Lecture Notes: Particle Physics

Part III: University of Calcutta

Dr. Pintu Mandal

Department of Physics
St. Paul's Cathedral Mission College

November 22, 2016

Contents

List of Figures

List of Tables

1

Elementary Particles

> *I have heard it said that "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a 10,000 dollar fine."*
>
> – Willis Lamb, *Les Prix Nobel 1955, The Nobel Foundation, Stockholm*

Syllabus: (a) Four basic interactions in nature and their relative strengths, examples of different types of interactions. Quantum numbers-mass, charge, spin, isotopic spin, intrinsic parity, hypercharge. Charge conjugation, conservation laws.
(b) Classifications of elementary particles - hadrons and leptons, baryons and mesons, elementary ideas about quark structure of hadrons - octet and decuplet families.

This is a lecture note and it does not include the details of the topics. For an insight, the students are advised to consult text books and other references. While preparing this note, I have exclusively taken the help from many sources. Of particular to mention, are Nuclear Physics by *S. N. Ghoshal* (S. Chand), Introduction to Elementary Particles by *David Griffiths* (John Wiley & Sons), Introductory Nuclear Physics by *Kenneth S. Krane* (John Wiley & Sons), Wikipedia. I have frequently quoted the statements and explanations which I could not make lucid as they appear in these references.

In our Nuclear Physics course so far, we have gone through the electron, the proton and the neutron as the fundamental constituents of matters and hence they are the 'elementary' particles. The number of elementary particles is, however, not restricted to only three. Moreover, the proton and the neutron, which we know as the elementary particles, are not elementary; they are constituted with 'more elementary' particles called the quarks. The elementary particles, which are large in number now, differ from each other by various properties; not only the mass, electric charge but other properties like intrinsic spin and parity, isospin, strangeness etc. The particles also take part in different interactions like strong and weak interactions, apart from the gravitational and electromagnetic interactions.

This chapter is introductory of its kind. It introduces different elementary particles,

Table 1.1: Fundamental interactions with their relative strength, range and mediator

Interaction	Relative Strength	Range	Mediator
Strong	1	10^{-15} m	gluon
Electromagnetic	10^{-2}	∞	photon
Weak	10^{-13}	10^{-18} m	Z^0, $W^\pm$
Gravitational	10^{-38}	∞	graviton

their different properties and different fundamental interactions they take part in. The chapter is organized in the following way. Section 1.1 introduces four fundamental interactions and their characteristics. Section 1.2 introduces different elementary particles with their classifications. Conservation of various properties associated with elementary particle reactions are discussed in Section 1.3. The Eightfold Way, the Periodic Table of elementary particles is described in Section 1.4. The Quark Model is introduced in Section 1.5 and the Standard Model is outlined in Section 1.6.

1.1 Fundamental Interactions

Fundamental interactions between the elementary particles have been classified into four, namely the (a) Gravitational interaction, (b) Electromagnetic interaction, (c) Weak interaction and (d) Strong interaction. These interactions differ in their origin, nature and relative strength. In order to explore the nature of fundamental interactions, the following points should be addressed.
(i) What physical property of the particle is associated with the interaction?
(ii) How does an interaction vary with the separation between the particles? (Or, what is the range of the interaction?)
(iii) How strong is the interaction? In order to compare the relative strength of an interaction with others, which are different by origin and nature, a dimensionless quantity is defined for each interaction.
(iv) How is the interaction between two particles propagated in space? Is it carried out by a messenger? (Or, is there any mediator?)
(v) How long does the interaction take place?

The basic features of all these interactions are listed in the following.

1.1.1 Gravitational Interaction

The gravitational interaction is the earliest known but least understood interaction which is negligible in molecular dimensions, but important for mesoscopic to macroscopic objects (like planetary motion). The key features of this interaction are in the following.

Table 1.2: Field particles and their fundamental properties

Field Particle	Interaction	Mass (GeV)	Charge (e)	Spin ($\hbar$)
Photon (γ)	Electromagnetic	0	0	1
$W^{\pm}$ bosons	Electromagnetic, Weak	81	± 1	1
Z^0 boson	Weak	93	0	1
Gluon	Strong	0	0	1
Graviton (?)	Gravitational	0	0	2

(i) It acts between any particles having mass.
(ii) The interaction follows an inverse square law with the separation between the particles and it is governed by Newton's law of gravitation.
(iii) The range of gravitational interaction is infinity.
(iv) Strength of this interaction is characterized by a dimensionless constant $\frac{Gm_eM_p}{\hbar c} \simeq 3 \times 10^{-42}$, where m_e and M_p are the mass of an electron and a proton respectively.
(v) This is the weakest interaction in nature.
(vi) The gravitational interaction is supposed to be mediated by a boson called graviton.

1.1.2 Electromagnetic Interaction

The electromagnetic interaction binds electrons to nucleus, binds atoms to molecules. It is responsible for all chemistry and biology and acts in electron-positron annihilation. The key features of this interaction are:

(i) It acts between any particles having electric charge.
(ii) The interaction follows an inverse square law with the separation between the particles and it is governed by Coulomb's law.
(iii) The range of electromagnetic interaction is infinity.
(iv) Strength of the interaction is characterized by a dimensionless constant, the fine structure constant $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \simeq \frac{1}{137}$.
(v) The electromagnetic interaction stronger than the gravitational and week interactions. For example, the electromagnetic interaction between an electron and a proton is 10^{37} times larger than the gravitational interaction between them.
(vi) The electromagnetic interaction is mediated by photon, a boson.

1.1.3 Weak Interaction

The weak interaction comes into play in nuclear interaction like $\beta-$ decay and slow decay of elementary particles. The important features of weak interaction are in the following.

(i) It acts between particles having weak charges.

(ii) This is a short-ranged interaction where the range is given by $R = \frac{\hbar}{m_w c} \simeq 2.4\times10^{-18}$ m, where m_w is the mass of a W boson.
(iii) The strength of the weak interaction is characterized by a dimensionless constant $g_w = \left(\frac{g}{\hbar c}\right) \lambda_c^2 \simeq 3 \times 10^{-12}$, where g is the coupling constant of weak interaction ($g = 1.4 \times 10^{-62}$ J-m^3) and λ_c^2 is the reduced Compton wavelength for the electron.
(iv) The weak interaction is stronger than the gravitational interaction but weaker than the electromagnetic interaction.
(v) The interaction is mediated by Z^0 and $W^{\pm}$ bosons.
(vi) The characteristic time for the weak interaction is 10^{-10} s.

1.1.4 Strong Interaction

The strong interaction holds protons and neutrons in the nucleus together and acts between 'hadrons', but not between 'leptons'.

(i) The strong interaction acts between particles having color charges.
(ii) It is a short ranged interaction which acts within the nuclear distances. The range of the strong interaction is given by $R = \frac{\hbar}{m_\pi c} \simeq 10^{-15}$ m, where m_π is the mass of pion (= 140 MeV/c^2).
(iii) The characteristic strength parameter of strong interaction is around 0.3.
(iv) It is the strongest interaction in nature.
(v) Strong interaction is mediated by gluon.
(vi) The characteristic time for the strong interaction is 10^{-23} s.[1]

The characteristics of all the interactions are briefed in Table 1.1 while the properties of the mediators are tabulated in Table 1.2.

1.2 Classification of Elementary Particles

The elementary particles are broadly classified into two categories depending on the nature of fundamental interactions they take part in. One, the leptons, take part in weak interaction but not in strong interaction. Other, the hadrons, take part in both strong and weak interactions. The hadrons are also classified depending on other properties. For a clear picture, students are referred to the figure 1.1.

1.2.1 Leptons

The leptons are relatively lighter particles which do not take part in strong interaction. There are six 'particles' within lepton class, namely, *electron* (e^-), *muon* (μ^-), *tauon* (τ^-), *electron-neutrino* (ν_e), *muon-neutrino* (ν_μ) and *tauon-neutrino* (ν_τ). Corresponding to each of these particles, there exists an antiparticle (anti-lepton). The antiparticle of

---

[1] This can be realized by the following 'thought experiment'. Suppose two particles approach one another, moving at speeds comparable to the speed of light, i.e. 10^8 m/s. If the particles approach within 10^{-15} m of each other, they will interact via the strong interaction. The time that either particle spends near the other is thus approximately the time it takes for one particle to traverse a distance of 10^{-15} m, i.e. 10^{-23} s. Thus it can be concluded that whenever the particles spend at least 10^{-23} s within the range of their mutual strong interactions they will interact.

electron is positron (e^+). For other particles, the antiparticles are μ^+, τ^+, $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ respectively. Thus the number of members within the lepton family is 12. A quantum number, called the *Lepton number* (L) is assigned to each member under this class in order to distinguish from other classes of elementary particles. For 'particles' (i.e. leptons), L= 1; for antiparticles (anti-leptons), L= -1 and for others, L= 0. Beside the lepton number, lepton-family-numbers are also defined.

L_e, the electronic number for the electron, electron neutrino and corresponding antiparticles ($L_e = +1$ for the particles and $L_e = -1$ for the antiparticles).

L_μ, the muonic number for the muon, the muon neutrino and their antiparticles ($L_\mu = +1$ for the particles and $L_\mu = -1$ for the antiparticles).

L_τ, the tauonic number for the tauon, the tauon neutrino and associated antiparticles ($L_\tau = +1$ for the particles and $L_\tau = -1$ for the antiparticles).

All the leptons (and anti-leptons) have an intrinsic spin angular momentum 1/2 (in the unit of $\hbar$) and hence they are fermions. The electron is first discovered elementary particle and it has a mass of 0.51 MeV.

Muon decay: Muons are unstable elementary particles and are heavier than electrons and neutrinos but lighter than all other matter particles. They decay via the weak interaction. Because lepton numbers must be conserved, one of the product neutrinos of muon decay must be a muon-type neutrino and the other an electron-type antineutrino (antimuon decay produces the corresponding antiparticles, as detailed below). Because charge must be conserved, one of the products of muon decay is always an electron of the same charge as the muon (a positron if it is a positive muon).

$$\mu^- \rightarrow e^- + \bar{\nu_e} + \nu_\mu \tag{1.1}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu_\mu} \tag{1.2}$$

1.2.2 Hadrons

Hadrons are the particles which take part in strong interaction unlike the leptons. The hadrons are classified into two subgroups − mesons and baryons.

(a) Mesons: The mesons belong to the hadron class which are lighter (D mesons are heavier than the nucleons), having integral spin and hence bosons. Mesons include pions ($\pi^\pm$, π^0), kaons ($K^\pm$, K^0), $D^\pm$, D^0 etc. The mesons have short lifetime and they decay via electromagnetic and weak interactions.

(b) Baryons: Baryons belong to the hadron class of particles having heavier mass and half-integral spin (hence they are fermions). The number of particles in baryon class is large. In order to distinguish the particle within the baryon family, a quantum number called the the Baryon Number (B) has been assigned. For the particles in the baryon family $B = 1$ and for the antiparticles $B = -1$. For other groups of particles (leptons, mesons), $B = 0$.

Baryons are again subdivided into two groups − nucleons (proton and neutron) and hyperons (Λ^0, $\Sigma^\pm$, Σ^0, Ξ^-, Ξ^0 etc.). Hyperons are strange particles (strangeness quantum number $S \neq 0$) and heavier than the nucleons.

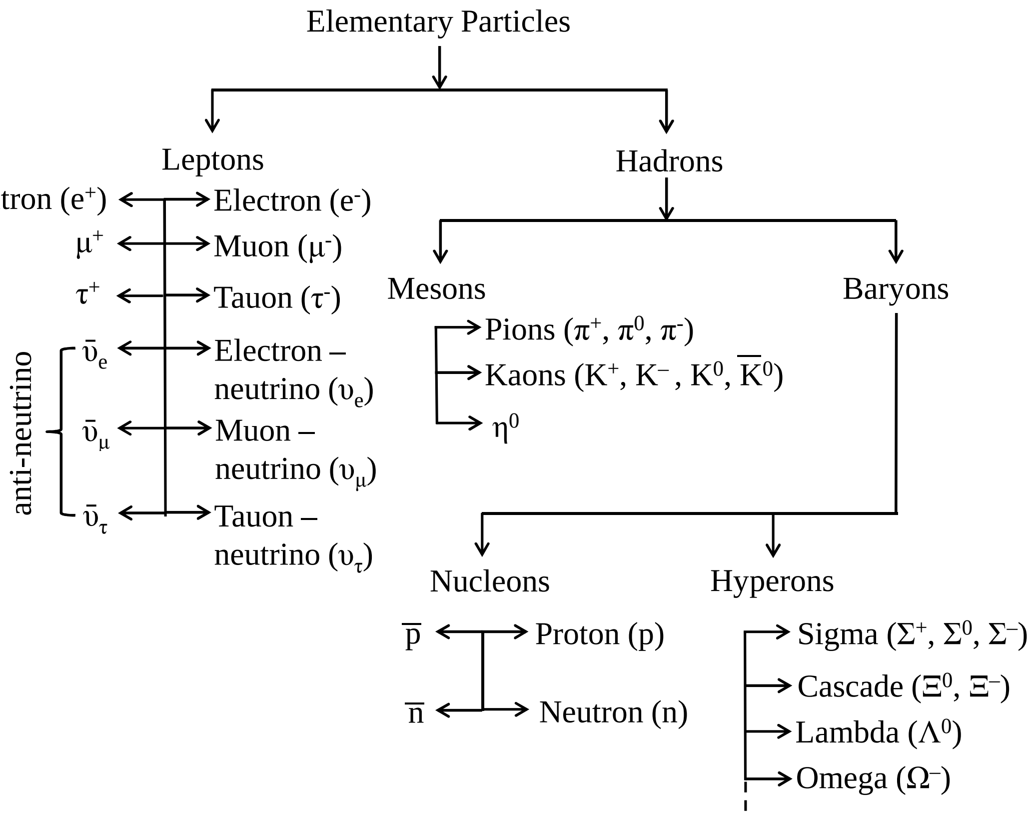

Figure 1.1: Classification of elementary particles

Resonance Particles: There are many particles within the hadron group which have ultra-short lifetime of the order of 10^{-23} s. Thus these particles cover a distance of the order of only 10^{-15} m in the interval between their creation and subsequent decay, and hence detection of such particles becomes impossible. Instead, such particles appear as resonant states in the interactions of longer-lived particles which are more readily observable. The term 'resonance' appears from the fact these particles are detected from the resonance peak in the collision cross section vs. energy graph.

1.3 Conservation Laws and Symmetries

All physical processes are governed by some conservation laws like the conservation of energy, conservation of linear and angular momenta, conservation of charge etc. Apart from their mass energy, momentum, charge, the elementary particles are associated with other various properties like the lepton number, baryon number, strangeness quantum number, isospin etc. In reactions involving elementary particles, conservation of some of these properties hold apart from more well-known conservation laws. Violation of some properties still allow the reaction to occur. In elementary particle physics, the physical processes occur via four fundamental interactions as already mentioned. Conservation or violation of some properties are characteristics of particular interactions.

1.3.1 Energy

Conservation of energy holds in all reactions involving elementary particles. It is related to the invariance of the physical laws under translation along the time axis (homogeneity of time). This means that the laws of interaction do not depend on the time of measurement.

1.3.2 Linear Momentum

Conservation of linear momentum also holds for all types of interactions. It is related to the invariance of the physical laws under translation in space (homogeneity of space). This means that the laws of interaction do not depend on the position of measurement.

1.3.3 Angular Momentum (J)

Each elementary particle has an intrinsic spin angular momentum. Moreover, it can have orbital angular momentum. The total angular momentum (vector sum of spin and angular momenta) remains conserved in all physical processes. This is related to the invariance of physical laws under rotation (isotropy of space).

1.3.4 Electric Charge (Q)

The total electric charge (Q) of the particles taking part in any reactions, must be conserved. This is related to the gauge invariance of the electromagnetic field.

1.3.5 Lepton Number (L)

In order to distinguish the particles within the lepton group from others, a quantum number, called the *lepton number* (L), is introduced. $L = +1$ for all particles and $L = -1$ for antiparticles within the lepton family. For all other particles $L = 0$. The lepton number (also the lepton-family-number) remains conserved in all interactions. Consider, for example, the following elementary particle reactions:

$$\begin{aligned} p &\rightarrow n + e^+ + \nu_e \\ L_e : 0 &\rightarrow 0 + (-1) + 1 \end{aligned} \tag{1.3}$$

$$\begin{aligned} \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu \\ L_\mu : +1 &\rightarrow 0 + 0 + 1 \\ L_e : 0 &\rightarrow 1 + (-1) + 0 \end{aligned} \tag{1.4}$$

In either case, the lepton number remains conserved.

1.3.6 Baryon Number (B)

The particles within the baryon family are distinguished from others by assigning a quantum number, called the *baryon number* (B). $B = 1$ for all particles and $B = -1$ for antiparticles within the baryon class. For all other particles, $B = 0$. The baryon number also remains conserved in all interactions. For example, let us consider the following reactions:

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu}_e \\ B : +1 &\rightarrow +1 + 0 + 0 \end{aligned} \tag{1.5}$$

$$\begin{aligned} \pi^- + p &\rightarrow K^+ + \Sigma^- \\ B : 0 + 1 &\rightarrow 0 + 1 \end{aligned} \tag{1.6}$$

$$\tag{1.7}$$

In either case, the baryon number remains conserved.

In order to test whether an elementary particle reaction is allowed, what all we need is to check whether the electric charge, the lepton number, the baryon number, the spin angular momentum (vector addition) all are conserved. Violation of any one of these properties does not allow the reaction to occur. Let us illustrate this with the following examples:

Eg.1: $n \rightarrow p + e^- + \bar{\nu}_e$
Conservation of electric charge $Q : 0 \rightarrow 1 + (-1) + 0$
Conservation of electron lepton number $L_e : 0 \rightarrow 0 + 1 + (-1)$
Conservation of baryon number $B : +1 \rightarrow +1 + 0 + 0$
Conservation of angular momentum (intrinsic spin) $J : \frac{1}{2} \rightarrow \frac{1}{2} + \frac{1}{2}(\uparrow) + \frac{1}{2}(\downarrow)$
Conservation of electric charge, lepton number, baryon number and angular momentum all hold in this reaction and hence it is allowed to occur.

Eg.2: $p + \nu_\mu \rightarrow n + \mu^+$
Conservation of electric charge $Q : 0 + 1 \rightarrow 0 + 1$
Conservation of muon lepton number $L_\mu : 1 + 0 \rightarrow 0 + (-1)$
Conservation of baryon number $B : +1 + 0 \rightarrow +1 + 0$
Conservation of angular momentum (intrinsic spin) $J : \frac{1}{2} + \frac{1}{2} \rightarrow \frac{1}{2} + \frac{1}{2}$
Conservation of electric charge, baryon number and angular momentum holds in this reaction. However, the lepton number is not conserved and hence it is forbidden.

1.3.7 Strangeness Quantum Number (S)

Rochester and Buttler published (1947) a cloud chamber photograph where cosmic ray particles strike a lead plate producing a neutral particle whose existence is revealed when it decays into two charged secondaries. These charged particles were a π^- and a π^+. Hence the neutral particle was identified as kaon (K^0).

$$K^0 \rightarrow \pi^- + \pi^+. \tag{1.8}$$

The kaons behave in some respects like heavy pions and hence the meson family was extended to include them.

Anderson's group found (1950) a neutral particle Λ^0 that decays in proton (p) and pion (π^-).

$$\Lambda^0 \to p + \pi^-. \tag{1.9}$$

This Λ^0 belongs to the baryon family.

These decay processes occur via weak interaction. On the other hand, these particles are produced via strong interaction. For example, in pion-proton collision, one might produce the following pairs of particles

$$\begin{aligned} \pi^- + p &\to K^+ + \Sigma^- \\ &\to K^0 + \Sigma^0 \\ &\to K^0 + \Lambda^0. \end{aligned}$$

Thus there is more technical sense in which these particles (like K^0, Λ^0) seem strange; they are produced by strong interaction, but decay by weak interaction. A new quantum number, called the *strangeness quantum number* (S), has been assigned to these strange particles. The strangeness quantum number remains conserved in strong interaction, but it may not be conserved in weak interaction. There exists a consistent assignment of S to the hadrons that accounts for the observed strong processes. The leptons and photon do not take part in strong interaction and hence the strangeness quantum number does not apply to them.

In order to test whether an elementary particle reaction occurs via strong interaction, we need to check whether the strangeness quantum number is conserved. If S is found to be conserved, the reaction occurs via strong interaction. Otherwise, it is a weak interaction. Let us illustrate this with the following examples:

Eg.1: $\pi^- + p \to K^0 + \Sigma^0$
Conservation of electric charge $Q : (-1) + 1 \to 0 + 0$
Conservation of lepton number $L : 0 + 0 \to 0 + 0$
Conservation of baryon number $B : 0 + 1 \to 0 + 1$
Conservation of angular momentum (intrinsic spin) $J : 0 + \frac{1}{2} \to 0 + \frac{1}{2}$
Conservation of strangeness quantum number $S : 0 + 0 \to -1 + 1$
Conservation of electric charge, lepton number, baryon number and angular momentum all hold in this reaction and hence it is allowed to occur. Since the strangeness quantum number is also conserved, the reaction occurs via strong interaction.

Eg.2: $\pi^- + p \to \Lambda^0 + \pi^0$
Conservation of electric charge $Q : (-1) + 1 \to 0 + 0$
Conservation of lepton number $L : 0 + 0 \to 0 + 0$
Conservation of baryon number $B : 0 + 1 \to 1 + 0$
Conservation of angular momentum (intrinsic spin) $J : 0 + \frac{1}{2} \to \frac{1}{2} + 0$
Conservation of strangeness quantum number $S : 0 + 0 \to -1 + 0$
Conservation of electric charge, lepton number, baryon number and angular momentum all hold in this reaction and hence it is allowed to occur. However, the strangeness quantum number is not conserved. Thus the reaction does not occur via strong interaction.

1.3.8 Isospin (T)

The isospin (also known as isotopic spin or the i-spin) is a *fictitious spin vector* (it is neither isotopic, nor spin), first introduced to the nucleons. The charge independence of nuclear force suggests that in most cases there is no need to distinguish in the formalism between the neutron and proton, and hence they can be grouped into a common family, the nucleon. The two state degeneracy is analogous to that of the magnetic interaction between spin-1/2 particles. The two degenerate nuclear states of the nucleon in the absence of electromagnetic fields, like the two degenerate spin states of a nucleon in the absence of a magnetic field, are then 'isospin-up' which is assigned to the proton, and 'isospin-down' the neutron. Thus the electric charge resolves the isospin degeneracy of the nucleons.

The concept of isospin has been extended to the hadrons with similar properties and nearly identical masses but different electrical charges. For examples, the sigma hyperons (Σ^+, Σ^0, Σ^-), delta hyperons (Δ^{++}, Δ^+, Δ^0, Δ^-), pi-mesons (π^+, π^0, π^-) *etc.* are grouped into isospin multiplets with number of members in the family (M) 3, 4, 3 respectively. The isospin quantum number (T) is related to the number of multiplets as $M = 2T + 1$. Thus for the sigma hyperons and pi-mesons $T = 1$, for delta hyperons $T = 3/2$ and for the nucleons $T = 1/2$.

Another quantity T_3, *third component of isospin* can be defined as

$$T_3 = Q - \bar{Q}, \tag{1.10}$$

where Q is the charge of a particle and $\bar{Q}$ is the average charge of the multiplet. For example, for the sigma hyperons multiplet, $\bar{Q} = 0$. Hence $T_3 = 1, 0, -1$ for Σ^+, Σ^0, Σ^- respectively.

The isospin quantum number remains conserved in strong interaction but violated in electromagnetic and weak interactions, while its third component is conserved in strong and electromagnetic interactions but violated in weak interaction.

1.3.9 Hypercharge (Y)

The Gell-Mann - Nishijima formula relates the hypercharge with the third component of isospin and the electric charge as

$$Q = T_3 + \frac{Y}{2} \tag{1.11}$$

Isospin creates multiplets of particles whose average charge ($\bar{Q}$) is related to the hypercharge by $Y = 2\bar{Q}$. Thus the hypercharge is the same for all members of a multiplet. The hypercharge is related to the strangeness and baryon number as $Y = S + B$.

Strong interaction conserves hypercharge, but weak interaction does not.

1.3.10 Parity (P)

The parity of a system is a quantum mechanical description of its symmetry under space reversal. The space reversal is described by the parity operator $\hat{P}$ which operating on a wave function $\psi(\vec{r})$, transforms it into $\psi(-\vec{r})$. If $\psi(-\vec{r}) = \pm\psi(\vec{r})$, the system is said to have a definite parity (even parity for $\psi(-\vec{r}) = \psi(\vec{r})$, odd parity for $\psi(-\vec{r}) = -\psi(\vec{r})$). The

Table 1.3: Conservation laws in different interactions

Properties	Strong	Electromagnetic	Weak
Energy (E)	$\surd$	$\surd$	$\surd$
Linear momentum (p)	$\surd$	$\surd$	$\surd$
Angular momentum (J)	$\surd$	$\surd$	$\surd$
Electric charge (Q)	$\surd$	$\surd$	$\surd$
Lepton number (L)	$\surd$	$\surd$	$\surd$
Baryon number (B)	$\surd$	$\surd$	$\surd$
Strangeness number (S)	$\surd$	$\surd$	$\times$
Isospin (T)	$\surd$	$\times$	$\times$
Third component of T (T_3)	$\surd$	$\surd$	$\times$
Hypercharge (Y)	$\surd$	$\surd$	$\times$
Parity (P)	$\surd$	$\surd$	$\times$
Charge conjugation (C)	$\surd$	$\surd$	$\times$

eigenvalues of the parity operator is ± 1. Each elementary particle has been associated to an intrinsic parity, either odd (-1) or even ($+1$). The parity remains conserved in strong and electromagnetic interactions, but is violated in weak interaction.

1.3.11 Charge Conjugation (C)

In particle physics, the term *charge* is used in more wider sense. It does not include only the electric charge (Q) but also other charges like the lepton charge (L), baryon charge (B), strangeness (S), isospin (T_3) *etc.* The charge conjugation is an operation that reverses the sign of all these charges. It, however, leaves other properties like the mass, energy, momentum unchanged. The charge conjugation operation transforms the particle into antiparticle. The operation is described by an operator $\hat{C}$ which operating on a wave function of a particle (ψ) transforms into the wave function of its antiparticle ($\bar{\psi}$) i.e. $\hat{C}\psi = \bar{\psi}$. Just like the parity operator, $\hat{C}^2\psi = \psi$. The charge conjugation symmetry is conserved in strong interaction. However, it is violated in weak interaction.

1.4 The Eightfold Way

The garden of elementary particles 'which seemed so tidy in 1947 had grown into a jungle by 1960, and hadron physics could only be described as chaos. The plethora of strongly interacting particles was divided into two great families−the baryons and the mesons−and the members of each family were distinguished by charge, strangeness and mass; but beyond that there was no rhyme or reason to it all. This predicament reminded many physicists of the situation in chemistry a century earlier, in the days before the Periodic Table, when scores of elements had been identified, but there was

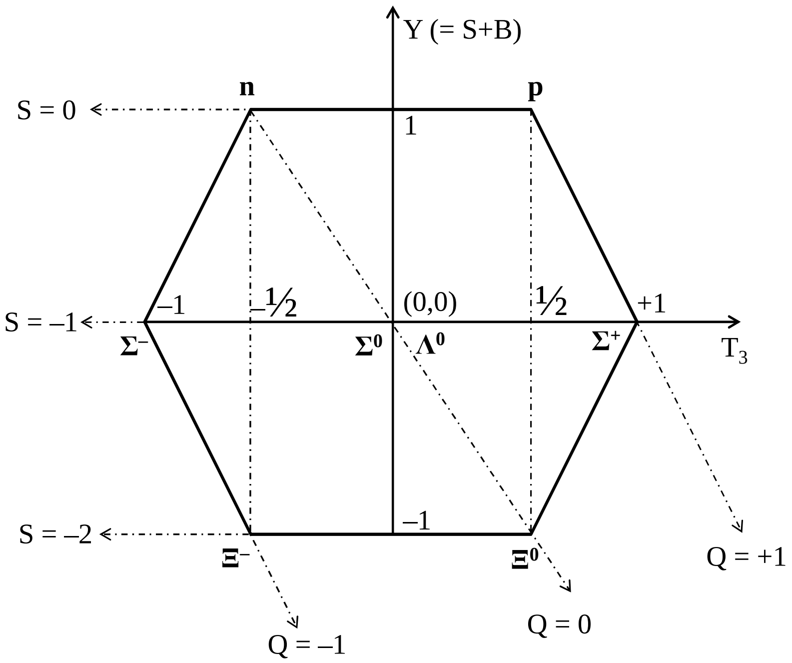

Figure 1.2: The baryon octet

no underlying order or system. In the 1960 the elementary particles awaited their own *Periodic Table*'[2].

The Mandeleev of elementary particle physics was M. Gell-Mann who introduced the so called eightfold way in 1961. The eightfold way arranges the baryons and mesons into wired geometrical pattern in $Y - T_3$ plot.

1.4.1 The baryon octet

Eight lightest, spin 1/2, even parity ($J^p = \frac{1}{2}^+$) baryons fit into a hexagonal array with six particles at six corners and two particles at the center (figure 1.2).

As can be seen from the $Y - T_3$ plot (figure 1.2), the particles lying in the same horizontal line have same strangeness (S). $S = 0$ for n and p at the top line, $S = -1$ for the three Σ's and Λ at the middle line, and $S = -2$ for the two Ξ's at the bottom line.

Similarly, the particles along the downward-slopping are associated to same electrical charge (Q). The proton and Σ^+ have same charge $Q = +1$ (in units of the proton charge), both of Σ^- and Ξ^- have $Q = -1$ and the rests (n, Σ^0, Λ, Ξ^0) along the diagonal line have $Q = 0$.

---

[2] Introduction to Elementary Particles, David Griffiths

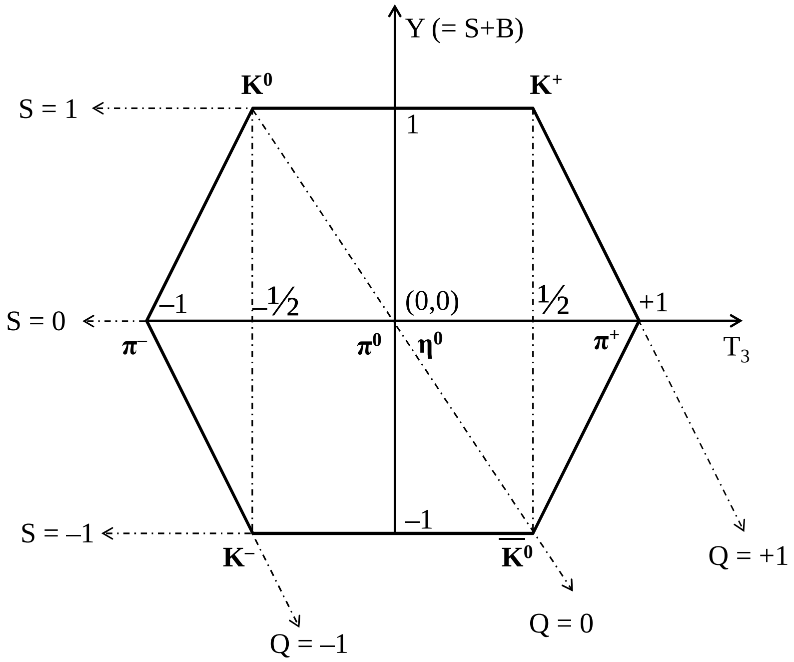

Figure 1.3: The meson octet

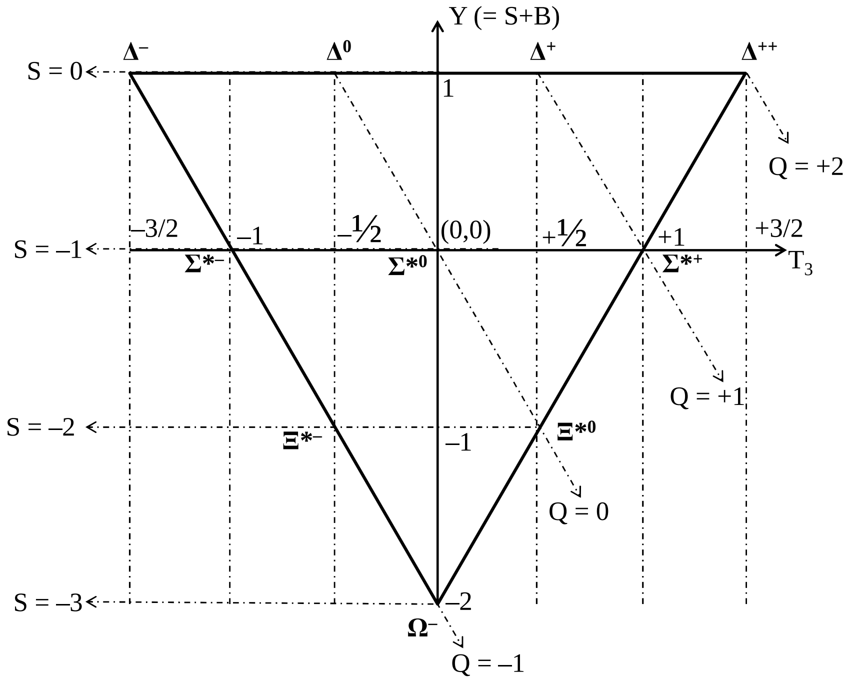

Figure 1.4: The baryon decuplet

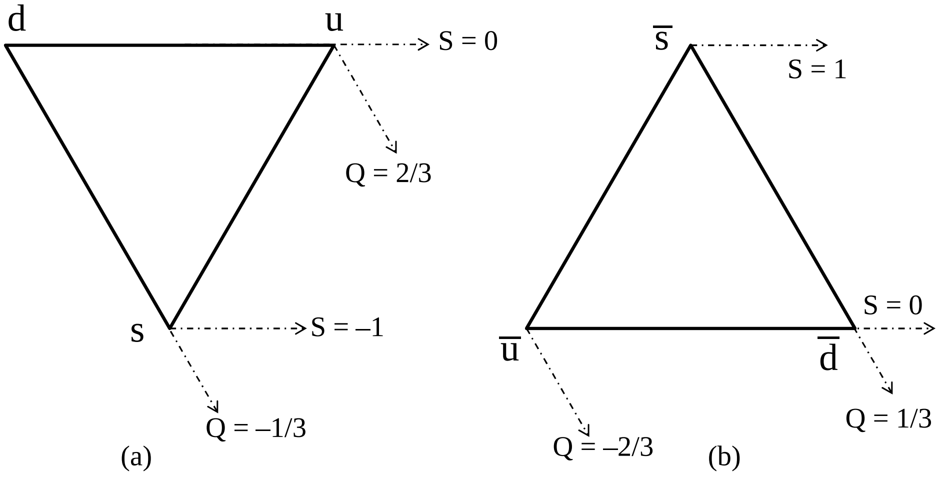

Figure 1.5: The Eightfold Way of quarks and antiquarks

1.4.2 The meson octet

In a fashion similar to that the baryon octet, eight lightest mesons have been arranged with six mesons at six corners and two mesons at the center. All the mesons have intrinsic spin 0 and odd parity ($J^p = 0^-$).

Once again, the particles with same strangeness lie along the horizontal lines while the particles with like charge lie along the diagonal lines. As can be read from the figure 1.3, K^0 and K^+ have same strangeness $S = +1$, K^- and $\bar{K}^0$ have $S = -1$, and the three π's and η have $S = 0$. Similarly, K^+ and π^+ have same charge $Q = +1$, π^- and K^- have $Q = 0$ and the rests (K^0, π^0, η, $\bar{K}^0$) have $Q = 0$.

1.4.3 The baryon decuplet

There are geometrical patterns other than the hexagonal one. Ten heavier baryons are arranged in a triangular pattern as shown in the figure 1.4. Each particle within the baryon decuplet is spin 3/2 and even parity ($J^p = \frac{3}{2}^+$). Like the baryon octet and the meson octet, particles with same strangeness lie along the horizontal lines while the particles with same charge lie along the downward-sloping lines.

1.5 Quark Model

'But the very success of the Eightfold Way begs the question: Why do the hadrons fit into these curious pattern? The Periodic Table had to wait many years for quantum mechanics and the Pauli exclusion principle to provide its explanation. An understanding of the Eightfold Way, however, came already in 1964, when Gell-Mann and Zweig independently

Table 1.4: Properties of quarks and anti-quarks

q or, $\bar{q}$	Q	S	J	B
u (up)	$+\frac{2}{3}$	0	$\frac{1}{2}$	$+\frac{1}{3}$
d (down)	$-\frac{1}{3}$	0	$\frac{1}{2}$	$+\frac{1}{3}$
s (strange)	$-\frac{1}{3}$	-1	$\frac{1}{2}$	$+\frac{1}{3}$
$\bar{u}$	$-\frac{2}{3}$	0	$\frac{1}{2}$	$-\frac{1}{3}$
$\bar{d}$	$+\frac{1}{3}$	0	$\frac{1}{2}$	$-\frac{1}{3}$
$\bar{s}$	$+\frac{1}{3}$	$+1$	$\frac{1}{2}$	$-\frac{1}{3}$

proposed that all hadrons are in fact composed of even more elementary constituents, which Gell-Mann called quarks'[3].

The quarks are of three types (or *flavours*) forming a triangular Eightfold Way pattern (figure 1.5(a)). These are *up* quark (u), *down* quark (d) and *strange* quark (s). The u carries a charge of $2/3$ while each of d and s carries a charge of $-1/3$. The u and d do not carry any strangeness ($S = 0$) while the s carries a strangeness of -1. Corresponding to each quark (q) there exists an anti-quark ($\bar{q}$) with opposite charge and strangeness[4]. The antiquarks also form a similar triangular Eightfold Way pattern (figure 1.5(b)). Each quark and antiquark are spin $1/2$ particles and hence fermions.

The quark model asserts that

1. Every baryon is composed of three quarks and every antibaryon is composed of three antiquarks.

2. Every meson is composed of a quark and an antiquark.

These two rules allow us to find out the quark content of the baryon octet, meson octet and the baryon decuplet. What we require is to look at the charge and strangeness of the hadron and find a suitable combination of the quarks and the antiquarks which fits to that charge and strangeness. Let us find out the quark content of proton. It is of charge $Q = 1$, strangeness $S = 0$ and it is a baryon (and hence composed of three quarks). Hence the suitable combination is uud. Similarly, for the π^- meson ($Q = -1$, $S = 0$, one quark and one antiquark), the quark content is $\bar{u}d$. The quark contents of baryon octet, baryon decuplet and the meson octet are given in Table 1.5, Table 1.6 and Table 1.7 respectively.

---

[3] Introduction to Elementary Particles, David Griffiths

[4] In addition, there are three more quarks namely, *charm* quark (c), *bottom* quark (b), *top* quark (t), and three anti-quarks $\bar{c}$, $\bar{b}$ and $\bar{t}$. The charm quark carries *charm quantum number* $C = 1$ (for $\bar{c}$, $C = -1$). Another new quantum number, the *beauty quantum number* (b) has been assigned to the bottom quark. For b quark, it is 1 and for $\bar{b}$, it is -1. Likewise, the top quark carries a *truth quantum number* $t = 1$. For $\bar{t}$, it is -1.

Table 1.5: Quark content of baryon octet

Particles	Charge (Q)	Strangeness (S)	Quark content (qqq)
n	0	0	udd
p	1	0	uud
Σ^-	-1	-1	dds
Σ^0	0	-1	uds
Λ^0	0	-1	uds
Σ^+	1	-1	uus
Ξ^-	-1	-2	dss
Ξ^0	0	-2	uss

Table 1.6: Quark content of baryon decuplet

Particles	Charge (Q)	Strangeness (S)	Quark content (qqq)
Δ^-	-1	0	ddd
Δ^0	0	0	udd
Δ^+	1	0	uud
Δ^{++}	2	0	uuu
Σ^{*-}	-1	-1	dds
Σ^{*0}	0	-1	uds
Σ^{*+}	1	-1	uus
Ξ^{*-}	-1	-2	dss
Ξ^{*0}	0	-2	uss
Ω^-	-1	-3	sss

Table 1.7: Quark content of meson octet

Particles	Charge (Q)	Strangeness (S)	Quark content ($q\bar{q}$)
K^0	0	1	$d\bar{s}$
K^+	1	1	$u\bar{s}$
π^-	-1	0	$\bar{u}d$
π^0	0	0	$u\bar{u}$
η^0	0	0	$d\bar{d}$
π^+	1	0	$u\bar{d}$
K^-	-1	-1	$s\bar{u}$
$\bar{K}^0$	0	-1	$s\bar{d}$

1.6 The Standard Model

The Standard Model of particle physics is a theory of elementary particles and the way they interact. It concerns three fundamental interactions, the strong interaction, the electromagnetic interaction and the weak interaction[5]. The model includes members of two major classes of elementary particles, fermions and bosons; which in turn can be distinguished by other characteristics such as leptonic charge, color charge *etc.* as described in the following.

1.6.1 Fermions

In Standard Model, there are six leptons (electron, electron neutrino, muon, muon neutrino, tauon and tauon neutrino) and six quarks (up, down, charm, strange, top and bottom) which are spin$-1/2$ particles and known as fermions. Quarks carry color charge and take part in strong interaction. Each quark appears in three colors (R, G, B) and hence the total number of quarks is 18. The leptons, however, do not carry any color charge and take party in weak interaction. Each lepton and quark has its antiparticle. Hence the number of fermions in the Standard Model is 48.

1.6.2 Bosons

In Standard Model, the bosons are the force carriers or the mediators of the strong, weak and electromagnetic interactions. Except the Higgs boson, all the mediators in the Standard Model are vector bosons with spin equal to 1. The vector bosons include photon, gluon, $W^\pm$ and Z^0 bosons.

The photon is massless and mediates the electromagnetic force between electrically charged particles. The $W^\pm$ and Z^0 bosons are massive and mediate the weak interaction between the particles of different flavors (all quarks and leptons). The $W^\pm$ bosons carry electric charge of $+1$ and -1 and couple to the electromagnetic interaction. Gluons

---

[5] The Standard Model does not include the gravitational interaction

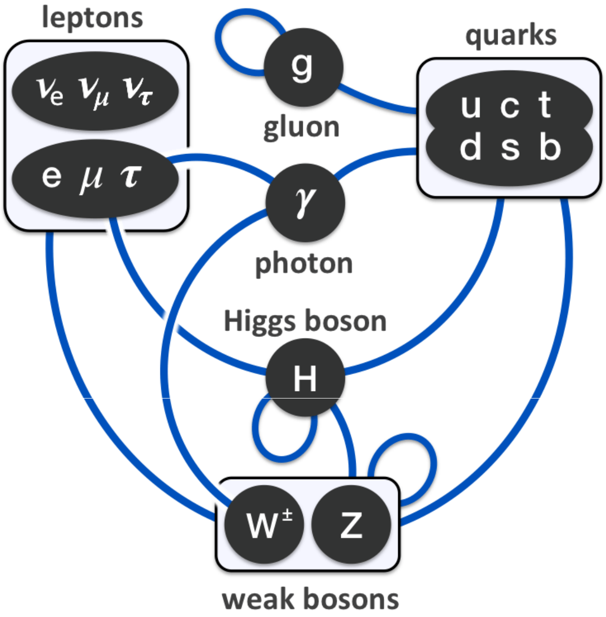

Figure 1.6: Schematic of interaction between the particles described in Standard Model (Courtesy: Wikipedia)

appear in eight flavors and mediate the strong interaction between the particles having color charges (the quarks). Gluons are massless. Because the gluons have an effective color charge, they also interact among themselves.

The Higgs boson is a massive scalar boson (spin $= 0$) named after one of its introducers Peter Higgs. The existence of the Higgs particles has been tentatively confirmed in 2013. ‘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 $W^{\pm}$ and Z^0 bosons are very heavy. Elementary particle masses, and the differences between electromagnetism (mediated by the photon) and the weak force (mediated by the $W^{\pm}$ and Z^0 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 tauon) and quarks. As the Higgs boson is massive, it must interact with itself’ [6]. Figure 1.6 schematically describes the interaction between the elementary particles via different mediators as prescribed in the Standard Model.

Thus the total number of particles in the Standard Model is 61. Though the Standard Model does not include the gravitational interaction, it explains a wide variety of experimental results for which it is sometimes regarded as a “theory of almost everything”.

---

[6] Wikipedia