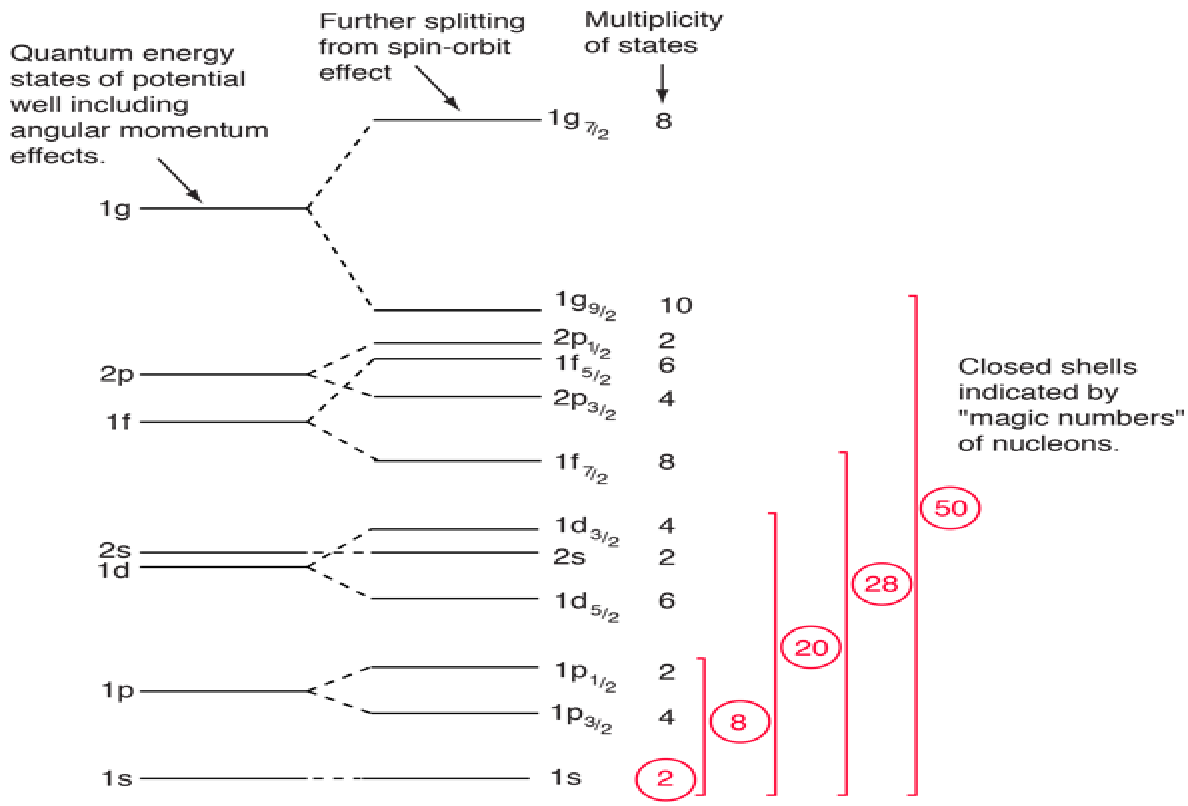
$$E_b^{even-even} \approx E_b^{even-odd} + \frac{11.18MeV}{\sqrt{A}}$$
$$E_b^{odd-odd} \approx E_b^{even-odd} - \frac{11.18MeV}{\sqrt{A}}$$

Nuclear Shell Model

Visualizing the densely packed nucleus in terms of orbits and shells seems much less plausible than the corresponding shell model for atomic electrons. You can easily believe that an atomic electron can complete many orbits without running into anything, but you expect protons and neutrons in a nucleus to be in a continuous process of collision with each other. But dense-gas type models of nuclei with multiple collisions between particles didn't fit the data, and remarkable patterns like the "magic numbers" in the stability of nuclei suggested the seemingly improbable shell structure.

With the enormous strong force between them and with so many nucleons to collide with, how can nucleons possibly complete whole orbits without interacting? This has the marks of a Pauli exclusion principles, where two fermions cannot occupy the same quantum state. If there are no nearby, unfilled quantum states that are in reach of the available energy for an interaction, then the interaction will not occur. This is essentially a quantum idea - if there is not an available "hole" for a collision to knock a nucleon into, then the collision will not occur. There is no classical analog to this situation.

The evidence for a kind of shell structure and a limited number of allowed energy states suggests that a nucleon moves in some kind of effective potential well created by the forces of all the other nucleons. This leads to energy quantization in a manner similar to the square well and harmonic harmonic oscillator potentials. Since the details of the well determine the energies, much effort has gone into construction of potential wells for the modeling of the observed nuclear energy levels. Solving for the energies from such potentials gives a series of energy levels like that at left below. The labels on the levels are somewhat different from the corresponding symbols for atomic energy levels. The energy levels increase with orbital angular momentum quantum number l, and the s,p,d,f... symbols are used for l=0,1,2,3... just like the atomic case. But there is really no physical analog to the principal quantum number n, so the numbers associated with the level just start at n=1 for the lowest level associated with a given orbital quantum number, giving such symbols as 1g which could not occur in the atomic labeling scheme. The quantum number for orbital angular momentum is not limited to n as in the atomic case.



In addition to the dependence on the details of the potential well and the orbital quantum number, there is a sizable spin-orbit interaction which splits the levels by an amount which increases with orbital quantum number. This leads to the overlapping levels as shown in the illustration. The subscript indicates the value of the total angular momentum j, and the multiplicity of the state is 2j + 1. The contribution of a proton to the energy is somewhat different from that of a neutron because of the coulomb repulsion, but it makes little difference in the appearance of the set of energy levels.

Magic Numbers in Nuclear Structure

With this set of identified nuclear states and the magic numbers, we can predict the net nuclear spin of a nucleus and represent it's nuclear state based on the identification of the level of the odd nucleon in the order of states shown above. The parity of the state can also be predicted, so the single particle shell model has shown itself to be of significant benefit in characterizing nuclei.

It is found that nuclei with even numbers of protons and neutrons are more stable than those with odd numbers. In particular, there are "magic numbers" of neutrons and protons which seem to be particularly favored in terms of nuclear stability:

2, 8, 20, 28, 50, 82, 126

Magic Numbers

Nuclei which have both neutron number and proton number equal to one of the magic numbers can be called "doubly magic", and are found to be particularly stable.

Calcium provides a good example of the exceptional stability of "doubly magic" nuclei since it has two of them. The existence of several stable isotopes of calcium may have to do with the fact that Z=20, a magic number. The two highlighted isotopes have neutron numbers 20 and 28, also magic numbers. Compared to the binding energy calculated from the Weizsaecker formula, they both have more than the expected binding energy.

The existence of these magic numbers suggests closed shell configurations, like the shells in atomic structure. They represent one line of reasoning which led to the development of a shell model of the nucleus. Other forms of evidence suggesting shell structure include the following.

Enhanced abundance of those elements for which Z or N is a magic number.

The stable elements at the end of the naturally occuring radioactive series all have a "magic number" of neutrons or protons.

The neutron absorption cross-sections for isotopes where N = magic number are much lower than surrounding isotopes.

The binding energy for the last neutron is a maximum for a magic neutron number and drops sharply for the next neutron added.

Electric quadrupole moments are near zero for magic number nuclei.

The excitation energy from the ground nuclear state to the first excited state is greater for closed shells.

Yukawa Meson Theory

Hideki Yukawa received the Nobel Prize in physics for 1949 for predicting the existence of what became to be known as the pi mesons and later as pions. In his 1934 article Yukawa argued that the nuclear strong force is carried by a particle with a mass approximately 200 times that of an electron. This **theory** gives an idea about how the **nuclear** acts **force** between two neighbouring nucleons. The **nuclear force** between two nucleons due to exchange of subatomic particle called as **mesons** continuously. **Mesons** are that parts of atomic particle which may be charged or uncharged. Shortly after Yukawa's prediction a particle with almost precisely this mass was discovered in cosmic ray phenomena. It looked at first that Yukawa had been uncannily accurate, but there were problems with the particle found in the cosmic ray records. Although its mass was 207 times that of an electron, it was a fermion with half-integral spin rather than a boson of integral spin as Yukawa predicted for the carrier of the strong nuclear force. It turned out that the cosmic ray particle was not the particle Yukawa was talking about. Instead the cosmic ray particle was essentially a heavy electron, which is now called the muon. Later three particles with masses approximately 270 times that of an electron were found. These did have the properties that Yukawa had predicted. One was of positive charge, one of negative charge and one was neutral. They were called pi-mesons but now they are known as pions

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DEPARTMENT OF PHYSICS

UNIT – II - RADIOACTIVE DECAYS – SPHA5401

An Overview

Radioactive decay is the process by which an unstable atomic nucleus loses energy by radiation. A material containing unstable nuclei is considered radioactive. Three of the most common types of decay are alpha decay, beta decay, and gamma decay, all of which involve emitting one or more particles or photons.

Alpha Particle

Alpha particles were first described in the investigations of radioactivity by Ernest Rutherford in 1899, and by 1907 they were identified as He2+ ions. By 1928, George Gamow had solved the theory of alpha decay via tunneling. The alpha particle is trapped in a potential well by the nucleus. Alpha decay or α-decay is a type of radioactive decay in which the atomic nucleus emits an alpha particle thereby transforming or decaying into a new atomic nucleus. Here the atomic mass number of the newly formed atom will be reduced by four and the atomic number will be reduced by two. The emitted alpha particle is also known as a helium nucleus. The mass of the alpha particles is relatively large and has a positive charge.

Ernest Rutherford distinguished alpha decay from other forms of radiation by studying the deflection of the radiation through a magnetic field. The deflection of alpha decay would be a positive charge as the particles have +2e charge. Following is the general equation of the alpha decay:

$AZX \rightarrow A-4Z-4Y+42He$

Alpha decay occurs in very heavy elements like uranium, thorium, and radium. They are called parent nucleus and they are basically unstable. Because the nuclei of these atoms have a lot more neutrons in their nuclei than protons, that is, they have too large a proton to neutron ratio, which makes these elements neutron-rich. This richness makes alpha decay possible. Thus, emitting its two protons and two neutrons in the form of an alpha particle and a forming of new daughter nucleus and attains a very stable configuration. Alpha decay can be described like this:

The nucleus of these nuclei (parent nucleus) rich atoms splits into two parts.

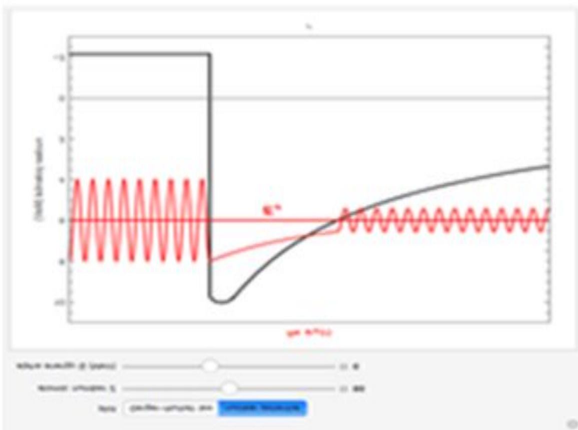
The alpha particle goes zooming off into space.

The nucleus left behind (daughter nucleus) has its atomic number reduced by 2 and its mass number reduced by 4.

Gamow Theory of Alpha Decay

The Geiger–Nuttall law or Geiger–Nuttall rule relates the decay constant of a radioactive isotope with the energy of the alpha particles emitted. This relation also states that half-lives are exponentially dependent on decay energy, so that very large changes in half-life make comparatively small differences in decay energy, and thus alpha particle energy.

As per this rule, short-lived isotopes emit more energetic alpha particles than long-lived ones. This law was stated by Hans Geiger and John Mitchell Nuttall in the year 1911, hence the name was dedicated to these physicists.



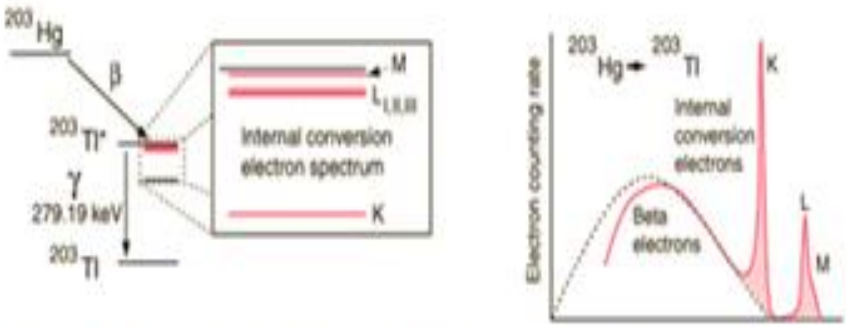
Fermi’s Beta Decay

In particle physics, Fermi's interaction (also the Fermi theory of beta decay) is an explanation of the beta decay, proposed by Enrico Fermi in 1933. ... This interaction explains beta decay of a neutron by direct coupling of a neutron with an electron, a neutrino (later determined to be an antineutrino) and a proton

When a nucleus turns into a different nucleus emitting an electron or a positron (positive charged particle with the same mass as the electron), we say that nucleus has undergone a beta decay. Like alpha decay, it is a spontaneous process, with a well-defined energy of disintegration and half-life. Beta decay is a statistical process. There are three different types of beta decay: beta negative, beta positive and electron capture.

In the negative beta: what decays is an electron that is the transformation of a neutron (n) into a proton (p) along with an electron (β-) and an antineutrino (ve). "Negative beta decay can occur when the atomic mass of the original neutral atom is greater than the corresponding mass of the final atom." $n \rightarrow p + \beta^- + ve$

Internal Conversion



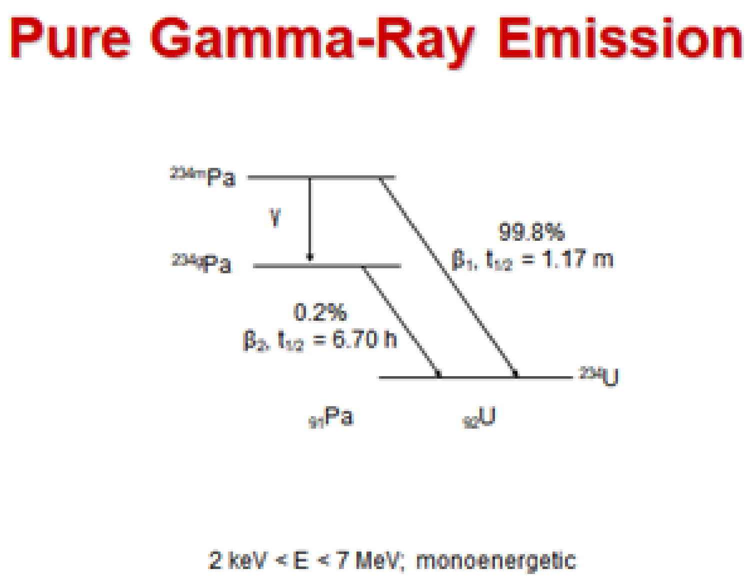
The excited nucleus transfers the energy to an orbital electron, which is then ejected from the atom (monoenergetic).

$E_{IC\ electron} = E_{trans} - BE_{atomic\ electron}$

IC and gamma decay are competing processes

Internal conversion coefficient (α)

α= Fraction of decays occurring by gamma emission/Fraction of decays occurring by IC

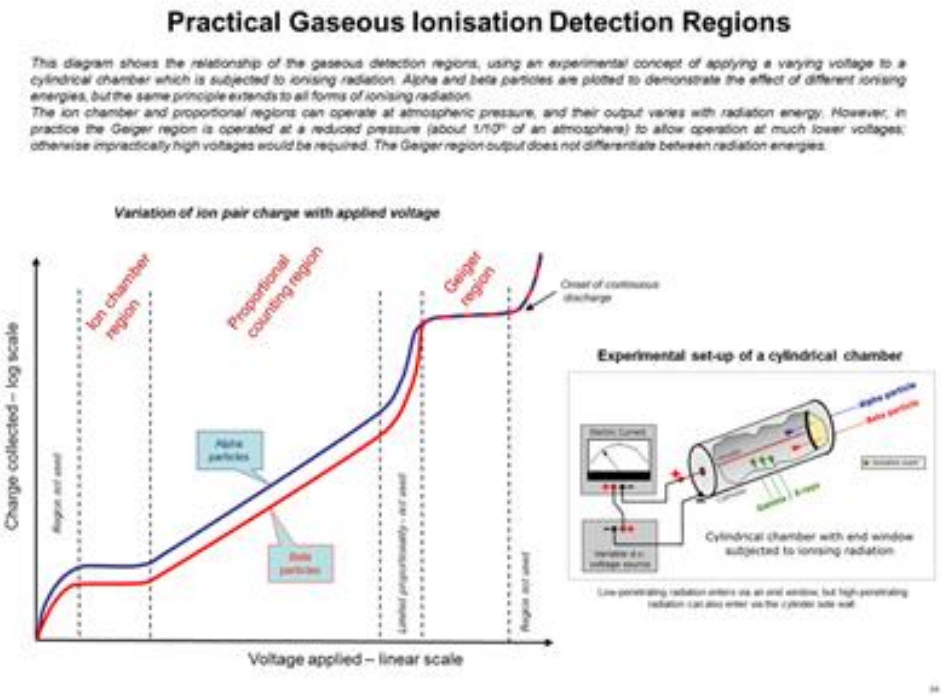


Proportional Counter

The proportional counter is a type of gaseous ionization detector device used to measure particles of ionizing radiation. The key feature is its ability to measure the energy of incident radiation, by producing a detector output pulse that is proportional to the radiation energy absorbed by the detector due to an ionizing event; hence the detector's name.

It is widely used where energy levels of incident radiation must be known, such as in the discrimination between alpha and beta particles, or accurate measurement of X-ray radiation dose.

In a proportional counter the fill gas of the chamber is an inert gas which is ionized by incident radiation, and a quench gas to ensure each pulse discharge terminates; a common mixture is 90% argon, 10% methane, known as P-10. An ionizing particle entering the gas collides with an atom of the inert gas and ionizes it to produce an electron and a positively charged ion, commonly known as an "ion pair". As the ionizing particle travels through the chamber it leaves a trail of ion pairs along its trajectory, the number of which is proportional to the energy of the particle if it is fully stopped within the gas. Typically a 1 MeV stopped particle will create about 30,000 ion pairs.



The chamber geometry and the applied voltage is such that in most of the chamber the electric field strength is low and the chamber acts as an ion chamber. However, the field is strong enough to prevent re-combination of the ion pairs and causes positive ions to drift towards the cathode and electrons towards the anode. This is the "ion drift" region. In the immediate vicinity of the anode wire, the field strength becomes large enough to produce Townsend avalanches. This avalanche region occurs only fractions of a millimeter from the anode wire, which itself is of a very small diameter. The purpose of this is to use the multiplication effect of the avalanche produced by each ion pair. This is the "avalanche" region.

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GM Counter

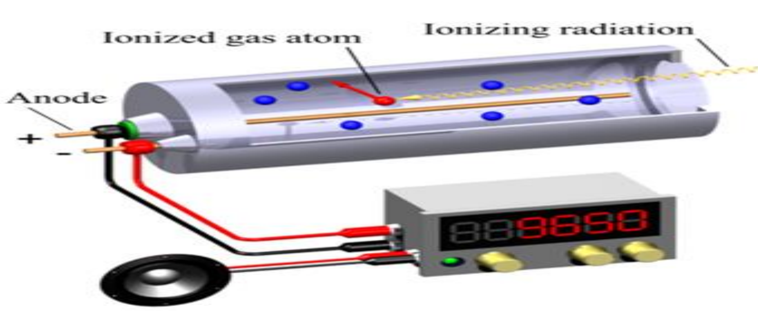
A Geiger counter is an instrument used for detecting and measuring ionizing radiation. Also known as a Geiger–Muller counter (or Geiger–Müller counter), it is widely used in applications such as radiation dosimetry, radiological protection, experimental physics, and the nuclear industry.It detects ionizing radiation such as alpha particles, beta particles, and gamma rays using the ionization effect produced in a Geiger–Müller tube, which gives its name to the instrument.

In wide and prominent use as a hand-held radiation survey instrument, it is perhaps one of the world's best-known radiation detection instruments.

Principle of Operation

A Geiger counter consists of a Geiger–Müller tube (the sensing element which detects the radiation) and the processing electronics, which displays the result.The Geiger–Müller tube is filled with an inert gas such as helium, neon, or argon at low pressure, to which a high voltage is applied. The tube briefly conducts electrical charge when a particle or photon of incident radiation makes the gas conductive by ionization.

The ionization is considerably amplified within the tube by the Townsend discharge effect to produce an easily measured detection pulse, which is fed to the processing and display electronics. This large pulse from the tube makes the Geiger counter relatively cheap to manufacture, as the subsequent electronics are greatly simplified. The electronics also generate the high voltage, typically 400–900 volts, that has to be applied to the Geiger–Müller tube to enable its operation. To stop the discharge in the Geiger–Müller tube a little halogen gas or organic material (alcohol) is added to the gas mixture.

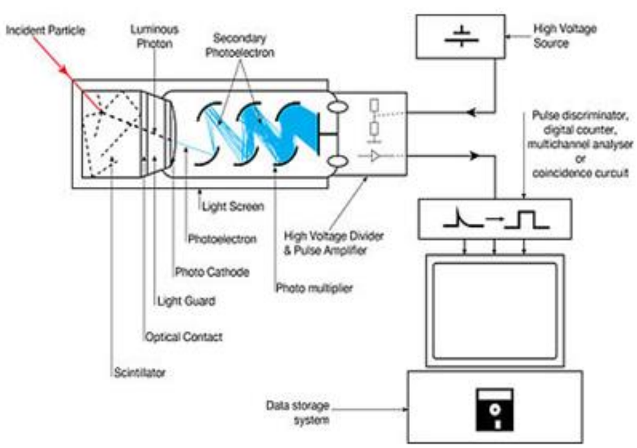


Scintillation Counter

A scintillation counter is an instrument for detecting and measuring ionizing radiation by using the excitation effect of incident radiation on a scintillating material, and detecting the resultant light pulses.It consists of a scintillator which generates photons in response to incident radiation, a sensitive photodetector (usually a photomultiplier tube (PMT), a charge-coupled device (CCD) camera, or a photodiode), which converts the light to an electrical signal and electronics to process this signal.

Principle of Operation

When an ionizing particle passes into the scintillator material, atoms are excited along a track. For charged particles the track is the path of the particle itself. For gamma rays (uncharged), their energy is converted to an energetic electron via either the photoelectric effect, Compton scattering or pair production. The chemistry of atomic de-excitation in the scintillator produces a multitude of low-energy photons, typically near the blue end of the visible spectrum. The quantity is proportional to the energy deposited by the ionizing particle. These can be directed to the photocathode of a photomultiplier tube which emits at most one electron for each arriving photon due to the photoelectric effect



SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

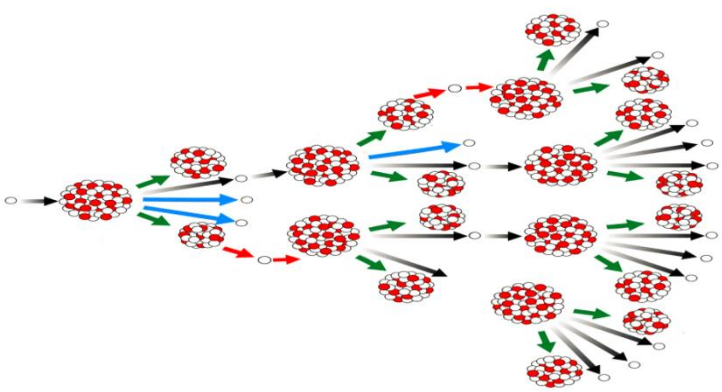
UNIT – III - NUCLEAR FISSION – SPHA5401

NUCLEAR FISSION

An Overview

In nuclear physics and nuclear chemistry, nuclear fission is a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into two or more smaller, lighter nuclei.

Nuclear chain reaction occurs when one single nuclear reaction causes an average of one or more subsequent nuclear reactions, thus leading to the possibility of a self-propagating series of these reactions. The specific nuclear reaction may be the fission of heavy isotopes.



Four Factor Formula

The four-factor formula, also known as Fermi's **four factor formula** is used in nuclear engineering to determine the multiplication of a nuclear chain reaction in an infinite medium.

The multiplication factor, k, is defined as (see Nuclear chain reaction):

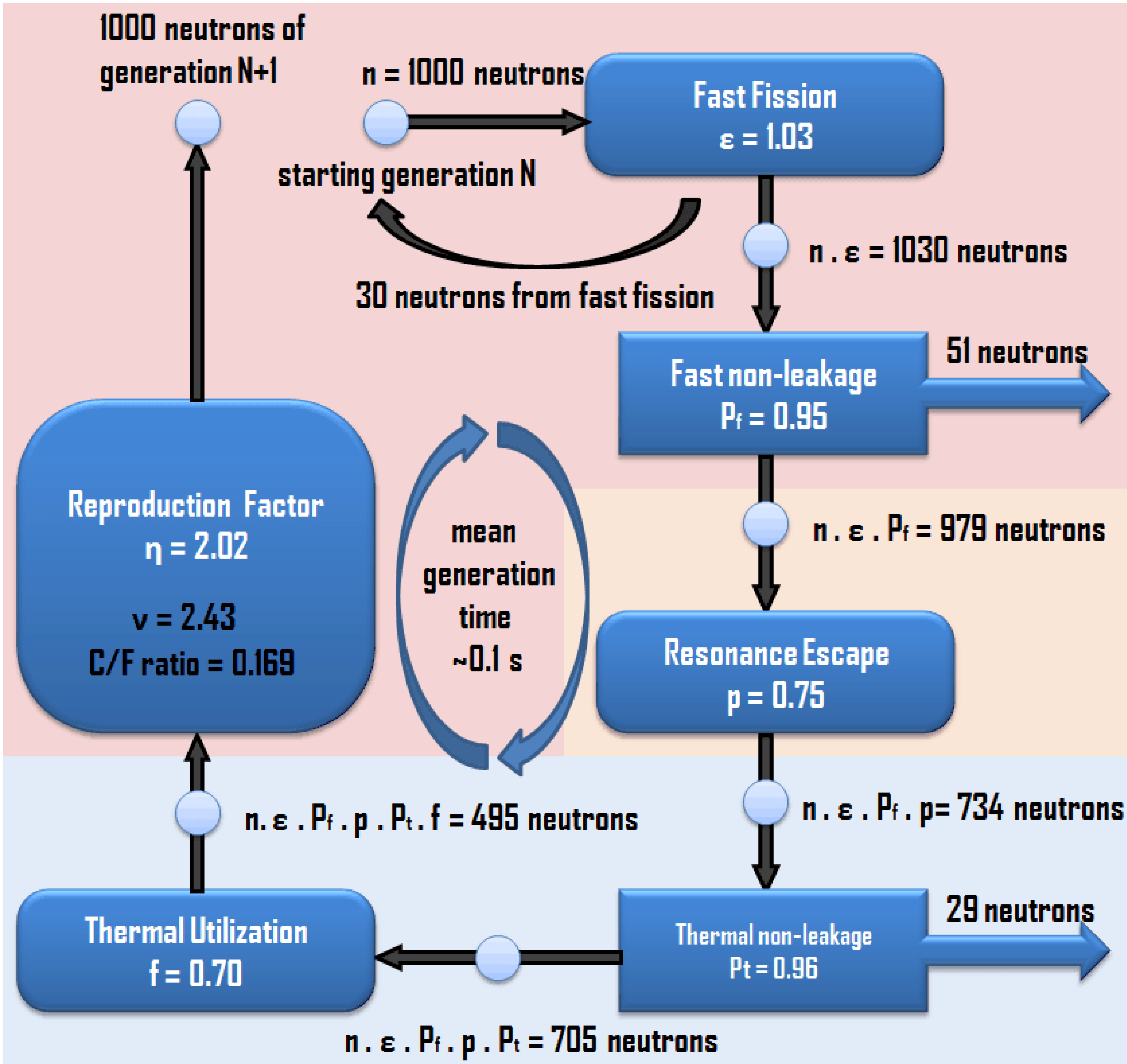
k = neutron population following nth generation neutron population during nth generation

If k is greater than 1, the chain reaction is supercritical, and the neutron population will grow exponentially.

If k is less than 1, the chain reaction is subcritical, and the neutron population will exponentially decay.

If k = 1, the chain reaction is critical and the neutron population will remain constant.

In an infinite medium, neutrons cannot leak out of the system and the multiplication factor becomes the infinite multiplication factor, k which is approximated by the four-factor formula.



The infinite multiplication factor is derived based on the assumption of no neutrons leak out of the reactor (i.e. a reactor is infinitely large). But in reality, each nuclear reactor is finite and neutrons can leak out of the reactor core. The multiplication factor that takes neutron leakage into account is the effective multiplication factor – k_{eff}, which is defined as the ratio of the neutrons produced by fission in one neutron generation to the number of neutrons lost through absorption and leakage in the preceding_neutron generation.The effective multiplication factor (k_{eff}) may be expressed mathematically in terms of the infinite multiplication factor (k_∞) and two additional factors which account for neutron leakage during neutron thermalisation (fast non-leakage probability) and neutron leakage during neutron diffusion (thermal non-leakage probability) by following equation, usually known as the six factor formula:

$$k_{eff} = k_\infty . P_f . P_t$$

Nuclear Reactor

Nuclear reactor physics is the branch of science that deals with the study and application of chain reaction to induce a controlled rate of fission in a nuclear reactor for the production of energy.[1] Most nuclear reactors use a chain reaction to induce a controlled rate of nuclear fission in fissile material, releasing both energy and free neutrons. A reactor consists of an assembly of nuclear fuel (a reactor core), usually surrounded by a neutron moderator such as regular water, heavy water, graphite, or zirconium hydride, and fitted with mechanisms such as control rods that control the rate of the reaction.

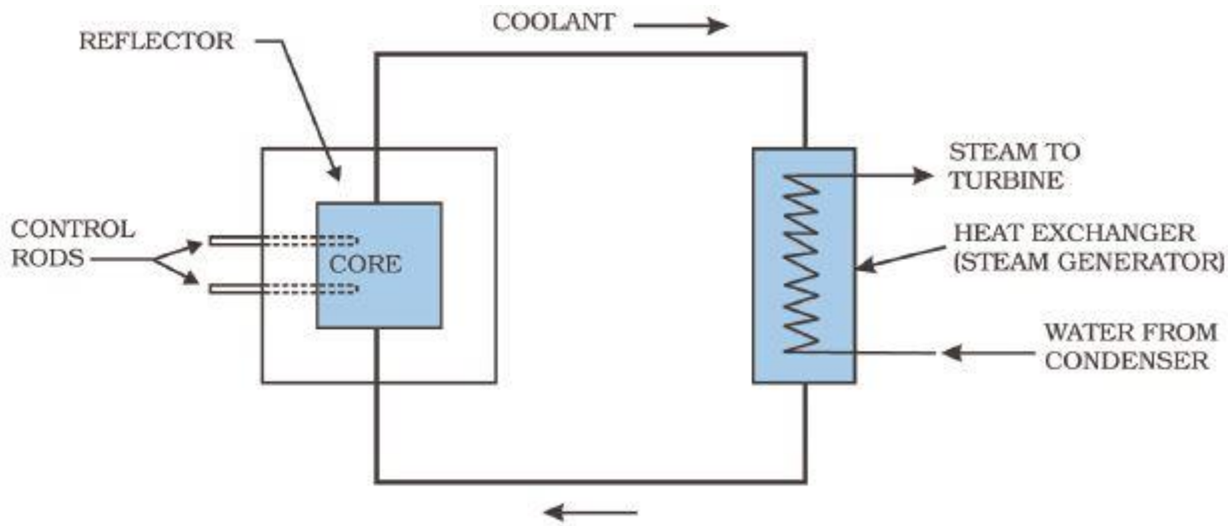
The physics of nuclear fission has several quirks that affect the design and behavior of nuclear reactors

Principle: It works on the principle of achieving controlled chain reaction of Uranium 238U enriched with 235U and as a result generating huge amount of energy. The controlled chain is made possible by :

- slowing down the fission neutrons to thermal neutrons by using a moderator.
- inserting rods that can absorb neutrons(control rods) and use them to maintain the reaction rate.

Working:
Clearly explained in the image.

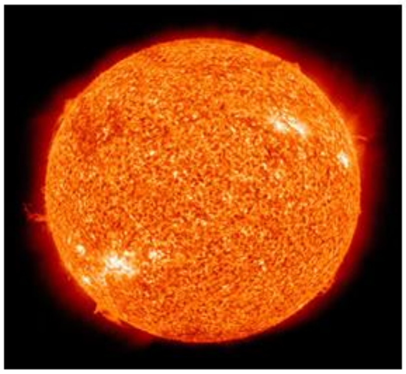
- In general the fuel used is 235U which is filled in aluminium cylindrical rod.
- The moderator used are D2O heavy water, salt water and graphite block.
- The materials like Beryllium and Cadmium rods are used as control rods which controls the chain reaction by absorbing the neutron emitted in the nuclear reaction.
- Cold water is circulated through the water pipes surrounding ht nuclear reactor to absorb heat.



Nuclear Fusion

Nuclear fusion is a reaction in which two or more atomic nuclei are combined to form one or more different atomic nuclei and subatomic particles (neutrons or protons). The difference in mass between the reactants and products is manifested as either the release or absorption of energy. This difference in mass arises due to the difference in atomic "binding energy" between the atomic nuclei before and after the reaction.

Fusion is the process that powers active or "main sequence" stars, or other high magnitude stars.



Fusion In Stars

An important fusion process is the stellar nucleosynthesis that powers stars and the Sun. In the 20th century, it was recognized that the energy released from nuclear fusion reactions accounted for the longevity of stellar heat and light. The fusion of nuclei in a star, starting from its initial hydrogen and helium abundance, provides that energy and synthesizes new nuclei as a byproduct of the fusion process. Different reaction chains are involved, depending on the mass of the star (and therefore the pressure and temperature in its core).Around 1920, Arthur Eddington anticipated the discovery and mechanism of nuclear fusion processes in stars. A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus. Nucleus in turn produces neutrons, and the process repeats. The process may be controlled (nuclear power) or uncontrolled (nuclear weapons).

Thermo Nuclear Reaction

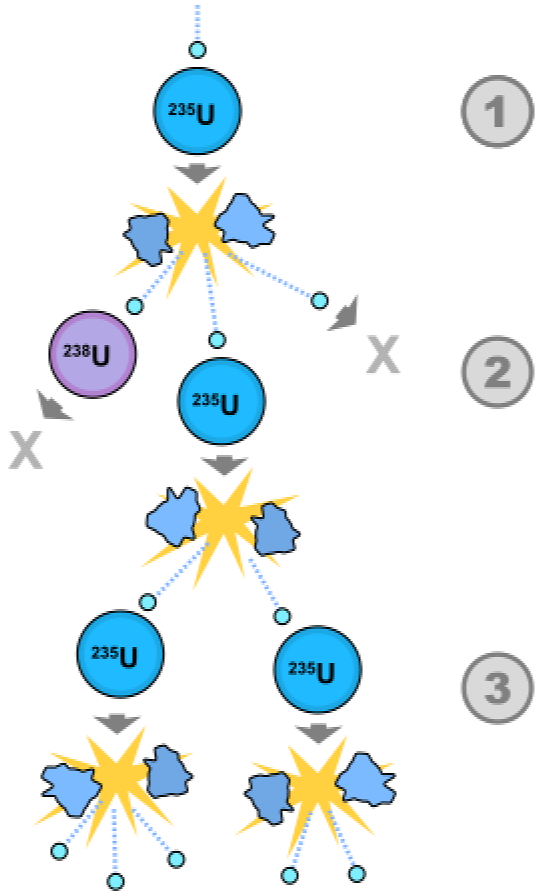
Thermonuclear reactions occurring in the Sun (thermonuclear fusion of deuterium and tritium) are the source of solar energy. Because of those reactions, the temperature of the Sun's core is at the level of 10^7 K. Density of the Sun's core is approximately 100 times higher than that of water. The Sun consists approximately of 80% hydrogen and 20% helium; other elements constitute only 0.1%. Thermonuclear fusion reactions occurring in the Sun have been, and still remain, a subject of multiple research studies. It is believed that a similar process could be replicated in a controlled manner on the Earth, thus helping to solve our energy demand problems. During the fusion process, four hydrogen nuclei (protons ^{1}p) form single helium nucleus (alpha particle $^4\alpha$). An alpha particle consists of two neutrons ^{1}n and two positively charged protons ^{1}p. Moreover, each such reaction releases two positrons e^+ and two neutrinos ν_e as well as energy. Thermonuclear fusion reaction in its entirety is described by the equation

Chain Reaction

Nuclear chain reaction occurs when one single nuclear reaction causes an average of one or more subsequent nuclear reactions, thus leading to the possibility of a self-propagating series of these reactions. The specific nuclear reaction may be the fission of heavy isotopes (e.g., uranium-235, ^{235}U). The nuclear chain reaction releases several million times more energy per reaction than any chemical reaction.

- A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus.
- This nucleus in turn produces neutrons, and the process repeats.

- The process may be controlled (nuclear power) or uncontrolled (nuclear weapons).



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SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

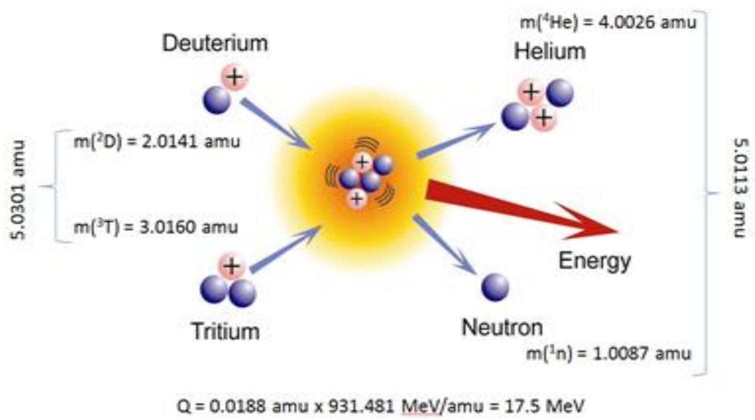
UNIT – IV - NUCLEAR REACTIONS – SPHA5401

NUCLEAR REACTIONS

An Overview

In nuclear physics and nuclear chemistry, a nuclear reaction is semantically considered to be the process in which two nuclei, or else a nucleus of an atom and a subatomic particle from outside the atom, collide to produce one or more nuclides that are different from the nuclide that began the process.

In nuclear and particle physics the energetics of nuclear reactions is determined by the Q-value of that reaction. The Q-value of the reaction is defined as the difference between the sum of the masses of the initial reactants and the sum of the masses of the final products, in energy units (usually in MeV). Consider a typical reaction, in which the projectile a and the target A gives place to two products, B and b. This can also be expressed in the notation that we used so far, a + A → B + b, or even in a more compact notation, A(a,b)B.



Q Value Energetics of Nuclear Reaction

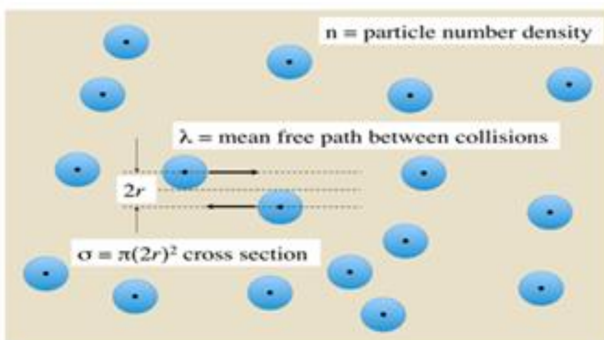
For reactions in which there is an increase in the kinetic energy of the products Q is positive. The positive Q reactions are said to be exothermic (or exergic). There is a net release of energy, since the kinetic energy of the final state is greater than the kinetic energy of the initial state.

For reactions in which there is a decrease in the kinetic energy of the products Q is negative. The negative Q reactions are said to be endothermic (or endoergic) and they require a net energy input

Nuclear Cross Section

The cross section is a measure of probability that a specific process will take place in a collision of two particles. For example, the Rutherford cross-section is a measure of probability that an alpha-particle will be deflected by a given angle during a collision with an atomic nucleus; the absorption cross-section of a black hole is a measure of probability that a particle will be absorbed during a collision with the black hole. Cross section is typically denoted σ (sigma) and is expressed in terms of the transverse area that the incident particle must hit in order for the given process to occur.

When two particles interact, their mutual cross section is the area transverse to their relative motion within which they must meet in order to scatter from each other. If the particles are hard inelastic spheres that interact only upon contact, their scattering cross section is related to their geometric size. If the particles interact through some action-at-a-distance force, such as electromagnetism or gravity, their scattering cross section is generally larger than their geometric size. When a cross section is specified as a function of some final-state variable, such as particle angle or energy, it is called a differential cross section. When a cross section is integrated over all scattering angles (and possibly other variables), it is called a total cross section.



Validity of Born Approximation: Note that the first Born's Approximation is valid when scattered wave is very little Different from incident wave.
We know,

$$\boxed{\psi(\vec{r}) = \phi_{inc}(\vec{r}) - \frac{\mu}{2\pi\hbar^2}\int \frac{e^{ik|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} V(\vec{r}\,')\psi(\vec{r}\,')\, d^3r'.}$$

The first Born approximation is valid if

$$\left|\frac{\mu}{2\pi\hbar^2}\int \frac{e^{ik|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} V(r')e^{i\vec{k}_0\cdot\vec{r}\,'}\, d^3r'\right| \ll |\phi_{inc}(\vec{r})|^2 .$$

----------(21)

Since $\phi_{inc} = e^{i\vec{k}_0\cdot\vec{r}}$ we have

$$\left|\frac{\mu}{2\pi\hbar^2}\int \frac{e^{ik|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} V(r')e^{i\vec{k}_0\cdot\vec{r}\,'}\, d^3r'\right| \ll 1. \qquad \text{-------(22)}$$

In elastic scattering $k_0 = k$ and assuming that the scattering potential is largest near $r = 0$, we have

$$\left|\frac{\mu}{\hbar^2}\int_0^\infty r'e^{ik\vec{r}\,'}V(r')\,dr'\int_0^\pi e^{ikr'\cos\theta'}\sin\theta' d\theta'\right| \ll 1,$$

$$\boxed{\frac{\mu}{\hbar^2 k}\left|\int_0^\infty V(r')\left(e^{2ikr'}-1\right)\,dr'\right| \ll 1.} \qquad \text{------(23)}$$

Now note that the energy of incident particle is $E_i = \hbar^2 k^2 / 2\mu$ which is directly proportional to momentum k.

Keeping in mind this line and looking back into Eq. (23), we observe that the first Born approximation is valid for large incident energies and weak scattering potentials.

When the interaction energy between incident particle and scattering potential is much smaller than the particle's incident kinetic energy the scattered wave can be considered as plane wave

Scattering from a Screened Coulomb Potential

- A standard Born approximation example is Rutherford Scattering, that is, Coulomb scattering of a particle of charge in a screened Coulomb potential. The exponential represents the screening of the nuclear charge by atomic electrons. Without screening, the total Coulomb scattering cross section is infinite because the range of the force in infinite.The potential energy then is

$$V(r) = \frac{Z_1 Z_2 e^2}{r} e^{-r/a}$$

We need to calculate its Fourier Transform.

$$\tilde{V}(\vec{\Delta}) = Z_1 Z_2 e^2 \int d^3 r e^{-i\vec{\Delta}\cdot\vec{r}} \frac{e^{-r/a}}{r}$$

Since the potential has spherical symmetry, we can choose

$$
\begin{aligned}
\tilde{V}(\vec{\Delta}) &= Z_1 Z_2 e^2 2\pi \int_0^\infty r^2 dr \int_{-1}^{1} d(\cos\theta) e^{-i\Delta r\cos\theta} \frac{e^{-r/a}}{r} \\
&= Z_1 Z_2 e^2 2\pi \int_0^\infty r^2 dr \left[\frac{e^{-i\Delta r x}}{-i\Delta r}\right]_{x=-1}^{x=1} \frac{e^{-r/a}}{r} \\
&= Z_1 Z_2 e^2 \frac{2\pi}{i\Delta} \int_0^\infty dr \left[e^{-i\Delta r} - e^{i\Delta r}\right] e^{-r/a} \\
&= Z_1 Z_2 e^2 \frac{2\pi}{-i\Delta} \int_0^\infty dr \left[e^{-(\frac{1}{a}+i\Delta)r} - e^{-(\frac{1}{a}-i\Delta)r}\right] \\
&= Z_1 Z_2 e^2 \frac{2\pi}{-i\Delta} \left[-\frac{e^{-(\frac{1}{a}+i\Delta)r}}{\frac{1}{a}+i\Delta} + \frac{e^{-(\frac{1}{a}-i\Delta)r}}{\frac{1}{a}-i\Delta}\right]_0^\infty \\
&= Z_1 Z_2 e^2 \frac{2\pi}{-i\Delta} \left[\frac{1}{\frac{1}{a}+i\Delta} - \frac{1}{\frac{1}{a}-i\Delta}\right] \\
&= Z_1 Z_2 e^2 \frac{2\pi}{-i\Delta} \left[\frac{\frac{1}{a}-i\Delta-\frac{1}{a}-i\Delta}{\frac{1}{a^2}+\Delta^2}\right] \\
&= Z_1 Z_2 e^2 \frac{2\pi}{-i\Delta} \left[\frac{-2i\Delta}{\frac{1}{a^2}+\Delta^2}\right] \\
&= \frac{4\pi Z_1 Z_2 e^2}{\frac{1}{a^2}+\Delta^2}
\end{aligned}
$$

Since $\vec{\Delta} = \vec{k}_f - \vec{k}_i$ we have

$$\Delta^2 = k_f^2 + k_i^2 - 2k_f k_i \cos\theta$$

For elastic scattering, $\Delta^2 = 2k^2(1 - \cos\theta)$

The differential cross section is

$$\begin{aligned}
\frac{d\sigma}{d\Omega} &= \frac{\mu^2}{4\pi^2\hbar^4}\left|\tilde{V}(\vec{\Delta})\right|^2 \\
&= \frac{\mu^2}{4\pi^2\hbar^4}\left|\frac{4\pi Z_1 Z_2 e^2}{\frac{1}{a^2} + 2k^2(1 - \cos\theta)}\right|^2 \\
&= \left|\frac{\mu Z_1 Z_2 e^2}{\frac{\hbar^2}{2a^2} + p^2(1 - \cos\theta)}\right|^2 \\
&= \left|\frac{Z_1 Z_2 e^2}{\frac{\hbar^2}{2\mu a^2} + 4E\sin^2\frac{\theta}{2}}\right|^2
\end{aligned}$$

The screened Coulomb potential gives a finite total cross section. It corresponds well with the experiment Rutherford did in which particles were scattered from atoms in a foil. If we scatter from a bare charge where there is no screening, we can take the limit in which

$a \to \infty$

$$\left| \frac{Z_1 Z_2 e^2}{4E \sin^2 \frac{\theta}{2}} \right|^2$$

The total cross section diverges in due to the region around zero scattering angle.

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DEPARTMENT OF PHYSICS

UNIT – V - ELEMENTARY PARTICLES – SPHA5401

ELEMENTARY PARTICLES

An Overview

In particle physics, an elementary particle or fundamental particle is a subatomic particle with no sub structure, thus not composed of other particles.

Almost each elementary particle has an antiparticle, that has the same mass, but the electric charge of an opposite sign (e□ and e^{+}, electron and positron).When a particle and its antiparticle come together, they destroy each other (annihilation). The lost mass reappears as energy in the form of □ rays.

Fundamentals Forces in Nature

Strong Force

- Short range ~ 10^{-15} m (1 fermi)
- Responsible for binding of quarks into neutrons and protons
- Gluon

• Electromagnetic Force

- 10^{-2} as strong as strong force
- $1/r^2$ force law
- Binding of atoms and molecules
- Photon

• Weak force

- ~ 10^{-6} times as strong as the strong force
- Responsible for beta decay, very short range ~10^{-18} m
- W^+, W^- and Z^0 bosons

• Gravitational Force

- 10^{-43} times as strong as the strong force
- Also $1/r^2$ force law

– Graviton

Particle Classification

Hadrons (strong force interaction, composed of quarks)

– We already met the mesons (middle weights)

• Decay into electrons, neutrinos and photons

– Baryons, i.e. the proton and neutron (the **heavy** particles)

– Still other more exotic baryons:

• L, S, X, □ all are heavier than the proton

• Decay into end products that include a proton

- Leptons
  - Small or light weight particles
  - Are point like particles – no internal structure (yet)
  - 6 leptons
  - Electron e, muon μ, tau τ
  - and their associated neutrinos: ν_e, ν_μ, ν_τ
  - Also, their antiparticles
  - Neutrinos have tiny mass, ~3 eV/c^2

In Physics we have conservation of energy, momentum (linear and angular), charge, spin. Now we add more to help balance particle reactions

• **Baryon number**:

– B = +1 for baryons, -1 for anti-baryons

– Eg. Proton, neutron have B = +1

– antiparticles have B = -1

– B = 0 for all other particles (non-baryons) Lepton number

– L = +1 for leptons, -1 for anti-leptons

– L = 0 for non-leptons

- Example for electrons:
- Electron e, electron neutrino n_e have L_e = +1
- Anti electron and antineutrino have L_e = -1
- Other leptons have L_e = 0 **BUT** have their own lepton numbers, L_m, L_t

Baryon Conservation

In low-energy nuclear reactions, the number of nucleons is always conserved. Empirically this is part of a more general conservation law for what is assigned a new quantum number called *baryon number* that has the value $B = +1$ for baryons and −1 for antibaryons, and 0 for all other particles.*The conservation of baryon number requires the same total baryon number before and after the reaction*.

Although there are no known violations of baryon conservation, there are theoretical indications that it was violated sometime in the beginning of the universe when temperatures were quite high. This is thought to account for the preponderance of matter over antimatter in the universe today.

Lepton Conservation

The leptons are all fundamental particles, and *there is a conservation of leptons for **each** of the three kinds (families) of leptons*. *The number of leptons from each family is the same both before and after a reaction.* We let $L_e = +1$ for the electron and the electron neutrino; $L_e = -1$ for their antiparticles; and $L_e = 0$ for all other particles. We assign the quantum numbers L_μ for the muon and its neutrino and L_τ *for the tau and its neutrino similarly*.

Strangeness

- Thus three additional conservation laws. In the early 1950s physicists had considerable difficulty understanding the myriad of observed reactions and decays. For example, the behavior of the K mesons seemed very odd.
- There is no conservation law for the production of mesons, but it appeared that K mesons, as well as the Λ and Σ baryons, were always produced in pairs in the proton reaction studied most often, namely the $p + p$ reaction.
- In addition, the very fast decay of the π^0 meson into two photons (10^{-16} s) is the preferred mode of decay.
- One would expect the K^0 meson to also decay into two photons very quickly, but it does not. The long and short decay lifetimes of the K^0 are 10^{-8} and 10^{-10} s, respectively.

- *Strangeness*, *S*, is conserved in the strong and electromagnetic interactions, but not in the weak interaction.
- The kaons have $S = +1$, lambda and sigmas have $S = -1$, the xi has $S = -2$, and the omega has $S = -3$.
- When the strange particles are produced by the $p + p$ strong interaction, they must be produced in pairs to conserve strangeness. Several particles found to have unusual (strange) properties:
- Always produced in pairs
- $p^- + p^+$ □ $K^0 + L^0$ *but not* $p^- + p^+$ □ $K^0 + n$
- Decay is slow (indicative of weak interaction rather than strong) Half-lives of order of 10^{-10} to 10^{-8} sec
- Members of the strange club: K, L, S

Isospin

It was discovered that particles with

approximately the same mass, and the same

(ordinary) spin existed in "charge multiplets":

p and **n** □ $I_3 = ½, - ½$ (a doublet)

$\prod^+$ $\prod^-$ $\prod^{\mathbf{0}}$ □ $I_3 = 1, -1, 0$ (a triplet)

number of states = 2I +1

Hypercharge

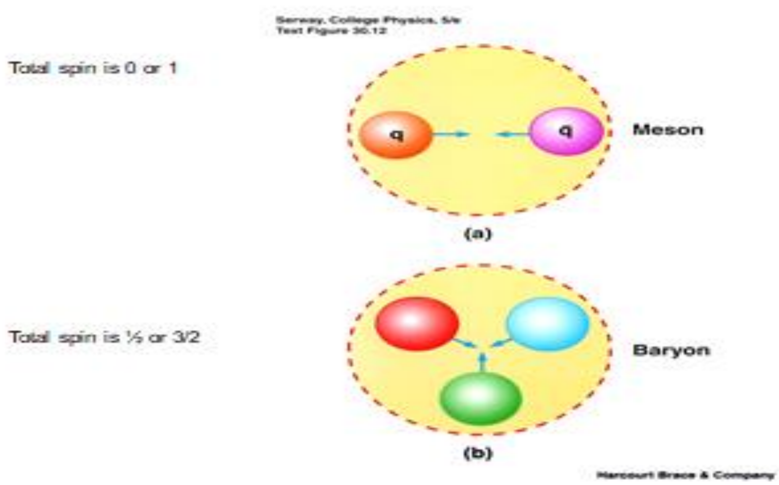
- One more quantity, called **hypercharge**, has also become widely used as a quantum number.
- The hypercharge quantum number *Y* is defined by $Y = S + B$.
- Hypercharge, the sum of the strangeness and baryon quantum numbers, is conserved in strong interactions.
- The hypercharge and strangeness conservation laws hold for the strong and electromagnetic interactions, but are violated for the weak interaction.

Quark Model

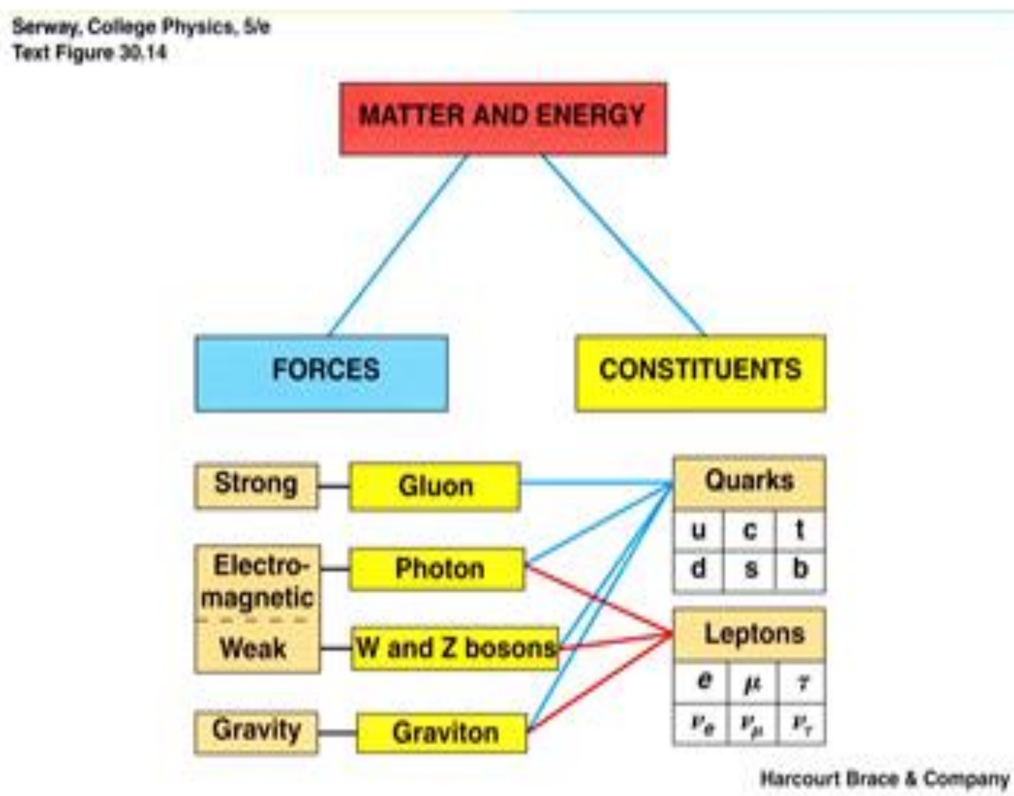
- Gell-Mann (1961) proposed hadrons have structure, i.e. composed of a more fundamental type of particle.
- Quarks have fractional charge e/3 or 2e/3
- Three types u, d, s: up, down, strange
- Mesons were made of 2 quarks: q, q
- Baryons were made of 3 quarks
- Soon after, experimental discrepancies required the addition of three more quarks

  Top, bottom and charm: t, b, c ,and three more conservation laws: C, B, T for charm, bottomness and topness

Quarks combinations with color



The Standard Model



Symmetry Operation

Many of the profound ideas in nature manifest themselves as symmetries. A symmetry in a physical experiment suggests that something is conserved, or remains constant, during the experiment. So conservation laws and symmetries are strongly linked.

Three of the symmetries which usually, but not always, hold are those of charge conjugation (C), parity (P), and time reversal (T):

Charge Conjugation: reversing the electric charge and all the internal quantum numbers.

Parity: space inversion; reversal of the space coordinates, but not the time.

Time Reversal: replacing t by -t. This reverses time derivatives like momentum and angular momentum.

Conservation laws for parity, isopin, and strangeness have been developed by detailed observation of particle interactions. The combination of charge conjugation (C), parity (P) and time reversal (T) is considered to be a fundamental symmetry operation - all physical particles and interactions appear to be invariant under this combination. Called CPT invariance, this symmetry plumbs the depths of our understanding of nature.

CPT Invariance

Associated with the conservation laws which govern the behavior of physical particles, charge conjugation (C), parity (P) and time reversal (T) combine to constitute a fundamental symmetry called CPT invariance.

The strong and electromagnetic interactions leave systems invariant under any of the three operations applied alone, but the weak interaction does not.

The beta decay of cobalt-60 established the violation of parity in 1957, and led to our understanding that the weak interaction violates both charge conjugation and parity invariance.

However, the weak interaction does appear to leave systems invariant under the combination CP.

Examination of the case of the neutrino is instructive at this point. The parity operation on a neutrino would leave its spin in the same direction while reversing space coordinates.

Neither of these things is observed to happen in nature; neutrinos are always left-handed, anti-neutrinos always right-handed.

But if you add the charge conjugation operation, the result of the combined operation gives you back the original particle.

CP invariance was thought to be a general conservation principle until the details of the neutral kaon decay process were examined by Cronin and Fitch. After intense study over many years, the consensus is that CP is violated by a small amount. In 2001 CP violation was confirmed in B-meson decay.

The small violation of CP symmetry suggests some departure from T symmetry in some weak interaction processes since CPT invariance seems to be on very firm ground.

Charge Congugation

Associated with the conservation laws which govern the behavior of physical particles, charge conjugation (C), parity (P) and time reversal (T) combine to constitute a fundamental symmetry calledCPTINVARIANCE.

It also involves reversing all the internal quantum numbers like those for lepton number, baryon number and strangeness.

Thinking of charge conjugation as an operator, C, then electromagnetic processes are invariant under the C operation since Maxwell's equations are invariant under C.

This restricts some kinds of particle processes. Das and Ferbel proceed by defining a charge parity of $\eta_C(\gamma) = -1$ for a photon since the C operation reverses the electric field.

This constrains the electromagnetic decay of a neutral particle like the π^0. The decay of the π^0 is:
$\pi^0 \rightarrow \gamma + \gamma$

This implies that the charge parity or behavior under charge conjugation for a π^0 is:
$\eta_C(\pi^0) = \eta_C(\gamma)\eta_C(\gamma) = (-1)^2 = +1$
Charge conjugation symmetry would imply that the π^0 will not decay by
$\pi^0 \rightarrow \gamma$ which we already know because it can't conserve momentum, but the decay
$\pi^0 \rightarrow \gamma + \gamma + \gamma$ can conserve momentum. This decay cannot happen because it would violate charge conjugationsymmetry.
While the strong and electromagnetic interactions obey charge conjugation symmetry, the weak interaction does not. As an example, neutrinos are found to have intrinsic parities: neutrinos have left-handed parity and antineutrinos right-handed. Since charge conjugation would leave the spatial coordinates untouched, then if you operated on a neutrino with the C operator, you would produce a left-handed antineutrino. But there is no experimental evidence for such a particle; all antineutrinos appear to be right-handed. The combination of the parity operation P and the charge conjugation operation C on a neutrino do produce a right-handed antineutrino, in accordance with observation. So it appears that while beta decay does not obey parity or charge conjugation symmetry separately, it is invariant under the combination CP

Conservation of Parity

- The conservation of parity *P* describes the inversion symmetry of space,

  Inversion, if valid, does not change the laws of physics.

- The conservation of parity is valid for the strong and electromagnetic interactions, but not in the weak interaction (experimentally).

Time Reversal

- Here time *t* is replaced with *–t*.
- When all three operations are performed (*CPT*), where *T* is the time reversal symmetry, conservation holds.
- We speak of the *invariance* of the symmetry operators, such as *T*, *CP*, and *CPT*.

Quarks

Quarks and Leptons are the building blocks which build up matter, i.e., they are seen as the "elementary particles".

In the present standard model, there are six "flavors" of quarks. They can successfully account for all known mesons and baryons (over 200).

The most familiar baryons are the proton and neutron, which are each constructed from up and down quarks. Quarks are observed to occur only in combinations of two quarks (mesons), three quarks (baryons). There was a recent claim of observation of particles with five quarks (pentaquark), but further experimentation has not borne it out.

*The masses should not be taken too seriously, because the confinement of quarks implies that we cannot isolate them to measure their masses in a direct way.

The masses must be implied indirectly from scattering experiments.

Types of Quarks

The up and down quarks are the most common and least massive quarks, being the constituents of protons and neutrons and thus of most ordinary matter

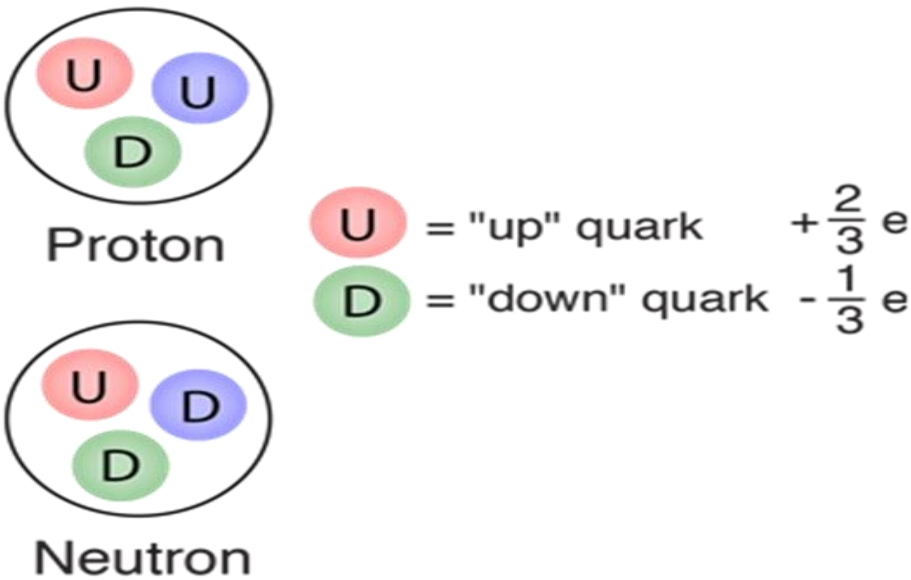
The Strange Quark

In 1947 during a study of cosmic ray interactions, a product of a proton collision with a nucleus was found to live for a much longer time than expected: 10^{-10} seconds instead of the expected 10^{-23} seconds! This particle was named the lambda particle (Λ^0) and the property which caused it to live so long was dubbed "strangeness" and that name stuck to be the name of one of the quarks from which the lambda particle is constructed. The lambda is a baryon which is made up of three quarks: an up, a down and a strange quark.

The shorter lifetime of 10^{-23} seconds was expected because the lambda as a baryon participates in the strong interaction, and that usually leads to such very short lifetimes. The long observed lifetime helped develop a new conservation law for such decays called the "conservation of strangeness". The presence of a strange quark in a particle is denoted by a quantum number S=-1. Particle decay by the strong or electromagnetic interactions preserve the strangeness quantum number. The decay process for the lambda particle must violate that rule, since there is no lighter particle which contains a strange quark - so the strange quark must be transformed to another quark in the process. That can only occur by the weak interaction, and that leads to a much longer lifetime. The decay processes show that strangeness is not conserved:

TYPES OF QUARKS

Quark	Symbol	Spin	Charge	Baryon Number	S	C	B	T	Mass*
Up	U	1/2	+2/3	1/3	0	0	0	0	1.7-3.3 MeV
Down	D	1/2	-1/3	1/3	0	0	0	0	4.1-5.8 MeV
Charm	C	1/2	+2/3	1/3	0	+1	0	0	1270 MeV
Strange	S	1/2	-1/3	1/3	-1	0	0	0	101 MeV
Top	T	1/2	+2/3	1/3	0	0	0	+1	172 GeV
Bottom	B	1/2	-1/3	1/3	0	0	-1	0	4.19 GeV(MS) 4.67 GeV(1S)



The Top Quark

Convincing evidence for the observation of the top quark was reported by Fermilab 's Tevatron facility in April 1995. The evidence was found in the collision products of 0.9 TeV protons with equally energetic antiprotons in the proton-antiproton collider. The evidence involved analysis of trillions of 1.8 TeV proton-antiproton collisions. The Collider Detector Facility group had found 56 top candidates over a predicted background of 23 and the D0 group found 17 events over a predicted background of 3.8. The value for the top quark mass from the combined data of the two groups after the completion of the run was 174.3 +/- 5.1 GeV. This is over 180 times the mass of a proton and about twice the mass of the next heaviest fundamental particle, the Z0 vector boson at about 93

The Charm QuarkIn 1974 a meson called the J/Psi particle was discovered by experimenters at Stanford (Richter) and Brookhaven National Laboratory (Ting). With a mass of 3100 MeV, over three times that of the proton, this particle was the first example of another quark, called the charm quark. The J/Psi is made up of a charm-anticharm quark pair. Richter and Ting shared the 1976 Nobel Prize for their discovery.

The lightest meson which contains a charm quark is the D meson. It provides interesting examples of decay since the charm quark must be transformed into a strange quark by the weak interaction in order for it to decay.

One baryon with a charm quark is a called a lambda with symbol Λ+c. It has a composition udc and a mass of 2281 MeV/c2.

The Quark Triplet

- Gell-Mann and others proposed that one might build all the experimentally observed particles from just **three quarks**: the **up**, the **down** and the **strange**.
- One way to “build” the particles is to think of the quarks as vectors in a two dimensional “imagined” space with **Y** along the vertical axis and $\mathbf{I_3}$ along the horizontal axis.
- The quark triplet is shown on the next slide.

The Standard Model/ Gauge theory of weak and strong interactions

Fermions

Summary of interactions between particles described by the Standard Model

The Standard Model includes 12 elementary particles of spin 1⁄2, known as fermions. According to the spin–statistics theorem, fermions respect the Pauli exclusion principle. Each fermion has a corresponding antiparticle.

Extended breakdown of particle interactions in the Standard Model if the hypothetical graviton were to be included.

Fermions are classified according to how they interact (or equivalently, by what charges they carry). There are six quarks (up, down, charm, strange, top, bottom), and six leptons (electron, electron neutrino, muon, muon neutrino, tau, tau neutrino). Each class is divided into pairs of particles that exhibit a similar physical behavior called a generation (see the table).

The defining property of quarks is that they carry color charge, and hence interact via the strong interaction. The phenomenon of color confinement results in quarks being very strongly bound to one another, forming color-neutral composite particles called hadrons that contain either a quark and an antiquark (mesons) or three quarks (baryons). The lightest baryons are the proton and the neutron. Quarks also carry electric charge and weak isospin. Hence they interact with other fermions via electromagnetism and the weak interaction. The remaining six fermions do not carry color charge and are called leptons. The three neutrinos do not carry electric charge either, so their motion is directly influenced only by the weak nuclear force, which makes them notoriously difficult to detect. By contrast, by virtue of carrying an electric charge, the electron, muon, and tau all interact electromagnetically.

Each member of a generation has greater mass than the corresponding particles of lower generations. The first-generation charged particles do not decay, hence all ordinary (baryonic) matter is made of such particles. Specifically, all atoms consist of electrons orbiting around atomic nuclei, ultimately constituted of up and down quarks. On the other hand, second- and third-generation charged particles decay with very short half-lives and are observed only in very high-energy environments. Neutrinos of all generations also do not decay and pervade the universe, but rarely interact with baryonic matter.

Gauge bosons

The above interactions form the basis of the standard model. Feynman diagrams in the standard model are built from these vertices. Modifications involving Higgs boson interactions and neutrino oscillations are omitted. The charge of the W bosons is dictated by the fermions they interact with; the conjugate of each listed vertex (i.e. reversing the direction of arrows) is also allowed.

In the Standard Model, gauge bosons are defined as force carriers that mediate the strong, weak, and electromagnetic fundamental interactions.

Interactions in physics are the ways that particles influence other particles. At a macroscopic level, electromagnetism allows particles to interact with one another via electric and magnetic fields, and gravitation allows particles with mass to attract one another in accordance with Einstein's theory of general relativity. The Standard Model explains such forces as resulting from matter particles exchanging other particles, generally referred to as force mediating particles. When a force-mediating particle is exchanged, the effect at a macroscopic level is equivalent to a force influencing both of them, and the particle is therefore said to have mediated (i.e., been the agent of) that force. The Feynman diagram calculations, which are a graphical representation of the perturbation theory approximation, invoke "force mediating particles", and when applied to analyze high-energy scattering experiments are in reasonable agreement with the data. However, perturbation theory (and with it the concept of a "force-mediating particle") fails in other situations. These include low-energy quantum chromodynamics, bound states, and solitons.

The gauge bosons of the Standard Model all have spin (as do matter particles). The value of the spin is 1, making them bosons. As a result, they do not follow the Pauli exclusion principle that constrains fermions: thus bosons (e.g. photons) do not have a theoretical limit on their spatial density (number per volume). The types of gauge bosons are described below.

Photons mediate the electromagnetic force between electrically charged particles. The photon is massless and is well-described by the theory of quantum electrodynamics.

Boson interacts with both left-handed particles and antiparticles. These three gauge bosons along with the photons are grouped together, as collectively mediating the electroweak interaction.

The eight gluons mediate the strong interactions between color charged particles (the quarks). Gluons are massless. The eightfold multiplicity of gluons is labeled by a combination of color and anticolor charge (e.g. red–antigreen).[note 1] Because gluons have an effective color charge, they can also interact among themselves. Gluons and their interactions are described by the theory of quantum chromodynamics.

The interactions between all the particles described by the Standard Model are summarized by the diagrams on the right of this section.

Higgs boson

The Higgs particle is a massive scalar elementary particle theorized by Peter Higgs in 1964, when he showed that Goldstone's 1962 theorem (generic continuous symmetry, which is spontaneously broken) provides a third polarisation of a massive vector field. Hence, Goldstone's original scalar doublet, the massive spin-zero particle, was proposed as the Higgs boson, and is a key building block in the Standard Model. It has no intrinsic spin, and for that reason is classified as a boson (like the gauge bosons, which have integer spin).

The Higgs boson plays a unique role in the Standard Model, by explaining why the other elementary particles, except the photon and gluon, are massive. In particular, the Higgs boson explains why the photon has no mass, while the W and Z bosons are very heavy. Elementary-particle masses, and the differences between electromagnetism (mediated by the photon) and the weak force (mediated by the W and Z bosons), are critical to many aspects of the structure of microscopic (and hence macroscopic) matter. In electroweak theory, the Higgs boson generates the masses of the leptons (electron, muon, and tau) and quarks. As the Higgs boson is massive, it must interact with itself.

Because the Higgs boson is a very massive particle and also decays almost immediately when created, only a very high-energy particle accelerator can observe and record it.