Project Report

Elementary Particle Physics

Submitted By Shyam Kumar

Introduction

There is a fundamental question with which this area of physics started “what is the smallest part of matter?”. If we view the history of this area of physics we will find, this area of physics was quite puzzled. Initially it was believed that matter is made up of electrons, protons, neutrons and these all particles are considered to be the smallest part of matter which cannot be divided into smaller part, but now it is to be found that protons and neutrons are made up of smaller particles which we call quarks. Electrons are absolutely identical but there is no analogue of it in macroscopic world. Each fundamental particle is specified by charge, mass, spin etc. next question comes if we have the above fundamental particles “How they interact with one another and to make our macroscopic things?”. If you have two macroscopic object and you want to know their interaction, you would simply suspend them by string at various distances and will measure the force between them. By this method coulomb determined the law of electrical attraction and repulsion between two charged balls and Cavendish measured the law of gravitational attraction of two lead weights. For elementary particles there is a big problem we cannot tie them on the string because they are too small so we have to find different way for the study of their interaction. There are three experimental techniques by which we can get information about them: (1) scattering process, in which we fire one particle at another and measure the angle of deflection (2) radioactive decay in which particle spontaneously disintegrates and emits alpha, beta, gamma rays (3) bound states in which two or more particles bound together and we will study the properties of that composite object formed with particles. The above three experimental techniques is needless because determining the interaction law from such indirect evidence is a very difficult task. General procedure is to guess the form of interaction and do the theoretical calculations based on that guess and then match it with the experimental data if it matches then we say our guess is correct, if not we will do some improvement in our guess then again do the same process. The formulation of guess is called the model based on certain general principles, it will of special relativity and quantum mechanics because particles are so small and their velocity is very large. In the diagram below it is shown how the general principles (realm of mechanics) are used in Model.

Small ↑

Quantum Mechanics	Quantum Field Theory
Classical Mechanics	Relativistic Mechanics

→ Fast

Figure: four realms of mechanics

The world is macroscopic and is governed by laws of classical mechanics due to Newton but if the object is moving very fast as compare to the velocity of light these rules are modified by special relativity given by Einstein and for the object that is very small compare to the size of atom, but not moving very fast, classical mechanics is replaced by quantum mechanics, if the object is very small and moving very fast we will have to use a theory which uses the principles of relativity and quantum mechanics, which we call Quantum field theory. These are the general rules that are used in the formation of a model (guess).

If we can find the force between the particles by studying their interaction, then we can use mechanics to find the motion of particles. Hence the goal of elementary particle dynamics then is to guess the force laws which, incorporates with quantum field theory and correctly describes the particle behavior. However there are some general features which have nothing to do with the detailed form of interactions. Instead they follows directly from the principles of relativity or quantum mechanics or both. Now let us take the process $\Delta \rightarrow p + \pi$ is perfectly acceptable, since the mass of Δ is greater than the two particles present on right so it is not allowed classically where mass is strictly conserved . In relativity, principle of conservation of energy and momentum are always holds but rest mass not, in the above process conservation of energy and momentum holds, so this process is allowed relativistically. In classical mechanics idea of zero weight is acceptable but the idea of zero mass is meaningless but relativity allows the particle of zero rest mass, their mass may not be zero when they are moving as photons, neutrinos, and gluons all are mass less. In quantum field theory we have negative energy particles which we call antiparticles, that is not possible in classical mechanics. There are four types of forces in nature electromagnetic, weak , strong, and gravitational force. In the last few years a theory has developed that describes all of the known forces except gravity. Gravity plays very weak role in case of elementary particle processes. This theory is the collection of theories, quantum electrodynamics, theory of electroweak processes given Glashow-Weinberg- Salam , and quantum chromo dynamics is called “Standard Model”.

Production and Detection of elementary particles-

After the introduction about elementary particles, now we will study how to produce these particles. For electrons simply heat the metal, they come out. If beam of electrons is required then arrange anode near the metal to attract them, and cut a small hole in it, then electrons coming out from the hole will constitute electron beam this arrangement is known as electron gun. For proton simply ionize hydrogen atom. If you want to use proton as a target you need not worry about electron. A sea of hydrogen is essentially the sea of protons, for other particles, there are three main sources cosmic rays , particle accelerators and nuclear reactors. Cosmic rays comes from the outer space they are much energetic than the energy that we can produce in the lab but they are uncontrollable this is the main disadvantage for using it. The disintegration of a radioactive nucleus, gives alpha, beta and gamma rays and several other particles can also be produced by this method as neutrons, neutrinos etc., particle accelerators are used in modern time to produce heavier particles in which the particles are accelerated up to high energy then they collide and produce heavier particles. The two particle accelerators are SLAC(Stanford linear accelerator), LHC(large hadrons collider) are created for this purpose . In general if you want to produce heavy particle you need high energy according to Einstein mass energy relation (E $=mc^2$). This is why if we see the history of elementary particle physics, we find that light weight particles are discovered first and as the accelerators become powerful higher mass particles are discovered. Today the heaviest known particle is Z^0, its mass is approximately 100 times the mass of proton. Today peoples are interested in high energy physics because if energy will be high, colliding particles will be at much closer distance and we can study the short range interaction. If we want to probe small distances using a particle, then the de Broglie wavelength associated with the particle will be the order of that distance. Since $\lambda = h/p$, λ will be small if p is large that means to probe small distances we need of high energy.

How do we know that a particular particle is produced for this we need the particle detector. There are many particle detectors at present time as GM-counter, cloud chambers, bubble chambers, spark chambers , photographic emulsions , photomultipliers etc., modern detectors has the combination of all these and connected with a computer that tracks out the particles on computer screen. Much of the detection criteria are based on the fact when high energy charged particles passes through the matter they ionizes the matter along their path. Bubble chamber is also used for the detection of particles which is placed in between the poles of two giant magnet of magnetic field B, when a charged particle of enter in it perpendicular to magnetic field the it will move in to the circle of radius R. if m be the mass, v is the velocity of charge particle then

$$\frac{mv^2}{R} = qvB$$

$$R = mv/qB \qquad ; \quad \text{since} \quad p = mv$$

If we can measure the curvature of path experimentally, then we can calculate the momentum of particle, the sign of the charge can be calculated by using flemming's rule. The above formula is known as cyclotron formula.

ATLAS detector is present at CERN is for detecting Higgs boson, similarly PMD (photon multiplicity detector)is used for finding the multiplicity of photon.

Elementary Particles

History with explanation:

Elementary particle physics was born in 1897, with the discovery of electron by J.J. Thomson. He find that the cathode rays emitted by a hot filament could be deflected by magnet. From the direction of curve he find these rays carries negative charge. Thomson called these particles corpuscles, and their charge the electron, later electron was used for both corpuscles and charge also. Since atom is much heavier than electron and as a whole neutral, Thomson give a model for the atom, he said atom is a positive sphere in which electrons are putted like the plums in the pudding, his model is known as plums pudding model which was rejected after the experiment of Rutherford of scattering of alpha particles by gold foil. Rutherford's experiment implies that much of the part of the atom is hollow and something very heavy, hard putted at the center of the atom he called it the nucleus, it has positive charge, and approximately whole of the mass. Rutherford experimental set us is shown below:

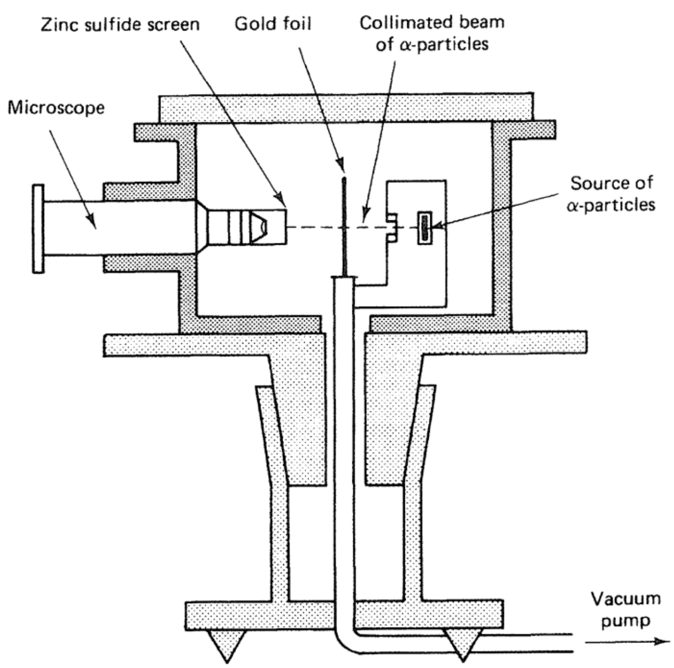


Figure: Rutherford experimental setup of scattering of α particles by gold foil.

The nucleus of the lightest atom (hydrogen) was given the name proton by Rutherford. In 1932 James Chadwick discovered neutron- an electrical twin of proton. A nitrogen atom consists of 7 protons, 7 electrons and 7 neutrons. In 1932 it was believed that matter is made of protons, neutrons and electrons.

Next elementary particle discovered is photon in the discovery of it the first contribution was made by Planck in 1900. Planck was attempting to explain Blackbody spectrum for the electromagnetic radiation emitted by hot object. He found that he could escape the ultraviolet catastrophe by assuming electromagnetic radiations quantized i.e.

$$\mathcal{E} = nh\nu$$

where n is a positive integer, h is Planck constant; $h = 6.626$ x 10^{-34} joule-second. Planck did not profess to know why radiation was quantized. Einstein in 1905 argued that quantization is the feature of electromagnetic field itself. Using Planck idea Einstein explained the phenomenon of photoelectric effect and He got the Nobel Prize for it. He said that when light falls on metallic surface, electrons comes out the metallic surface, the energy of coming electron depends on the energy of light quanta and on work function of metal(work function is fixed for a metal). So the energy of coming electron:

$$\varepsilon \leq h\nu - w$$

hence in this way photon is discovered, there is another phenomena Compton effect is also explained after the discovery of photon. In this phenomena a photon strikes on the free or loosely bound electron, after the scattering photon is gone with less energy and electron is recoiled. The diagram is shown below:

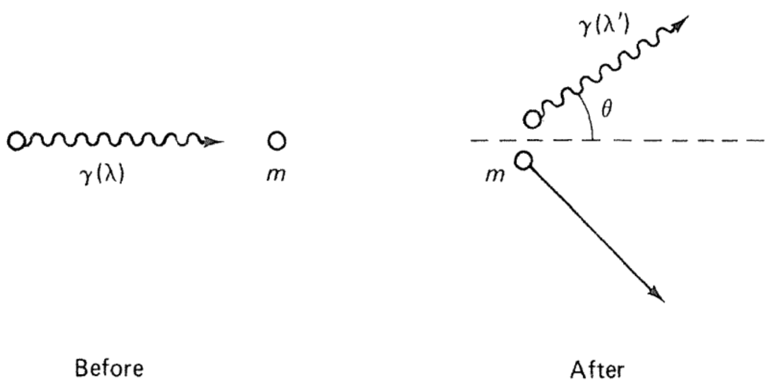


Figure: a photon is striking on free or loosely bound electron at rest, after scattering photon has gone with less energy and electron is recoiled

The next particle discovered by Yukawa is mesons, it is responsible for the strong force inside the nucleus, there are three types of mesons π^+, π^-, π^0 . electrons are called leptons (means: light weight), protons and neutrons are called baryons (means: heavy weight). Since the mass of Yukawa's particle lies between baryons and leptons so we called it meson(means: middle weight). π meson is copiously produced in the upper atmosphere, but disintegrates before reaching the ground, so it is very hard to detect at ground level, for the detection of this particle Powell's group exposed their photographic emulsions on mountain tops. The next particles are antiparticle are discovered when relativistic version of quantum mechanics came in to existence in which relativistic free scalar(spin 0) particle is described by Klein Gordan equation which is second order in time .Relativistic formula $E^2 = P^2c^2+m_0^2c^4$, it implies that we have the positive energy solution as well as negative energy. These negative energy particles created the problem in their interpretation. After a lot of effort of Dirac it was proved that negative energy solution is also possible He called these negative energy particles antiparticles. Anderson discovered positron having same mass of electron but opposite charge of electron. The dualism in Dirac's equation is a profound and universal feature of Quantum field theory: for every kind of particle, there must exist a corresponding antiparticle with the same mass and opposite charges, the positron is anti electron, antiproton is the antiparticle of proton, antineutron is antiparticle of neutron. Antiparticles are denoted by an over bar, some neutral particles are its antiparticles as photon is its antiparticle. Now question arises how neutrons differs from antineutron? The answer is neutron carry baryon number (quantum numbers) which changes sign for antiparticles but both have charge zero. There is a general principle in particle physics that goes under the name of crossing symmetry (it is possible due to the existence of antiparticles). It says suppose that the reaction given below

$$A + B \to X + Y$$

Occurs then the following reactions will also be allowed due to the existence of antiparticles denoted by over bar.

$$A \to \bar{B} + X + Y$$

$$A + \bar{X} \to \bar{B} + Y$$

$$\bar{X} + \bar{Y} \to \bar{A} + \bar{B}$$

But here there is a problem that for each reaction conservation of energy should be hold. If A weighs less than the sum of B, C and D, then reaction $A \to \bar{B} + C + D$ will not be occur kinematically. Similarly in the second reaction if A and C are light , B and D are heavy, then this reaction will not be occur unless initial kinetic energy exceeds a certain threshold value. So I will crossed reaction is dynamically permissible, but it may or may not be kinematically allowed. Now take the Compton scattering

$$\gamma + e^- \to \gamma + e^-$$

is really the same process as annihilation described as

$$e^- + e^+ \to \gamma + \gamma$$

but in laboratory they are completely different phenomenon. The next elementary particle is neutrino which is discovered for the explaining the phenomena of β-decay. In the β decay a radioactive nucleus A is transformed in to lighter nucleus B, with the emission of an electron. The reaction is:

$$A \rightarrow B + e^{-}$$

Conservation of charge requires here that B should carry one unit more charge than A, this can also be written as the conversion of a neutron in A in to a proton in B. The position of the new nucleus in periodic table is given by Soddy, Fajan and Russel law. Since it is a two body decay, the outgoing energies are kinematically determined in the centre of mass frame, conservation of energy dictates that the electron energy is

$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A}\right)c^2$$

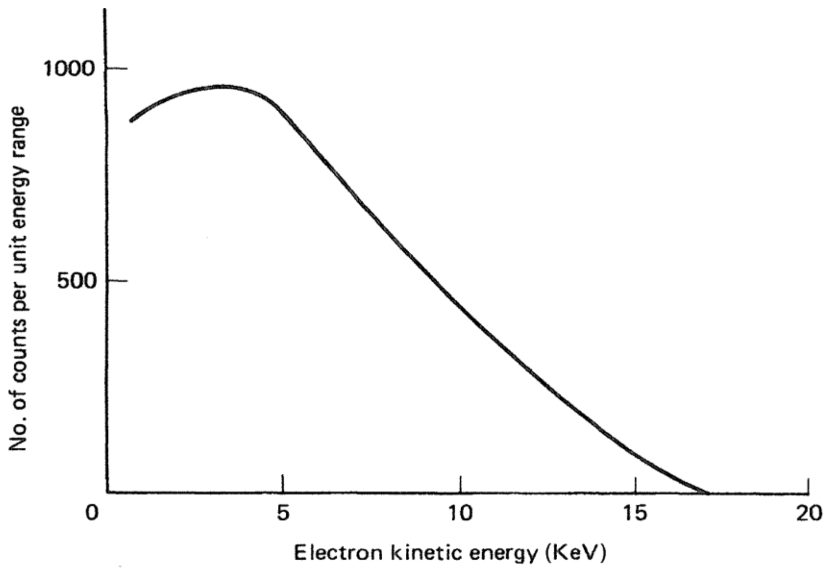


Figure: Beta decay spectrum of tritium ($^3_1H \rightarrow {}^3_2He$)

Notice here that E is fixed, once three masses are specified, but experimental result that the emitted electrons vary considerably in energy, this was a most disturbing result . Niels Bohr was ready to abandon the law of Conservation of energy. Pauli took a more sober view, suggesting that another electrical neutral (to conserve charge) particle was emitted along with electron, that carries of the missing energy. Pauli called it neutron. From the above equation of energy we can say that the new particle is extremely light as we know its mass is in fact zero, Femi called it the neutrino. the fundamental beta decay process can be described as:

$$n \rightarrow p^{+} + e^{-} + \bar{\nu}$$

In this process neutron goes to proton plus electron plus antineutrino. If we use the cross symmetry then the reaction,

$$\nu + n \rightarrow p^{+} + e^{-}$$

must occur with the same rate as beta decay process. Davis looked if we take antineutrino in the left i.e.

$$\bar{\nu} + n \rightarrow p^{+} + e^{-} \qquad (1)$$

He find that the above reaction does not occur that means neutrino and antineutrino are distinct particles. In 1953 Konopinski and Mahmoud discovered a simple rule for checking which reaction is possible and which not. He assigned lepton numbers (specific quantum numbers) to all particles as all the leptons carry lepton number $+1$ and all anti leptons carry lepton number -1. The particles have lepton numbers zero if they do not belong to lepton family. He said that for any reaction to be occur all the lepton numbers must be conserved. Since in the reaction (1) LHS has lepton number -1 and RHS has lepton number +1, so here lepton numbers are not conserved so this reaction is not possible. If we apply the above conservation law , then decay of pion and muon can be written logically as:

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu$$

$$\mu^{+} \rightarrow e^{+} + \nu + \bar{\nu}$$

$$\mu^{-} \rightarrow e^{-} + \nu + \bar{\nu}$$

Then neutrino and antineutrino are distinguished by lepton numbers, all neutrino has total lepton number 1 and all antineutrino has lepton numbers -1. Helicity operator in Quantum field theory is written as $\frac{1}{2}\sigma.\hat{p}$ is also used for differentiate between neutrinos and antineutrinos, it has two values $\pm\frac{1}{2}$. Positive value of it describes right handedness, and negative value of it describes right handedness. So if a neutrino, with positive energy (particle) and positive helicity is right handed neutrino, a neutrino with negative energy (antiparticle that means antineutrino) and negative helicity is left handed anti neutrino and similarly left handed neutrino and right handed antineutrinos are also possible. Note helicity is a good quantum number for a massive particle. Now take the process

$$\mu^{-} \rightarrow e^{-} + \gamma \qquad (2)$$

In this process conservation of charge holds, conservation of lepton number holds(both side lepton number is 1). But this is never detected in laboratory. Then suggestion is given that lepton numbers associated with electrons, muons, tauons must conserved individually for a reaction to be possible (L_e, L_μ and L_τ must be conserved individually), these values are given in the table below.

Leptons and anti leptons	L_e	L_μ	L_τ	$L = L_e + L_\mu + L_\tau$
e^-, ν_e	1	0	0	1
μ^-, ν_μ	0	1	0	1
τ^-, ν_τ	0	0	1	1
e^+, $\bar{\nu}_e$	-1	0	0	-1
μ^+, $\bar{\nu}_\mu$	0	-1	0	-1
τ^+, $\bar{\nu}_\tau$	0	0	-1	-1

Table: showing lepton numbers for leptons

Where L_e, L_μ, L_τ are electron lepton numbers, muon lepton numbers and tauon leton numbers respectively, L denotes the total lepton numbers, given in the above table has the value 1 for leptons and -1 for anti leptons. ν_e, ν_μ, and ν_τ are called as electron type neutrino, muon type neutrino and tauon type neutrino respectively. Similarly $\overline{\nu_e}$ is electron type anti neutrino and same terminology for others. In the process (2) L_μ is not conserved so this process is forbidden. Now nuclear beta decay process , decay of pion and decay of muon can be described as:

$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$

$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$$

$$\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$$

These all reaction follows the conservation of L_e, L_μ, L_τ so these all reactions are allowed. Hadrons is a collective word for baryons and mesons. The next particles discovered are strange particles. Rochester and Butler the photograph of cloud chamber shown in figure below. In this photograph cosmic rays enters from the upper left, then strike to the lead plate, produces a neutral particle which decays in to two particles forming V in the lower right side. The detailed analysis shows that these particles are π^+ and π^-. This new neutral particle has mass two times the mass of pion. We call it K^0(kaon)

$$K^0 \rightarrow \pi^+ + \pi^-$$

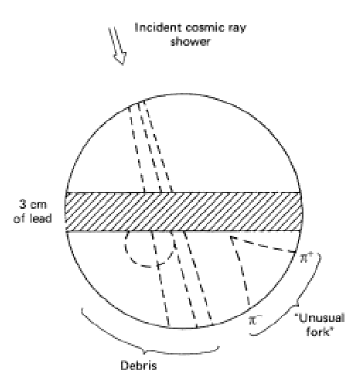


Figure: in this figure when cosmic rays strikes to the lead plate, it produces which decays in to π^{+} and π^{-}.

In 1949, Powell published the photograph, which shows the decay of charged kaon:

$$K^{+} \rightarrow \pi^{+} + \pi^{+} + \pi^{-}$$

Kaons are made of pi- meson so they are heavy meson and belong to meson family. There are some new mesons discovered which are ω, ρ, φ etc. In 1950 new particle is discovered, this particle has mass higher than proton; we call Λ, belongs to baryon family and it decays as:

$$\Lambda \rightarrow p^{+} + \pi^{-}$$

In 1938 question had arisen Why proton is stable?, it does not decay in to positron and gamma(i.e. $p^{+} \rightarrow e^{+} + \gamma$) because it violate the law of conservation of lepton number but this law is not known until 1953, then Stuckelberg has given the reason by asserting a new conservation law known as conservation of baryon number. He said all baryons (p, n etc.) carry baryon number +1 and all anti baryons ($\bar{p}$, $\bar{n}$ etc.) carry baryon number -1. This law forbids the process, $p^{+} \rightarrow e^{+} + \gamma$, in the left baryon number is +1 and in the right baryon number is 0, so baryon number is not conserved. In the coming few years there are some new baryons discovered which are Σ, Ξ (cascade), Λ etc. these new particles discovered are completely unexpected, at first they seemed to be strange and so are called strange particles. These strange particles are produced by strong force and decay by weak force (beta decay and the process in which neutrino are involved). Pais scheme says that these particles are produced in pairs but it was unclear at that time. For explaining it Gell Mann and Nishijima assigned each particle a new property, called strangeness (denoted by S), is conserved in strong interaction but not conserved in weak interaction. Kaons carry S= +1 and Σ's, Λ have S=-1, ordinary known particles have S=0 (as π, p, n etc.). Now take the processes:

$$\pi^{-} + p^{+} \rightarrow K^{+} + \Sigma^{-}$$

$$\pi^{-} + p^{+} \rightarrow K^{0} + \Sigma^{0}$$

$$\pi^- + p^+ \rightarrow K^0 + \Lambda$$

Here strange particles are produced in such a way, they follow the conservation of strangeness. If we take the process in which only one strange particle (with strangeness nonzero) is present then it will violate conservation of strangeness. Here there are some processes in which strangeness are not conserved:

$$\pi^- + p^+ \nrightarrow \pi^+ + \Sigma^-$$

$$\pi^- + p^+ \nrightarrow \pi^0 + \Lambda$$

$$\pi^- + p^+ \nrightarrow K^0 + \mathrm{n}$$

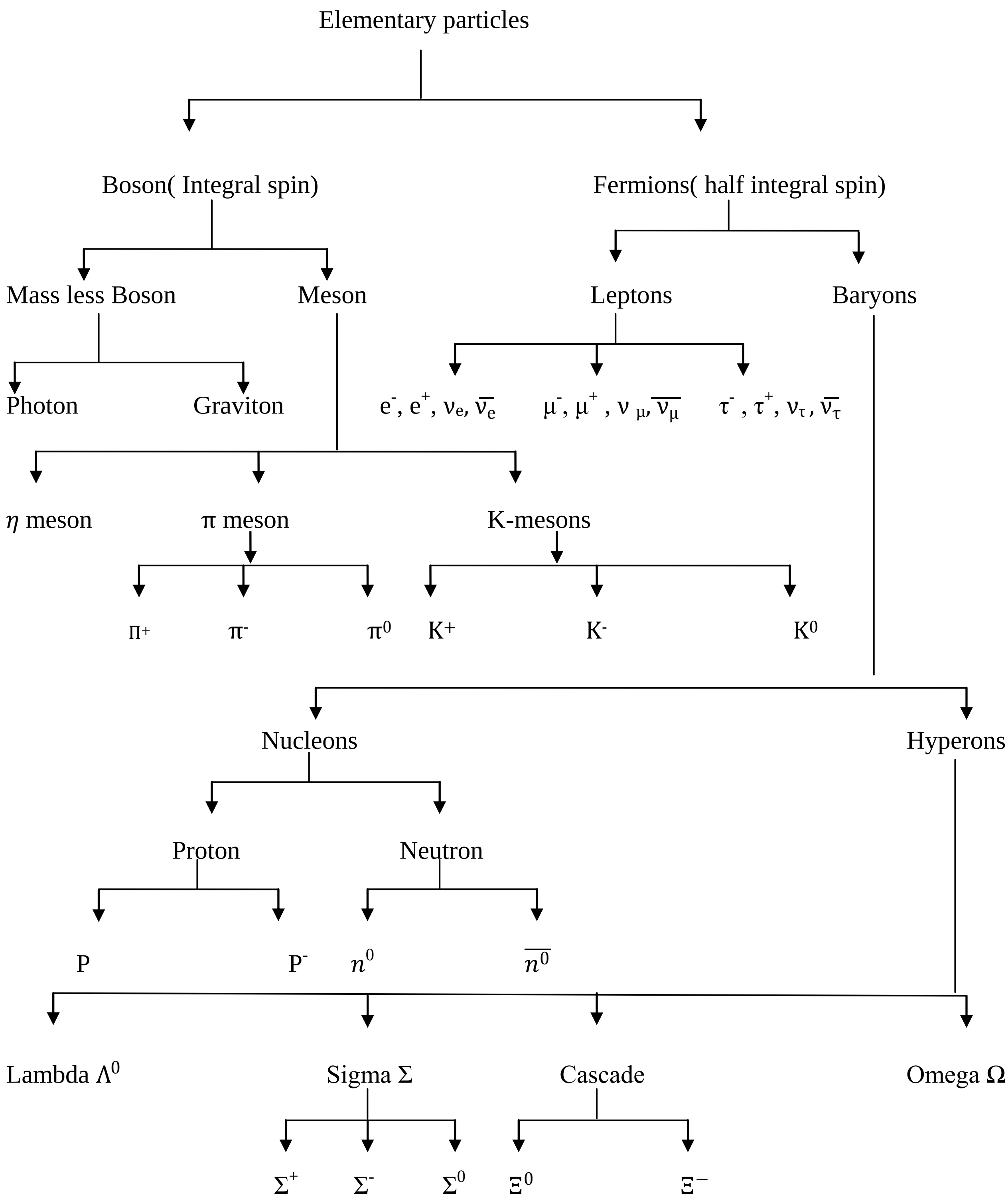
The above decays are not allowed. On the other hand the decays given below are allowed but they do not follow the conservation of strangeness.

$$\Lambda \rightarrow p^+ + \pi^-$$

$$\Sigma^+ \rightarrow p^+ + \pi^0$$

$$\Sigma^+ \rightarrow n + \pi^+$$

Since these all are weak processes in which conservation of strangeness does not hold. In the end we can classify the elementary particles by the following diagram given below:


Elementary particles
Boson(Integral spin)
Fermions(half integral spin)
Mass less Boson
Meson
Leptons
Baryons
Photon
Graviton
$e^-, e^+, \nu_e, \overline{\nu_e}$
$\mu^-, \mu^+, \nu_\mu, \overline{\nu_\mu}$
$\tau^-, \tau^+, \nu_\tau, \overline{\nu_\tau}$
η meson
π meson
K-mesons
Π^+
π^-
π^0
K^+
K^-
K^0
Nucleons
Hyperons
Proton
Neutron
P
P^-
n^0
$\overline{n^0}$
Lambda Λ^0
Sigma Σ
Cascade
Omega Ω
Σ^+
Σ^-
Σ^0
Ξ^0
Ξ^-

Quarks: Gell-Mann and Zweig proposed that all hadrons (mesons and baryons) are made up of very small elementary constituents, called quarks. This theory of quarks starts with the six types of flavor of quarks which is given below in the table:

Up (u)	Down(d)
Charm(c)	Strange(s)
Top(t)	Bottom(b)
Charge $+\frac{2}{3}$	Charge $-\frac{1}{3}$

Table: showing six flavor of quark

Only two quarks up and down quarks are stable, they make up all normal matters i.e. proton and deuterons. Top and bottom quarks are also called truth and beauty. Quark model says that, 1- Each baryon is made up of three quarks and anti baryons are made up of three anti quarks. 2- Each meson are made up of a quark and an anti quark. Proton is a baryon so is made up of three quarks, two up quarks and a down quark and neutron are also made up of three quarks, two down quark and an up quark. Since up and down quarks are the only stable quarks, hence neutron and proton are stable particles. Now we can find the charge of proton and neutron by applying quark model:

Charge of proton=charge of two up quark+ charge of a down quark

$$=2 * \frac{2}{3} + 1 * -\frac{1}{3}$$

$$=1$$

Charge of neutron= charge of two down quarks+ charge of an up quark

$$= 2 * -\frac{1}{3} + \frac{2}{3}$$

$$=0$$

Hence proton carry one unit of basic unit of charge (e) and neutron carry no charge i.e. neutral particle. We start by saying that there are six quarks, but actually there are 12 quarks, each quarks has it's anti quark. Anti quarks are stable, all anti quarks are given below in the table:

Anti up ($\bar{u}$)	Anti down ($\bar{d}$)
Anti charm ($\bar{c}$)	Anti strange ($\bar{s}$)
Anti top ($\bar{t}$)	Anti bottom ($\bar{b}$)

Table: showing six flavor of anti quarks

There is some problem in the quark model that it seems to violet the Pauli's exclusion principle. The original formulation of Pauli's exclusion principle is that two electrons cannot occupy the same state. Later it was observed that the same rule applies for all particles with half integer spin. Since quarks carry spin $\frac{1}{2}$, hence we can apply exclusion principle. Since Δ^{++} , is supposed to made up of three identical u quarks which are in the same state, so it violates exclusion principle. In 1964 Greenberg suggested that quarks not only carries flavors but also colors (color quantum numbers), he said these colors red, green and blue. In this way he resolved the problem by saying that three u's are not identical, they carry different color quantum numbers. If we take a red quark it carries red quantum number (redness) =1, blue quantum number (blueness) =0 and green quantum number (greenness) =0 and same for others. All natural particles carry are colorless means either total color is zero or all three colors are present in equal amounts. This explain a beautiful fact about quarks that individual quarks do not occur in nature, because the only colorless combinations from three colors are $q\bar{q}$, qqq, $\bar{q}\bar{q}\bar{q}$ etc., the individual quark cannot be colorless that is why it does not occur naturally. Since the total quarks and anti quarks are 12, each are of three types red or green or blue, hence there are 36 quarks and 12 leptons. Every force is mediated by some mediating particle, electromagnetic force is mediated by photon, weak force is mediated by intermediate vector bosons which are three in number, strong force is mediated by gluons they are 8 in numbers, so there are total 12 mediators and a Higg's boson (not discovered till now) in weak interaction theory. Hence there are at least 61 particles in the Standard model(gravity is not included inside it). I have described above much more about elementary particles, now I will describe the dynamics of elementary particles.

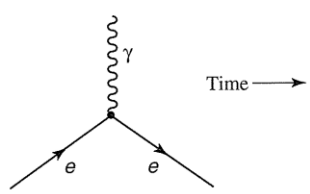
Elementary Particle Dynamics

Four forces: there are four known fundamental forces in nature: strong, electromagnetic, weak, gravitational. The study of these known forces are done in Chromo dynamics (strong force), Electro dynamics (electromagnetic force), Flavor dynamics (weak force), Geometro dynamics (gravitational force). All other forces that we feel in daily life are electromagnetic in origin. The all fundamental forces are given in the table below with details:

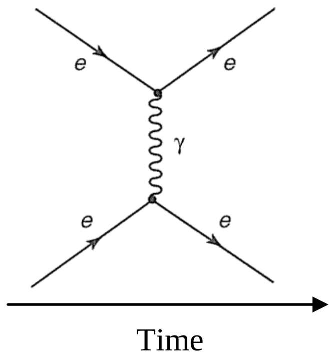
Force	Relative Strength	Theory	Mediator
Strong	10	Chromo dynamics	Gluon
Electromagnetic	10^{-2}	Electro dynamics	Photon
Weak	10^{-13}	Flavor dynamics	Intermediate vector boson
Gravitational	10^{-43}	Geometro dynamics	Graviton

Einstein's general theory of relativity is also known as Geometro dynamics which is the relativistic generalization of classical theory of gravity. Quantum theory of gravity has yet to be work out. Since in the case of elementary particle physics, particle have very small mass we can assume that gravity plays no role. Now I will explain about all the theories leaving Gemetro-dynamics.

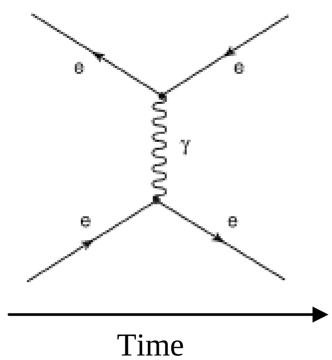
Quantum Electrodynamics(QED): the theory which describes the electromagnetic forces, are called electrodynamics.QED is the oldest of the all the all the theories given above. We can convert all the electromagnetic phenomena in to elementary process given below:



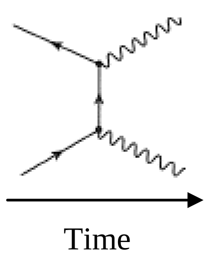
In this diagram (also known as basic Feynman diagram) a charged particle e enter and emits or absorbs a photon and exits. It can be any charged particle electron, quarks etc. but not neutrino because neutrino is neutral, and we know that electromagnetic force is proportional to the charge of particle, hence it does not experience electromagnetic force. The electric repulsion between two electrons can be described as:



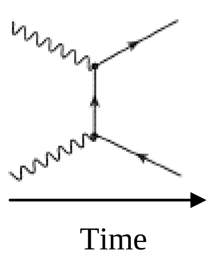
In this diagram electron repel each other by the exchange of mediating particle called photon. In QED repulsion of like charges are called Moller Scattering. These diagrams are called “Feynman diagrams”. The rule for constructing these diagrams is: a particle going forward in time is the particle and the particle going backward in time is to be interpreted as the antiparticle of the corresponding particle. Since photon is it’s own antiparticle that is why we have not shown the direction of photon by arrow. In QED the interaction of two opposite charges (coulomb attraction) is known as Bhabha scattering, the diagram of it is shown below:



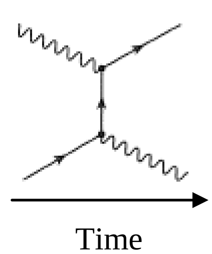
Using these Feynman diagrams, we can describe pair annihilation ($e^{+}+e^{-}\rightarrow\gamma$), compton scattering ($e^{-}+\gamma\rightarrow e^{-}+\gamma$) and pair production ($\gamma+\gamma\rightarrow e^{-}+ e^{+}$). These process are described below using Feynman diagrams:



Annihilation process

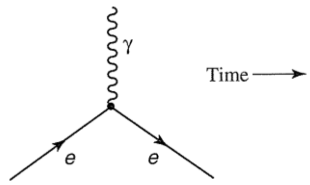


Pair production



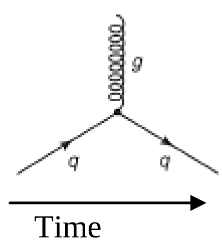
Compton scattering

The external lines represents here the real particle (virtual particle which last long enough and carry the correct mass) and tells us that which process is occurring, whereas internal lines describes the virtual particles (particle with short lifetime and do not carry the same mass) which are not observed and tells the mechanism involved in the physical process. In these diagrams conservation of energy and momentum hold at each vertex.

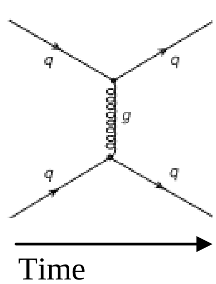


If we take it as the process that $e^- \rightarrow e^- + \gamma$ then it will not be allowed kinematically, it will violate the conservation of energy and if we take it as the process $e^- + \ e^+ \rightarrow \gamma$ then if we go to the centre of mass frame the total momentum in the left is zero and in the right we have photon with some momentum (velocity is c=3*10^8m/sec.), hence it violates the conservation of momentum. This is the reason when an electron and positron annihilate they produce two gamma photon to follow the conservation of momentum.

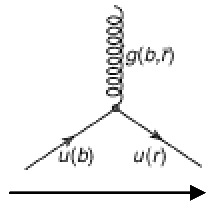
Quantum Chromodynamics (QCD): This theory is the study of strong interaction which is responsible for the stability of nucleus, while the nucleus proton –proton has repulsive coulomb force and neutron is neutral. Here color is dyanamic as charge in electrodynamics and the fundamental process like $e^- \rightarrow e^- + \gamma$ can be written as quark $\rightarrow$ quark + gluon ($q \rightarrow q + g$). Since leptons do not participate in strong interaction because they have no color. The basic diagram is given below:



Now we can combine two or more vertices for describing more complicated processes. The force between two quarks which is responsible for the creation of baryon and for the stability of nucleus can be described by the following two vertices diagram given below:



In this diagram the force between two quarks is mediated by exchange of gluon. In QED we have a single charge which is either positive or negative but in QCD quarks carries three colors red, green and blue(R,G, B). In this branch we study about strong interaction, in the case of strong interaction color of quark may change but flavor will not change.Now take the process $q \rightarrow q + g$



Time

In this process up blue quark goes to up red quark so upness (flavor) is conserved here and the difference in color is carried away by the gluon. Since here gluons also carries colors so they can couple with each other unlike photon (which carry no color). So in this case, we also have in addition to quark gluon vertices, gluon-gluon vertices. This coupling of gluon-gluon makes this subject more complicated. In the case of QED size of coupling constant $\frac{e^2}{\hbar c}$ is $\frac{1}{137}$ is very small so we consider small number of vertices, But in QCD this value is greater than 1 so we have to consider the more vertices and this makes the processes more complicated. Quark can exist only in the form of colorless combinations, this is known as quark confinement if QCD is correct it must prove it. So far no one has provided a conclusive proof of it. Yukawa's pion exchange model can be shown by the following diagram, but this is more complicated than Yukawa had imagined.

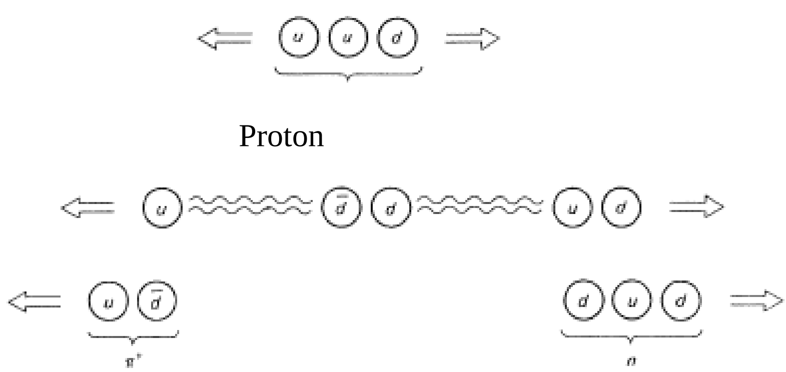
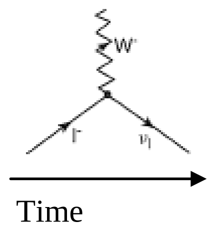


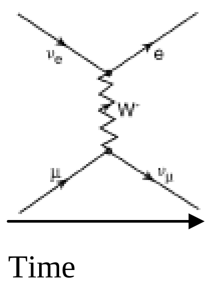
Figure : this is a possible picture of Quark confinement: here we have pulled an up quark out of the proton, a pair of quark is formed instead of a free quark. So we have at the end of process a pion and a neutron.

Weak Interactions: the study of weak interaction is done in the subject, Flavordynamics. There is no particular name for the stuff which is responsible for weak forces, as electric charge in the case of electromagnetic forces, Color for strong forces. yet some physicists call it weak charges. Since leptons have no color so they do not participate in strong interactions, neutrino is neutral so they do not participate in electromagnetic interactions, but both leptons and neutrino's participates in weak interactions. Quarks also participate in weak interactions. Now I will explain the weak interactions in the case of leptons.

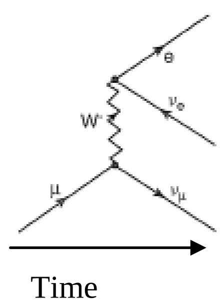
Leptons : the fundamental charged vertex is given by



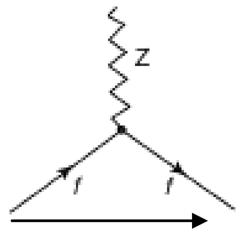
In this figure a negative lepton is changed in to a corresponding neutrino with the emission of W^- or absorption of W^+. This can written as $l^- \to \nu_l + W^-$ or $l^- + W^+ \to \nu_l$. Now like the previous processes, we will use more primitive vertices to describe more complicated processes. Consider the process, $\mu^- + \nu_e \to e^- + \nu_\mu$, is represented by the below diagram:



From the above process decay of muon can be written as, $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$, which can be observed easily than $\mu^- + \nu_e \to e^- + \nu_\mu$. The Feynman diagram for the decay of muon is:

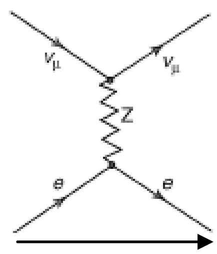


The fundamental neutral vertex is given by



Time

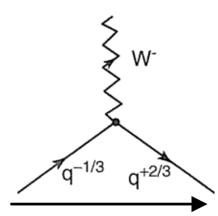
In this diagram f can be any lepton or quark and Z is the mediator in this process. In the scattering of neutrino and electron Z is the mediating particle described below:



Time

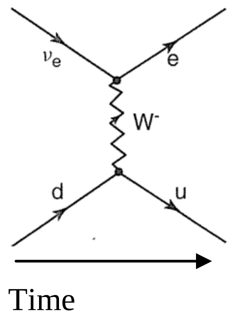
Theoretically neutral weak process was not believed up to 1958. The Glashow-Weinberg-Salam (GWS) theory has included the neutral weak processes as an essential ingredients, their existence was confirmed at CERN experimentally.

Quarks: In the case of leptonic weak vertices, we have seen each lepton goes to the neutrino of same generation e.g. electron goes to electron type neutrino with the emission of W^-, because this theory respects the conservation of electron number, muon number, tau number. Let us suppose that the same rule applies for quarks, then fundamental charged vertex will look like:

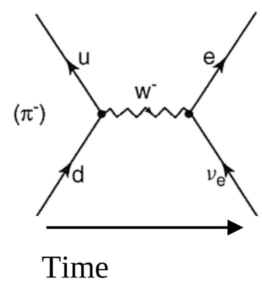


Time

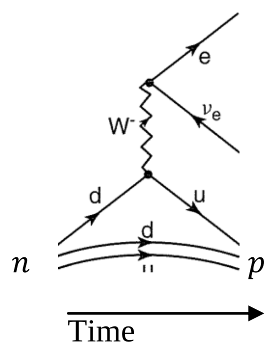
In this diagram a quark of charge $-\frac{1}{3}$ enters, and exit a quark of charge $+\frac{2}{3}$ with the emission of W^-. In this type of process color remains conserved i.e. outgoing quarks carries the same color as the entering quark carries. The flavor of outgoing quarks is different from the entering quarks and the changed flavor is carried away by W^-. By this process we can say flavor is not conserved in weak interactions. Note that here flavor is dynamic that is why this theory is called Flavordynamics. We have seen W^- can couple with leptons (semileptonic process), and also with the quarks (pure hadronic process). A semileptonic process is given by $d + \nu_e \rightarrow u + e$ is shown below:



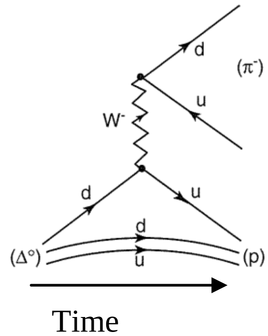
This process would never occur in nature because of quark confinement. The decay of pion $\pi^- \rightarrow e^- + \bar{\nu}$ can be represented by the following diagram:



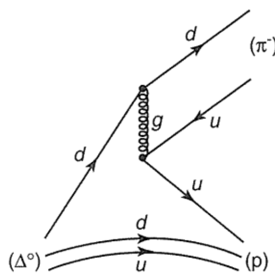
Beta decay process $n \rightarrow p^+ + e^- + \bar{\nu}_e$ can be represented by the following Feynman diagrams:



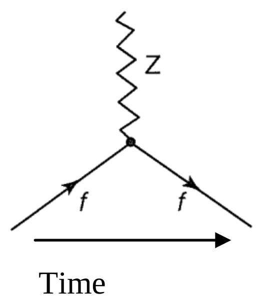
In this beta decay process in the left n is made of one up quark and two down quark, the flavor of one down quark is changed in to an up quark, after changing the flavor this is converted in to a particle with two up quark and a down quark which is proton, here W^-, electron and electron type neutrino is emitted. If we eliminate an electron neutrino vertex in the above beta decay process, then the process becomes $\Delta^0 \rightarrow p^+ + \pi^-$, $\Delta^0$is made up of an up quark and two down quark. This process can be described by the diagram given below:



This decay also happens by strong interactions given below:



Like the fundamental neutral vertex for leptons, let us suppose the same thing holds for quarks, so the fundamental vertex for quark is given by the process quark→ quark + Z:



Here f represents the quark (q). Neutrino scattering process $\nu_\mu + p \to \nu_\mu + p$ can also be described by using the Feynman diagram in which mediator is Z boson. Mass of $W\ and\ Z$ boson are given below:

$$M_w = 82 \pm 2\frac{Gev}{c^2} \quad \text{and } M_z = 92 \pm 2\frac{Gev}{c^2}$$

and the mass of proton is $M_p = 0.94\frac{Gev}{c^2}$.

Unification schemes: Many years before Electricity and Magnetism were considered as the two distinct subjects but in 1820 Oersted showed that when electric current lows through the wire, it deflects the magnetic compass needle putted near it. After 10 years of it, faraday discovered that a moving magnet can produce an electric current in the closed circuit then Maxwell put the whole theory together and called it Electromagnetism. With the same analogy Einstein dreamed combining gravity with electrodynamics in a single unified field theory, which is unsuccessful till today. Similarly Glashow, Weinberg and Salam try to combine weak forces with electromagnetic forces. The theory started with four massless mediators but as it proceeds, three of them $W^{+}, W^{-}\ and\ Z$ acquires mass by Higgs mechanism and only photon remains massless. Higgs mechanism says that Higgs field exist everywhere created by Higgs particle which is not detected till now, when a particle interacts with this field, this field drag that particle which is responsible for its rest energy and hence for rest mass, in this way particles acquire mass. Since photon does not interact with the Higgs field so it remains massless. The relative strength of the weak force is smaller than electromagnetic force because of the enormous mass of intermediate vector Bosons. The next obvious step is combining the strong force with the electroweak force, this is known as grand unified theory (GUT). The strong coupling constant decreases at short distances, same thing is true for weak coupling constant but electromagnetic coupling constant increases at small distances. Now a question arises Could all these converge to a common limiting value at extremely high energy?. From the functional form of coupling constants, it has been possible to find out that this unification occurs around 10^{15}Gev which is very large in comparison to the energy which we can produce in the lab.

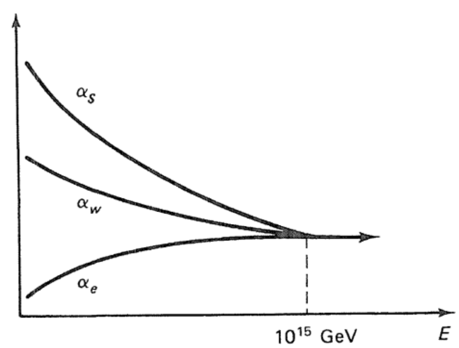


Figure: evolution of coupling constants.

If grand unification, works then whole of elementary particle physics will reduced in to the action of a single force, then the next step will be to combine gravity in this GUT, completing the Einstein's dream. Many theortical physicists are working in this area.

Noether's theorem: this theorem says for every symmetry there is a conservation law and conversely, every conservation law reveals an underlying symmetry. If the laws of physics are invariant with respect translation to time then this symmetry implies the conservation of energy. Some conservation laws associated with symmetry are shown below in the table:

Symmetry	Conservation law
Translation in time	Energy
Translation in space	Momentum
Rotation	Angular momentum
Gauge transformation	Charge

The set of symmetry operation, denoted by S have the following properties:

1. Closure- If R_i and R_j are in set S, then their product (defined operation) should also lie in the set S.

2. Identity- there must exist an element I in S such that $R_i I = IR_i = R_i$.

3. Inverse- for each R_i there must exist R_i^{-1} such that $R_i R_i^{-1} = R_i^{-1} R_i = I$

4- Associativity- $R_i\left(R_j R_k\right) = (R_i R_j)R_k$

If any set S satisfies all the above properties then S is called a group. If the elements of the group commutes i.e. $R_i R_j = R_j R_i$ then group is said to be abelian. There are some examples of group given bleow:

$U(n)$- collection of all n x n unitary matrices i.e. $UU^+ = I$

$SU(n)$- collection of all n x n unitary matrices with determinant 1

$O(n)$ - collection of all n x n orthogonal matrices i.e. $OO^+ = I$

$SO(n)$ - collection of all n x n orthogonal matrices with determinant 1

There are some symmetry operations which will be used in elementary particle physics are given below:

Parity-