18.10. Classification of elementary particles

All the elementary particles are grouped into three broad classes, baryons, mesons and leptons. The chief characteristic of the first two is that they are subject to strong nucleur interaction. Such particles are called *hadrons*. The leptons on the other hand are not subject to strong nuclear interaction. They are subject to weak nuclear interaction. The particles belonging to all the groups are of course subject to gravitational interaction, if they have mass. Besides, the charged particles in all the groups are subject to electromagnetic interaction.

Baryons : These include the nucleons (protons and neutrons) and the hyperons, which include the $\Lambda^0, \Sigma^\pm, \Sigma^0, \Xi^-, \Xi^0$ and Ω^- hyperons and their antiparticles. They are all strange particles. The strangeness quantum number S is conserved during their production by strong interaction. However, S is not conserved in the weak decay suffered by most of these particles. However, in the electromagnetic decay (as for Ξ^0) S is conserved.

All the hyperons are heavier than the nucleons. Their important properties are discussed in § 18.8 and are listed in Table 18.2.

The baryons have half-integral spin and even parity. They are fermions, obeying Fermi-Dirac statistics.

All baryons are characterized by a baryonic charge (baryon number) $B = 1$, which is conserved in their production and decay.

It is believed that the net number of baryons in the universe is a conserved quantity. Antibaryons have $B = -1$ so that the production of baryon-antibaryon pairs has no effect on the net baryon number.

We shall discuss about the quark structure of the baryons in § 18.16.

Mesons : These belong to the hadron class, with baryonic charge $B = 0$. Mesons include pions ($\pi^{\pm}, \pi^{0}$), kaons ($K^{\pm}, K^{0}$), η^{0} and ($D^{\pm}, D^{0}$). Of these the kaons are strange particles with $S = 1$. The rest are non-strange ($S = 0$). π^{0} and η^{0} decay by electromagnetic interaction. The rest undergo weak decay.

As discussed in Ch. XVII, the pions are the quanta of the strong internucleon field. All mesons have spin-parity of 0^{-}. They are bosons obeying Bose-Einstein statistics. The D-mesons are heavier than the nucleons. The others are lighter than the nucleons.

The important properties of the mesons are listed in Table 18.2. Some of these have been discussed in § 18.17.

Leptons : These are weakly interacting particles with the baryon number $B = 0$. Charged leptons also show electromagnetic interaction. All evidences point to the fact that the leptons have no internal structure and are point particles. They are considered more elementary than the hadrons which have internal structure (quark structure). Leptons and quarks seem to be at the same level of elementariness.

Apart from the electron-positron ($e^{+}e^{-}$) and $\mu^{+}\mu^{-}$ pairs, a third type of lepton, known as the τ–lepton or tauon was discovered around 1974-75. Both the τ^{+} and τ^{-} are known, which are antiparticles of each other. They are heavier than the nucleons.

Each type of lepton is associated with a neutrino, *viz*., the electron-neutrino (ν_e), the muon-neutrino (ν_{μ}) and the tauon-neutrino (ν_{τ}). All of them are probably mass zero particles.

The association of the charged leptons with their neutrinos (neutral) is believed to arise from the empirical law of leptonic charge (lepton number) conservation. There are three types of lepton numbers, l_e, l_{μ} and l_{τ}, all of which have the value +1 for the leptons and −1 for the antileptons. Thus in reactions involving leptons the three different lepton numbers must be conserved separately, l_e between electrons and e-neutrinos and their antiparticles (e^{+} and $\overline{\nu}_e$), l_{μ} between μ^{-} and ν_{μ} and their antiparticles (μ^{+} and $\overline{\nu}_{\mu}$) and l_{τ} between τ^{-} and ν_{τ} and their antiparticles (τ^{+} and $\overline{\nu}_{\tau}$). As an example, an electron can be destroyed through annihilation by combining with a positron ($l_e - l_e = 0$) or can be changed into a ν_e (both are $l_e = 1$ particles).

Some important properties of the different leptons are listed in Table 18.2.

18.15 Symmetry classification of elementary particles

We have seen that the large number of elementary particles discovered in recent years can be classified on the basis of their interactions. Since all charged particles are subject to electromagnetic interaction, the interactions which form the basis of classification are primarily the strong nuclear and the weak nuclear interactions. Particles which are subject to the strong nuclear interactions are grouped as hadrons while those subject to weak nuclear interactions are grouped as leptons. Hadrons can again be divided into two classes, baryons and mesons. Baryons obey Fermi-Dirac statistics and are fermions while the mesons which obey Bose-Einstein statistics are bosons. The mesons constitute the quanta of the internucleon field.

Hadrons of each of the above two groups can be classified on the basis of their isospin (I) which determines the multiplicity $M = 2I + 1$. For each group of particles of given I, the constituent particles have different values of the third component of the isospin (I_3) which can have the values $I, I-1 \ldots\ldots -I$. For a system of more than one particle, the isospin vectors can be compounded by the vector addition method while the values of their I_3 are added algebraically. For example, if there are two isospin doublets each with $I = 1/2$, $I_3 = \pm 1/2$ then by the above method of compounding, we can obtain the isospin multiplicities of particular groups made up from the above two isospin doublets. The process of forming different isospin multiplets from a number of isospin doublets, as above, is carried out by the rules of a special type of transformation, known as the Special Unitary Group of rank 2 or SU_2. The generators of such transformations are the 2×2 Hermitian matrices. The members of a doublet *e.g.*, p, and n, are transformed into each other by the SU_2 transformation.

There is a simpler graphical method of determining the multiplicities of the composite systems made from the basic isospin doublets such as p and n. The method is illustrated in Fig. 18.9 which is known as the *weight diagram*. The bottom line in the figure shows the two components of the isospin with $I_3 = +1/2$ and $-1/2$ respectively. We then superpose on this the second doublet in such a way that the centre of symmetry of the former is made to coincide with the positions of two components $+1/2$ and $-1/2$ of the first successively as shown on the middle line of the figure.

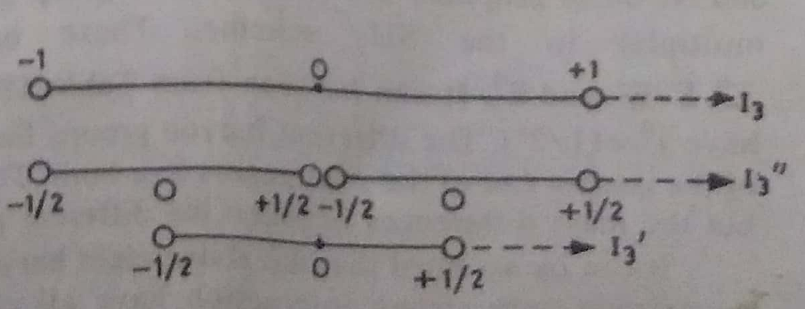


Fig. 18.9. Weight diagram for generating an isospin triplet and an isospin singlet from two isospin doubles.

The final result can be seen on the topmost line which shows the four I_3 values of the composite system *viz*., $+1, 0, -1$ (a triplet) and 0 (a singlet). The first three belong to a symmetric isospin triplet for which $I = 1$ while the second belongs to an antisymmetric isospin singlet with $I = 0$. The above result is written symbolically as

$$2 \otimes 2 = 3 \oplus 1$$

To get the higher multiplicities, the above method can be repeated by superposing the weight diagram of the basic isospin doublet first on that of the isospin triplet shown above and then on the isospin singlet to generate a quadruplet and two doublets :

$$2 \otimes 3 = 4 \oplus 2$$

and

$$2 \otimes 1 = 2$$

If the constituent particles belonging to a given isospin multiplet were subject to strong nuclear force only they would all have the same mass. However, the presence of the electromagnetic interaction breaks the symmetry so that the constituent particles have slightly different masses. Examples are the proton and the neutron belonging to the isospin doublet 'nucleon' which have slightly different masses because of the charge on the proton. Other examples are the three pions $\pi^{\pm}, \pi^0$ which have slightly different masses. due to the symmetry breaking role of the e.m. interaction.

The situation is similar to the effect of the spin-orbit force which splits the energy levels of given L and S into $(2S + 1)$ close lying components (for $L > S$), known as the fine-structure splitting of the atomic energy levels. The symmetry is broken due to the presence of the L-S force.

M. Gell-Mann and Y. Ne'eman independently proposed an extension of the scheme of classification of the elementary particles (1962) based on the values of I_3 and hypercharge $Y = B + S$ (see Eq. 18.11-13), known as the special Unitary Group of rank 3 or SU_3 symmetry (also known as the octet symmetry or eight-fold way).

In place of the simple isotopic invariance assumed in SU_2, Gell-Mann and Ne'eman proposed the existence of a group of eight baryons in a super multiplet in the SU_3 scheme. These baryons are $p, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^- \Xi^-$ and Ξ^0. It can be seen from Table 18.2 that all these baryons have $J^P = (1/2^+)$. The different baryon groups have different values either of the isospin I or of the strangeness S or both. They have different masses but the mass differences between the different groups are within 15%.

It can be assumed that the above eight baryons formed as a result of a common very strong interaction have all equal masses (eight fold degeneracy in strangeness and charge). This octet symmetry is broken due to the action of a moderately strong interaction (which depends on strangeness). This removes the strangeness degeneracy between the groups of different values of S within the superm-ultiplet. Finally in each group of a given S, the charge degeneracy is removed by the electromagnetic intraction. So that the components of same I with different I_3 have slightly different masses. The first splitting (due to the moderately strong interaction) is of the order $\Delta M/M \sim 10\%$ to 20% while the second splitting due to e.m. interaction within each group of the same S is of the order $\Delta M/M \sim 1\%$.

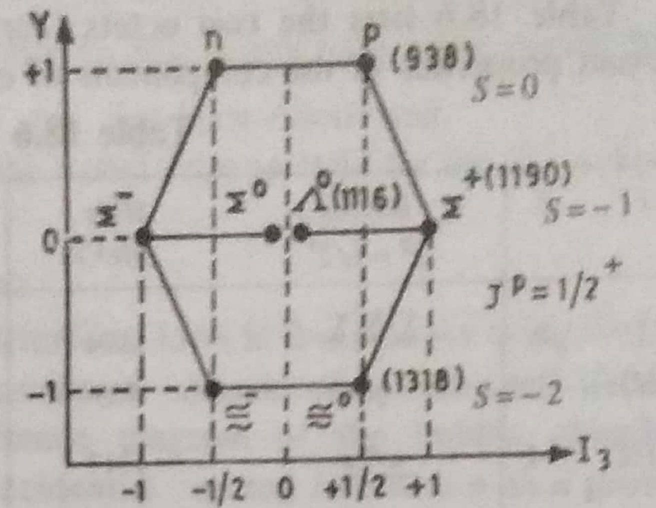


Fig. 18.10. Weight diagram ($I_3 - Y$ plot) for the baryon octet.

This scheme of classification on the basis of octet symmetry is best demonstrated by making a graphical plot (weight-diagram) of the baryon octet in the $I_3 - Y$ plane shown in Fig. 18.10. The members of the octet super-multiplet) form a symmetric hexagon with one baryon at each corner and two at the centre of the hexagon. As can be seen from the figure, the two nucleons ($S=0$) with $I_3 = \pm 1/2$ fall on the line $Y = B + S = 1$; the three Σ − hyperons ($S=-1$) with $I_3 = \pm 1, 0$ fall on the line $Y=0$; and the two Ξ-hyperons ($S=-2$) with $I_3 = \pm 1, 0$ fall on the line $\pm Y = -1$. Finally the single Λ-hyperon ($S=-1$) with $I_3 = 0$ is at the centre of the figure with $Y=0$ along with Σ_0.

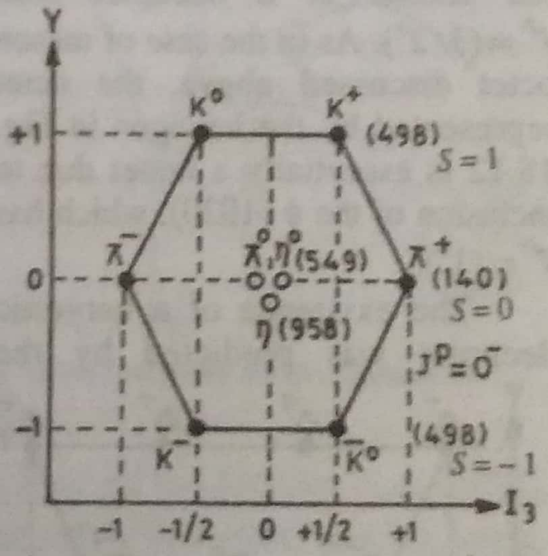


Fig. 18.11 Weight diagram for a meson octet.

A similar super-multiplet for mesons is shown in Fig. 18.11 consisting of the following members: the two kaons ($S=1$) with $I_3 = \pm 1/2$ on the line $Y=1$; the three pions ($S=0$) with $I_3 = \pm 1, 0$ on the line $Y=0$; and the two antikaons ($S=-1$) with $I_3 = \pm 1/2$ on the line $Y=-1$. The eighth member of the octet is the isospin singlet η^0-meson ($I_3 = 0, Y = 0$). It should be noted that in the weight diagram of the meson octet in Fig. 18.11, we have included the resonance particle η_0 (958) with $J^P = (0^-)$ thereby making it essentially a nonet. All the mesons in this diagram are pseudoscalar. The occurrence of the nonet is due to the

Table 18.6 lists the two octets (baryonic and mesonic) with the relevant properties of the components of each.

Table 18.6

I	Y	Baryon $J^P = 1/2^+$	Mass (MeV)	Meson $J^P = 0^-$	Mass (Mev)
1	0	$\Sigma^+\Sigma^0\Sigma^-$	1194	$\pi^+\pi^0\pi^-$	137
1/2	1	$p\,n$	939	K^+K^0	496
1/2	–1	$\Xi^0\Xi^-$	1317	$K^-\overline{K}^0$	496
0	0	Λ^0	1116	η^0	549

The masses shown in the table are the average masses for the isospin multiplet in each case.

Similar weight diagrams in the $Y - I_3$ plane can be constructed for the resonance particles. Two examples are shown in Figs. 18.12 and 18.13. The first is mesonic resonance octet with $J^P = (1^-)$ and the second is a decuplet with $J^P = (3/2^+)$. As in the case of meson octet discussed above, the octet represented by the hexagon in Fig. 18.12 is essentially a nonet due to inclusion of the ϕ (1020), which has $J^P = (1^-)$.

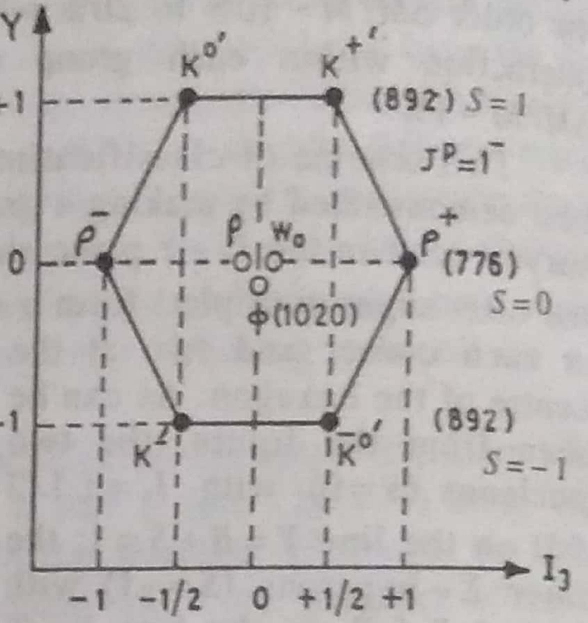


Fig. 18.12. Weight diagram for the meson resonance octet.

The existence of a baryonic decuplet was predicted by the SU$_3$ symmetry. Its weight diagram is an equilateral triangle. It comprises an isotopic quadruplet $\Delta(1232)$ with $S=0$, $Y=1$ and $I=3/2$; a triplet Σ^0 (1385) with $S=-1$, $Y=0$ and $I=1$; a doublet $\Xi^{0,-1}$ (1530) with $S=-2$, $Y=-1$ and $I=1/2$ and a singlet Ω^- (1632) with $S=-3$, $Y=-2$ and $I=0$.

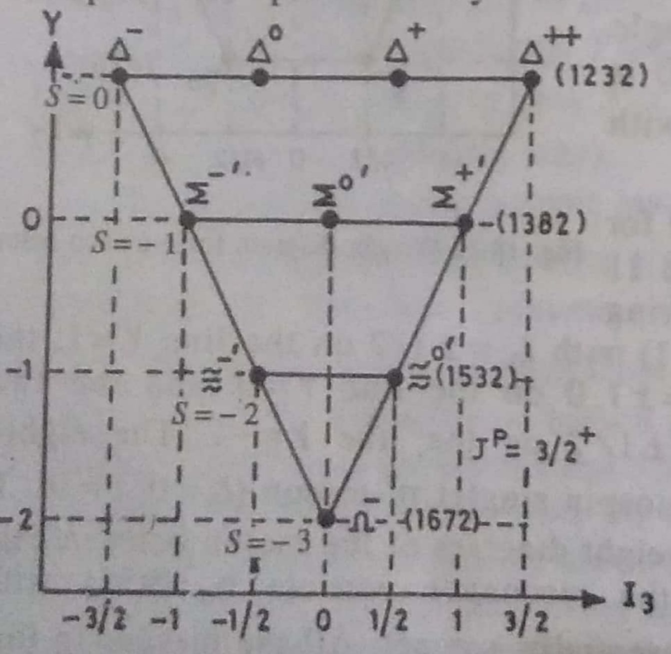


Fig. 18.13. Weight diagram for the baryon resonance decuplet.

At the time the decuplet was predicted, the existence of the Ω^- was not known. it was subsequently discovered which marked a great triumph for the SU_3 symmetry of Gell-Mann and Ne'eman. The properties of the Ω^- predicated by SU_3 theory have subsequently been verified. The antiparticle of Ω^- has also been discovered.

Gell-Mann was awarded the Nobel Prize in 1964 for the SU_3 scheme of classification.

Discovery of Ω^- Hyperon:

The Ω^- hyperon was discovered in 1964 at Brookhaven using the 2m hydrogon bubble chamber exposed to K^- mesons of momentum 5 GeV/c.

As shown in the schematic diagram of the bubble chamber photograph in Fig. 18.14 an incident K^- meson interacts with a proton producing the Ω^- according to the equation

$$K^- + P \longrightarrow \Omega^- + K^+ + K^-$$

$$S = -1 \quad 0 \quad -3 \quad +1 \quad -1$$

The strangeness quantum numbers of the incident and product particles are shown below the particles. The neutral K^o is not observed, but its presence is inferred from the analysis of energy and momentum balance. The Ω^- decays according to the scheme $\Omega^- \rightarrow \Xi^0 + \pi^-$. The unobserved Ξ^0 travels some distance before decaying into neutral products $\Lambda^0 \pi^0$: $\Xi \rightarrow \Lambda^0 + \pi^0$. The Λ is detected from the decay $\Lambda^0 \rightarrow P + \pi^-$. The π^0 decays into the two photons $\gamma_1 + \gamma_2$ each of which produces $e^+ e^-$ pairs.

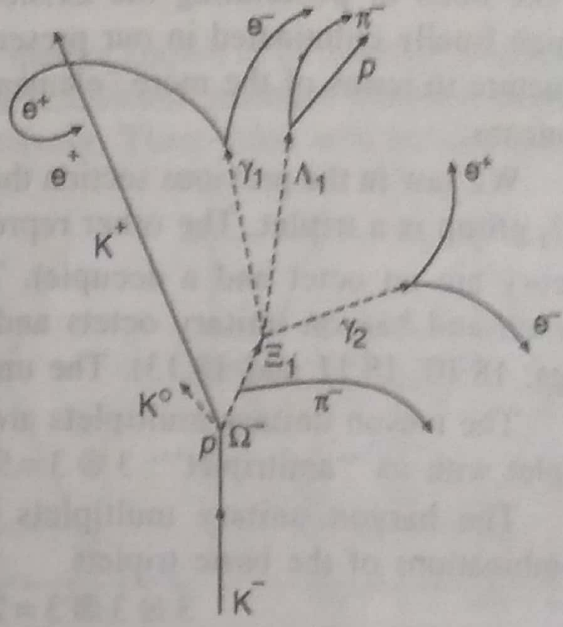


Fig. 18.14 Discovery of Ω^- hyperon.

In the diagram the broken lines denote the unobserved paths of the neutral particles deduced from measurements on the visible particle tracts.

Predictions of SU_3 symmetry : (*i*) One of the predictions is that the masses of the supermultiplet should be connected by the following relationship :

$$M_n + M\ (\Xi)^0 = \{M(\Sigma^0) + 3M(\Lambda^0)\}/2.$$

Susbstitution of the mass value given in Table 18.2 shows that the relation holds within an accuracy of 1%.

(*ii*) Another important prediction is

$$M_n - M_p + M\ (\Xi^-) - M\ (\Xi^0) + M(\Sigma^+) - M\ (\Sigma^-) = 0$$

Again this is found to hold quite well within the limits of experimental errors.

Some predictions are not satisfied. It may be mentioned that unitary symmetry is much broader in scope than the isotopic invariance based on SU_2 symmetry.

The mathematical description of unitary symmetry is obtained with the help of the SU_3 group for three row matrices. The simplest SU_3 multiplet is a triplet while the simplest SU_2 multiplet is doublet as we saw earlier. The next more complicated representation of the SU_3 group is the baryon octet.

24.7 THE QUARK MODEL

Murray Gell-Mann and G. Zweig proposed the quark model in 1964. This theory is based on the idea that the hadrons are built up from a limited number of "fundamental" units, which have acquired the name quarks. The original three quarks were labeled u (for "*up*"), d (for "*down*") and s (for "*strange*").

u quark has electric charge $+\frac{2}{3}e$ and strangeness 0.

d quark has electric charge $-\frac{1}{3}e$ and strangeness 0.

s quark has electric charge $-\frac{1}{3}e$ and strangeness -1.

Each quark has a baryon number of $B = 1/3$.

Each quark has an antiquark associated with it ($\overline{u}, \overline{d}$, and $\overline{s}$). The magnitude of each of the quantum numbers for the antiquarks has the same magnitude as those for the quarks, but the sign is changed.

Compositions of hadrons according to the quark model

Hadrons may be *baryons* or *mesons*. A baryon is made up of three quarks. For example, the proton is made up of two u quarks and a d quark (uud). For these quarks, the electric charges are $+2/3$, $+2/3$, and $-1/3$, for a total value of $+1$. The baryon numbers are $+1/3$, $+1/3$ and $+1/3$, for a total of $+1$. The strangeness numbers are 0, 0 and 0 for a total strangeness of 0. All are in agreement with the quantum numbers for the proton. Fig. 24.1 shows quark models of the proton, antiproton, neutron and antineutron. Electric charges are given in units of e.

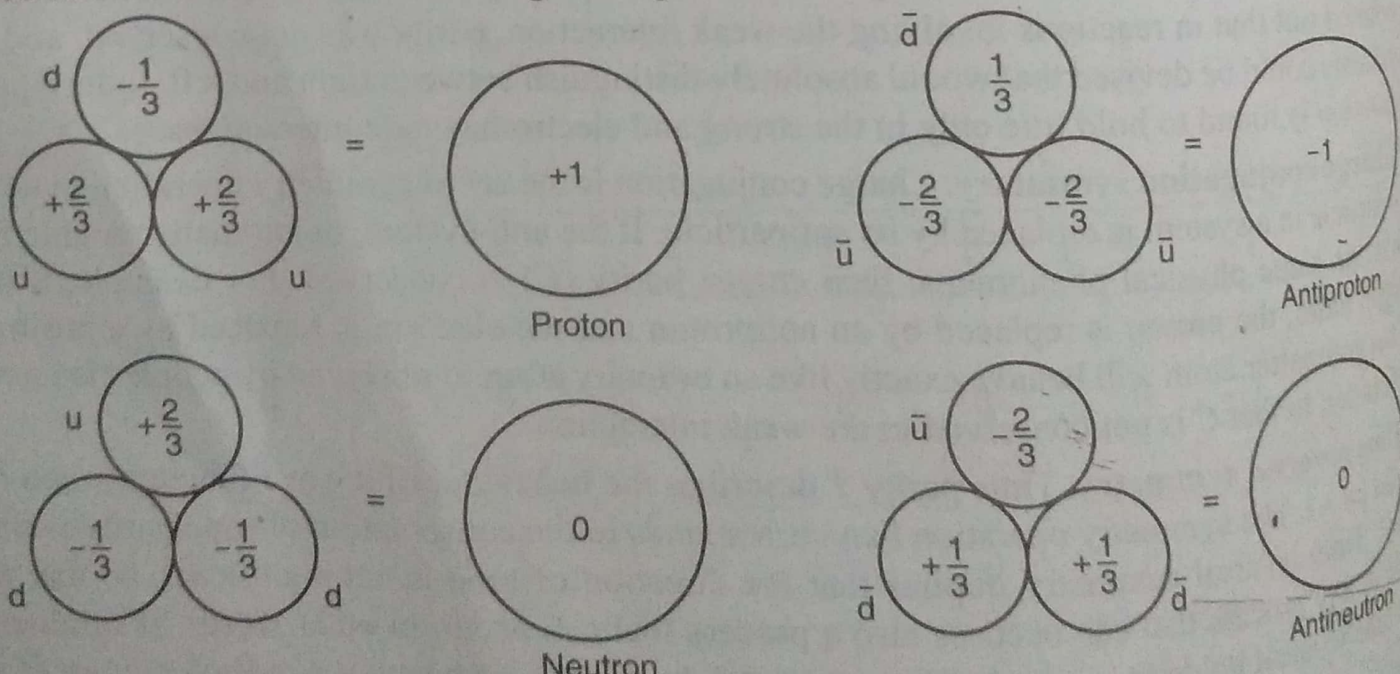


Fig. 24.1

A meson is made up of one quark and one antiquark. For example, the π^+ meson is the combination of a u quark and a d antiquark $(u\bar{d})$. Electric charges of these quarks are + 2/3 and + 1/3 for a total of + 1. The baryon numbers are + 1/3 and – 1/3 for a total baryon number of 0. The strangeness numbers are 0 and 0 for a total of 0. All of these are in agreement with the quantum numbers for the pi-meson. Quarks all have spins of 1/2, which accounts for the observed half-integral spins of baryons and the 0 or 1 spins of mesons.

All known hadrons can be explained in terms of the various quarks and their antiquarks. Table 24.4 shows the quark contents of five hadrons and how they account for the observed charges, spins, and strangeness numbers of these particles.

Table 24.4. Compositions of some hadrons according to the Quark Model

Hadron	*Quark content*	*Baryon number*	*Charge, e*	*Spin*	*Strangeness*
π^+	$u\bar{d}$	$\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$\uparrow\downarrow=0$	$0+0=0$
K^+	$u\bar{s}$	$\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$\uparrow\downarrow=0$	$0+1=+1$
P^+	uud	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$	$\uparrow\uparrow\downarrow=\frac{1}{2}$	$0+0+0=0$
n^0	ddu	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$-\frac{1}{3}-\frac{1}{3}+\frac{2}{3}=0$	$\downarrow\downarrow\uparrow=\frac{1}{2}$	$0+0+0=0$
Ω^-	sss	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$-\frac{1}{3}-\frac{1}{3}-\frac{1}{3}=-1$	$\uparrow\uparrow\uparrow=\frac{3}{2}$	$-1-1-1=-3$

Coloured quarks and gluons : There were problems with the quark model, one of them being Ω^- hyperon. It was believed to contain three identical s quarks (sss). This violates the Pauli exclusion principle, that prohibits two or more fermions from occupying identical quantum states. The proton, neutron, and others with two identical quarks would violate this principle also. We can resolve this difficulty by assigning a new property to the quarks. We can regard this new property as an additional quantum number that can be used to label the three otherwise identical quarks in the Ω^-. If this additional quantum number can take any one of three possible values, we can restore the Pauli principle by giving each quark a different value of this new quantum number, which is known as *colour*. The three colours are labeled red (R) blue (B) and green (G). The Ω^- for example, would then $s_R\,s_B\,s_G$. The antiquark colours are antired $(\bar{R})$ antiblue $(\bar{B})$ and antigreen $(\bar{G})$.

An essential component of the quark model with colour is that *all observed meson and baryon states are "colourless"*, *i.e.*, either colour anticolour combinations in the case of mesons, or equal mixtures of R, B and G in the case of baryons.

Since hadrons seem to be composed of quarks, the strong interaction between hadrons should ultimately be traceable to an interaction between quarks. The force between quarks can be modeled as an exchange force, mediated by the exchange of massless spin – 1 particles called gluons. Eight gluons have been postulated. The field that binds the quarks is a *colour field. Colour is to the strong interaction between quarks as electric charge is to the electromagnetic interaction between electrons.* It is the fundamental strong "charge" and is carried by the gluons. The gluons must therefore be represented as combinations of a colour and a possibly different anticolour. The gluons are massless and carry their colour-anticolour properties just as other particles may

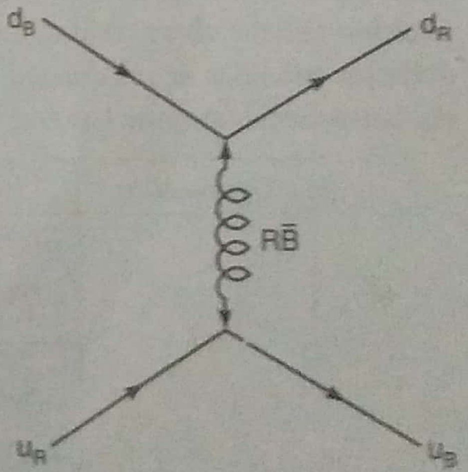
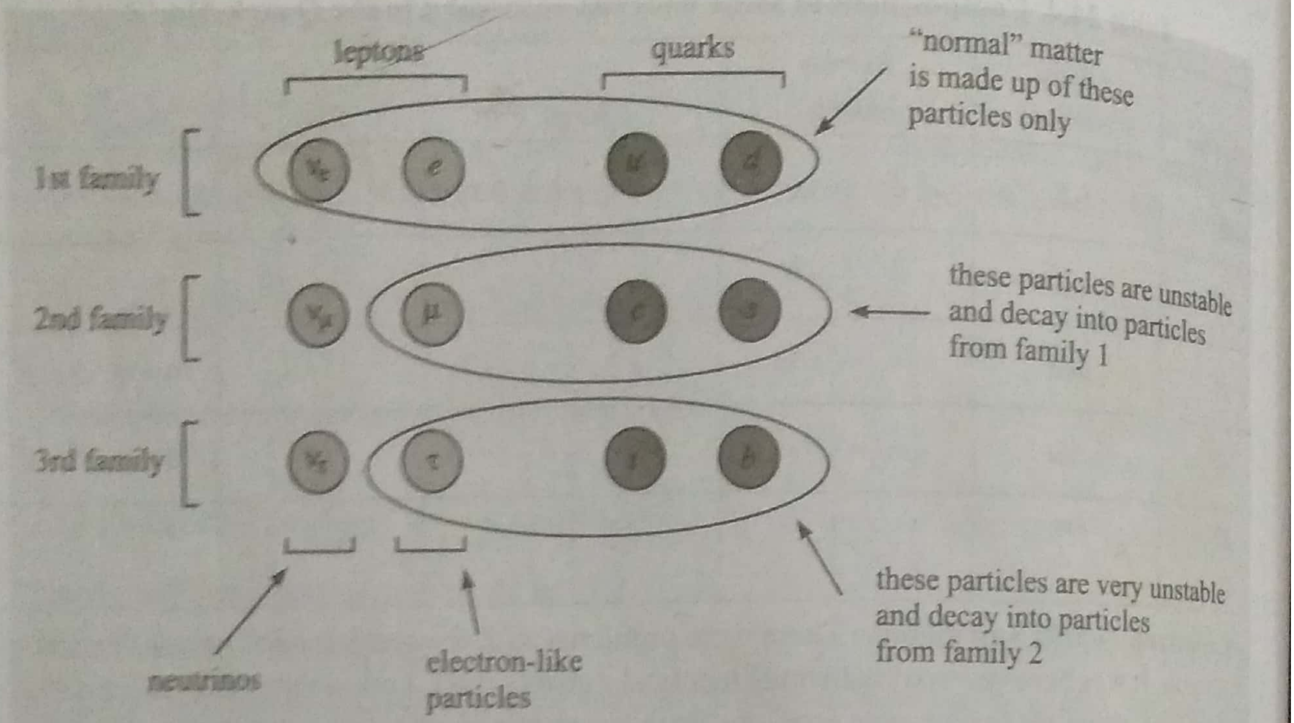


Fig. 24.2

carry electric charge. For example, Fig. 24.2 shows a gluon RB being exchanged by red and blue quarks. In effect the red quark emits its redness into a gluon and acquires blueness by also emitting antiblueness. The blue quark, on the other hand, absorbs the $R\bar{B}$ gluon, canceling its blueness and acquiring a red colour in the process.

Charm, Bottom, and Top. In 1970, Glashow, Iliopoulis, and Maiani proposed the existence of a fourth quark, called *c* or *charmed* quark. The charmed quark was suggested to explain the suppression of certain decay processes that are not observed. With only three quarks, the processes would proceed at measurable rates and should have been observed. The charm quark has a charge of $\frac{2}{3}e$, strangeness 0 and a charm quantum number of + 1. Other quarks have 0 charm.



In 1977, a new particle was discovered at Fermi Lab that provided evidence for yet another quark. This particle, called the upsilon-meson, was thought to be made up of the new quark called *b* (for bottom or beauty) along with the associated antiquark $\bar{b}$. *b* quark has electric charge –1/3e.

Because quarks seem to come in pairs, it is expected that there is a partner to the *b* quark, called *t* (for top, if *b* = bottom, or truth, if *b* = beauty). It has a charge of + 2/3*e*.

Three generations of quarks and leptons. Both leptons and quarks appear to come in three generations of doublets, with all particles having spin 1/2. Table 24.5 shows the properties of the three generations of quarks and leptons. The first generation contains two leptons, the electron and the electron neutrino, and two quarks, up and down. All the properties of ordinary matter can be understood on the basis of these particles. The second generation includes the muon and muon-neutrino and the charm and strange quarks. These particles are responsible for most of the unstable particles and resonances created in high energy collisions. The third generation includes the tau and the tau-neutrino and the top and bottom quarks.

Generation	*Lepton*	*Symbol*	*Charge, e*
1	Electron	e^-	– 1
	e-Neutrino	ν_e	0
2	Muon	μ^-	– 1
	μ-Neutrino	ν_μ	0
3	Tau	τ^-	– 1
	τ-Neutrino	ν	0

Table 24.5. Properties of the three generations of Quarks and Leptons

Generation	*Quark*	*Symbol*	*Charge, e*	*Strangeness*	*Charm*
1	Up	*u*	$+\frac{2}{3}$	0	0
	Down	*d*	$-\frac{1}{3}$	0	0
2	Charm	*c*	$+\frac{2}{3}$	0	+ 1
	Strange	*s*	$-\frac{1}{3}$	– 1	0
3	Top	*t*	$+\frac{2}{3}$	0	0
	Bottom	*b*	$-\frac{1}{3}$	0	0

24.2 PARTICLES AND ANTI-PARTICLES

Electron and Positron. The positron and the electron are said to be antiparticles. They have the same mass and the same spin but opposite charge. They annihilate each other with the emission of photons, when they come in contact with each other. The existence of an antiparticle for the electron was actually predicted by Dirac, because of a symmetry of the equations of the relativistic quantum theory of the electron. Positron was discovered by Anderson in 1932.

Proton and antiproton. Dirac's theory, anticipating the positron, could be interpreted as implying a particle identical to the proton, except for a negative charge. The existence of this particle, the *antiproton*, was established in 1955 by Segre, Chamberlain, and their collaborators. Antiprotons were produced by bombarding protons in a target with 6-GeV protons, thereby inducing the reaction

$$p + p(+\text{energy}) \rightarrow p + p + p + \overline{p}$$

The K.E. of the bombarding proton is converted to a proton-antiproton pair plus the K.E. of the four residual particles. Antiprotons interact strongly with matter and annihilate with protons. In a typical annihilation reaction, the rest mass of the annihilating pair appears as five pions and their K.E.

$$p + \overline{p} \rightarrow \pi^{+} + \pi^{-} + \pi^{+} + \pi^{-} + \pi^{0}.$$

Neutron and antineutron. The antiparticle of neutron, *antineutron*, was discovered in 1956 by Cork, Lamberton and Wenzel. The nature of the antineutron is not very well known. Both neutron and antineutron have zero charge and the same mass. However, since neutron is supposed to have a certain internal charge distribution, it is expected that the antineutron has an internal charge distribution opposite to that of the neutron. Antineutron is quickly annihilated, either by a proton or a neutron, usually with the production of several pions. If an antineutron is not annihilated by a nucleon, it decays by the reaction

$$\overline{n} \rightarrow \overline{p} + \beta^{+} + \nu .$$

Neutrino and antineutrino. As discussed in chapter 20, it is possible to avoid violations of the law of conservation of energy, linear and angular momenta and spin by assuming the existence of a particle, called a *neutrino*. It has *charge zero, spin* 1/2, *zero rest mass* (*rest mass very small in comparison with that of the electron*) *and magnetic moment smaller than* 10^{-8} *Bohr magneton or nearly zero.* The neutrino has a finite energy and momentum in flight. It travels with the speed of light *c*. It does not cause ionization on passing through matter.

The antiparticle of neutrino is *antineutrino.* The distinction between the neutrino ν and antineutrino $\bar{\nu}$ is a particularly interesting one. The spin of the neutrino is opposite in direction to the direction of its motion; viewed from behind, the neutrino spins-counterclockwise. But the spin of the antineutrino is in the same direction as its direction of motion; viewed from behind, it spins clockwise. Thus the neutrino moves through space in the manner of a left-handed screw, while the antineutrino does so in the manner of a right-handed screw. Thus a neutrino possesses a "left-handed" helicity; the antineutrino possesses a "right-handed" helicity, *i.e.*, *a neutrino and antineutrino differ only in the sense of their helicity.*

It is customary to call the particle accompanying a positron a neutrino, ν, while that accompanying an electron is called an antineutrino, $\bar{\nu}$. It is important to remember that positrons and electrons are never ejected alone. It is clear from experiments that neutrinos emitted in β decay (positron decay and *K*-capture) have a negative helicity, *i.e.*, they are longitudinally polarized with their spin axes antiparallel to their direction of travel.

$$\mathbf{H} = +1 \text{ for } \bar{\nu} \,;\, \mathbf{H} = -1 \text{ for } \nu .$$

Because of its lack of charge and magnetic moment, a neutrino has essentially no interaction with matter, except that which leads to inverse β decay. This interaction is extremely weak. The cross section for this process is only $\sigma \approx 10^{-48}\ \text{m}^2 \approx 10^{-20}$ *barn*. Matter is almost totally transparent to neutrinos.

24.4 THE FUNDAMENTAL INTERACTIONS

Four kinds of interaction between elementary particles can account for all known processes
the physical universe on all scales of size. In Table 24.2 the four basic interactions are summarise

Table 24.2. The four fundamental interactions

Interaction	*Particles Affected*	*Range*	*Relative Strength*	*Particles Exchanged*
Strong	Hadrons	$\sim 10^{-15}$ m	1	Mesons
Electro-magnetic	Charged Particles	∞	$\sim 10^{-2}$	Photons
Weak	Hadrons and leptons	$\sim 10^{-17}$ m	$\sim 10^{-13}$	Intermediate bosons
Gravitational	All	∞	$\sim 10^{-40}$	Gravitons

(1) **Strong interaction.** A familiar example of strong interaction is the forces which hold nucleons together (nuclear forces) in the atomic nucleus. The strong nuclear interaction is independent of the electric charge. The range of these interactions is about 10^{-15} m. Time interval of such an interaction is roughly 10^{-23} s.

(2) **Electromagnetic interaction.** It operates on all charged particles. Thus electromagnetic interactions are charge dependent (attractive as well as repulsive). The range is infinite and the interaction works through the *photon*. The formation of electron-positron pair from γ-ray is an example of electromagnetic interaction.

(3) **Weak interaction.** All strong interactions take place in times of about 10^{-23} s (characteristic time). Yet is has been observed that some of the resulting particles, although energetically unstable, suffer no decay until a time 10^{13} times greater than 10^{-23} is reached. That is, their decay takes place in time of about 10^{-10} s. For example, β-decay of radioactive nuclei does not take place until a time 10^{13} times greater than that involved in strong interactions has approached. Had there been strong nuclear or electromagnetic interactions, there would have been no such delay in the decay process. Therefore, this delay in the decay process suggests that either these particles are not subjected to strong interacting forces or there is some new conservation law or prohibition which forbids the decay. But since most of the particles involved are subjected to either nuclear force or have electric charge or both, there must be some rule which stops the process. But eventually the decays do happen, there must be some other type of interaction as predicted by Fermi to explain β-decay. Since particles take long time to respond to such an interaction, force involved must be very weak compared with strong nuclear forces. The range of such an interaction is less than 10^{-17} m. The characteristic time of this interaction is $\approx 10^{-10}$ s. Yukawa, in 1938, suggested that there should be a field quantum for the weak interaction, corresponding to the photon and pion. This so called *intermediate vector boson* has not been experimentally detected as a free particle. The weak interaction is responsible for the decay of strange and non-strange particles and for non-leptonic decays of strange particles.

(4) **Gravitational interaction.** It is the weakest of the four types of interactions. It has infinite range. Although gravity has a measurable influence on macroscopic bodies, its interaction with subnuclear particles is very small. Gravitation can be explained in terms of the interactions of '*gravitons*'. Their mass must be zero, and therefore, their velocity must be that of light. As the gravitational field is extremely weak, the gravitons can not be detected in the laboratory.

Of the four basic forces, only gravitational force is universal. Weak forces affect every particle other than photon. Electromagnetic force is confined to charged particles. Strong forces are the most selective and they serve as the criteria for classifying all known particles other than photons into two broad categories, the leptons and the hadrons. Leptons and photons are light particles and do not feel the strong forces. But hadrons feel the strong forces and participate in strong interactions besides taking part in other types of interactions as well. Thus the proton is a strongly interacting nuclear constituent and is therefore, a hadron. At the same time, because of its charge and mass, it must also experience electromagnetic and gravitational forces. The fact that it can be created by β-decay of neutron shows that the proton is involved in weak interactions as well.

18.7. K-mesons

K-mesons or koans are produced in strong interaction, either in *N-N* (nucleon-nucleon) collisions or in $\pi - N$ collisions.

Apart from the processes depicted by Eqs. (18.6-3) and (18.6-4) the following reactions have been observed :

$$\begin{aligned} p+p &\to p+p+K^+ + K^- \\ p+p &\to p+n+K^+ + \overline{K^0} \\ p+p &\to p+p+K^0 + \overline{K^0} \end{aligned} \qquad \text{...(18.7-1)}$$

In all these reactions, strangeness is conserved, since the K^- and the anti-particle $\overline{K^0}$ have $S = -1$

Decay modes and other properties of kaons :

Decay mode	*B.R.*	*Q* (MeV)
$K^+ \to \pi^+ \pi^- \pi^+ (\tau)$	5.59%	75
$K^+ \to \pi^+ \pi^0 \pi^0 (\tau)$	1.73%	84
$K^+ \to \pi^+ \pi^0 (\theta)$	21.16%	219
$K^+ \to \mu^+ \pi^0 \nu_\mu (\chi)$	3.20%	253
$K^+ \to \mu^+ \nu_\mu$	63.50%	388
$K^+ \to e^+ \nu_e \pi^0$	4.82%	358

Apart from the τ and θ modes of decay discussed earlier, a number of other decay modes of the kaons are known. The different decay modes of positive K-mesons with their relative branching ratios (B.R.) are given above.

The first three do not involve the emission of any leptons (non-leptonic decay) while the last three are leptonic decays.

From the Q-values of the different modes of decay, the mass of K^+ has been determined :

$$m(K^+) = 966.078\, m_e$$

$$m(K^+)\, c^2 = 493.668 \text{ MeV}$$

The mean life of decay of K^+ has been estimated to be

$$\tau(K^+) = 1.2371 \times 10^{-8} \text{ s}$$

The spin-parity of K^+ is 0^-, same as that of the pion. So it is a pseudoscalar meson like the π-meson (see Ch. XVII).

Though the decay properties of the negative K-mesons have not been studied extensively, since they are easily captured in matter (like the π^-) the decay modes are believed to be similar to those of K^+ given above, subject of course, to charge conservation.

Measured values of the mass and mean life of decay show that these are very close to the corresponding values for K^+ :

$$m(K^-)/m(K^+) = 0.999$$

$$\tau(K^-)/\tau(K^+) = 0.999$$

Thus K^- is taken to be the antiparticle of $K^+ : \overline{K^+} = K^-$. This is also predicted from charge conjugation principle (see § 18.11).

Spin-parity of K^- is 0^- as for K^+

The decay patterns of K^+ show that it has zero baryonic charge (see § 18.11). Because of its strong interaction, it is classed as a meson.

Neutral K-Mesons :

These were the first K-mesons to be discovered (see Eq. 18.6-1). Both τ and θ modes of decay are observed. In addition the χ mode is also observed. The first two are non-leptonic while the last is leptonic decay. All are weak decays.

The antiparticle of K^0 is $\overline{K^0}$. Together they constitute a charge conjugate pair. The θ^0 meson is the only neutral kaon observed in a nature. When it is produced in the reaction $\pi^- + p \rightarrow \Lambda^0 + \theta^0$ it resembles the K^0. But its two pion decay scheme $\theta^0 \rightarrow (\pi^+ \pi^-)$ or $(\pi^0 \pi^0)$ shows that this is not a simple K^0 decay. It is called a K_S^0 meson having a very short mean life ($\sim 10^{-10}$ s). There is another neutral meson, known as K_L^0 with a relatively *longer* mean life ($\sim 10^{-8}$ s) and different decay modes. Thus the neutral K mesons have dual character. They are formed as K^0 and $\overline{K^0}$ particles and behave like those in their interaction with matter. But they have different decay modes and different mean lives of decay.

$$K_S^0 \rightarrow \pi^+ \pi^- ; \pi^0 \pi^0 (\tau = 0.91 \times 10^{-10} \text{ s})$$

$$K_L^0 \rightarrow \pi^+ \pi^- \pi^0 ; \pi^0 \pi^0 \pi^0 (\tau = 5.7 \times 10^{-8} \text{s})$$

As we shall see later, this has important bearing on CP conservation (see § 18.11).

The isospin of the kaon is $I = 1/2$ which means that K^+ and K^0 constitute an isospin doublet with $I_3 = 1/2$ and $I_3 = -1/2$ respectively, as in the case of the nucleons p and n.

18.8 Hyperons

Λ^0-hyperons :

As seen in § 18.6 the first hyperon was discovered by Rochester and Butler in the cosmic rays. This is known as the Λ^0-hyperon. From an analysis of its decay products ($\Lambda^0 \rightarrow p + \pi^-$) studied in the bubble chamber as also in nuclear emulsion, the Q value of the decay process has been determined fairly accurately. It has been found that $Q = 37.76$ MeV which gives the mass of Λ :

$$m(\Lambda^0) = 2183.16\, m_e \,;\; m(\Lambda^0)\, c^2 = 1115.6\,\text{MeV}$$

The mean life of Λ^0 has been determined by measuring their path lengths from the points of formation to the points of decay in a large number of cases. It has been found that

$$\tau(\Lambda^0) = 2.63 \times 10^{-10}\,\text{s}$$

Another decay mode $\Lambda^0 \rightarrow n + \pi^0$ ($Q = 39.05$ MeV) is also known. The $(p\pi^-)$ mode of decay is observed in about 66.3% cases, while $(n\pi^0)$ is observed in 33.7% cases. Both are non-leptonic. In very few cases the leptonic decay $(p_e \nu_e)$ and $(p_\mu \nu_\mu)$ are also observed.

Beside the neutral Λ^0, other heavier hyperons (both charged and neutral) have also been observed, both in the cosmic rays, as also in accelerator based experiments.

Λ^0 is an isospin singlet with $I = 0$ and $I_3 = 0$. Its spin parity is $(1/2^+)$ like the other hyperons discussed below. The strangeness of Λ^0 is $S = -1$.

Σ-hyperon :

Three types of Σ hyperons are known Σ^+, Σ^- and Σ^0. They are produced in strong interaction. When a high energy pion or kaon strikes a nucleon, Σ hyperon is produced :

$$\pi^- + n \rightarrow \Sigma^- + K^0 \qquad \text{...(18.8-1)}$$

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

As stated before, strangeness is conserved in these processes. The strangeness quantum number of Σ is $S = -1$.

The following non-leptonic decay modes of the charged sigmas are known :

$$\Sigma^+ \rightarrow p + \pi^0\ (53\%),\ \tau = 0.81 \times 10^{-10}\text{s}$$

$$\rightarrow n + \pi^+\ (47\%), \qquad \text{...(18.8-2)}$$

$$\Sigma^- \rightarrow n + \pi^-\ (100\%),\ \tau = 1.48 \times 10^{-10}\text{s} \qquad \text{...(18.8-2}a\text{)}$$

The mean lives show that these are weak decays in which strangeness is not conserved.

Because of the differences in the decay schemes and decay life times, Σ^+ and Σ^- are considered different *i.e.*, they are not the antiparticles of each other.

The Q values of the decay processes give the masses of these particles. For the (p, π^0) decay of Σ^+, $Q = 116$ MeV, while the $(n\,\pi^+)$ decay has $Q = 110$ MeV. From these, the masses of Σ^+ and Σ^- have been estimated.

$$m(\Sigma^+) = 2327.5\, m_e$$

$$m(\Sigma^+)\, c^2 = 1189.37\text{MeV}$$

$$m(\Sigma^-) = 2343.1\, m_e$$

$$m(\Sigma^-)\, c^2 = 1197.34\text{MeV}$$

The spin-parity of $\Sigma^\pm$ is $(1/2^+)$.

The neutral Σ^0 was predicted theoretically and was subsequently discovered. It decays by electromagnetic interaction :

$$\Sigma^0 \to \Lambda^0 + \gamma,\ \tau = 5.8 \times 10^{-20}\ \text{s} \qquad \text{...(18.8-3)}$$

The mass of Σ^0 has been estimated from the Q value of the decay :

$$m(\Sigma^0) = 2333.57\, m_e$$

$$m(\Sigma^0)\, c^2 = 1192.48\ \text{MeV}$$

The spin-parity is $(1/2^+)$ and the strangeness $S = -1$. Σ^+, Σ^- and Σ^0 belong to an isospin triplet $(I = 1)$ with $I_3 = +1, -1$ and 0 respectively.

Ξ *(xi) – hyperon :*

Ξ hyperon was discovered in 1952. It decays in *cascade* as follows :

$$\Xi \to \Lambda^0 + \pi^-,\ \Lambda^0 \to p + \pi^- \qquad \text{...(18.8-4)}$$

The neutral Ξ^0 hyperon is also known to decay in cascade :

$$\Xi \to \Lambda^0 + \pi^0,\ \Lambda^0 \to p + \pi^- \qquad \text{...(18.8-5)}$$

Because of their cascade decay the xi hyperons are also known as *cascade particles.* From the Q values of the decay, the masses of Ξ^- and Ξ^0 have been estimated :

$$m\left(\Xi^-\right) = 2585.74\, m_e$$

$$m(\Xi^-)\, c^2 = 1321.29\ \text{MeV}$$

$$m\left(\Xi^0\right) = 2575.1\, m_e$$

$$m\left(\Xi^0\right) c^2 = 1314.9\ \text{MeV}$$

The mean lives of decay

$$\tau\left(\Xi^-\right) = 1.65 \times 10^{-10}\text{s}$$

$$\tau\left(\Xi^0\right) = 2.96 \times 10^{-10}\text{ s}$$

Thus both undergo weak–decay,

The spin-parity of Ξ^-, Ξ^0 is $(1/2^+)$. These two hyperons belong to the isospin doublet $(I = 1/2)$ with $I_3 = -1/2$ and $+1/2$ respectively. The strangeness of the Ξ hyperon is $S = -2$.

Ω^- –hyperon :

This is the heaviest known hyperon. Its existence was predicted on the basis of SU_3 symmetry and its discovery in 1964 constitutes the most important triumph of the theory. It undergoes the following weak cascade decay :

$$\Omega^- \rightarrow \Xi^0 + \pi^-, \quad \Xi^0 \rightarrow \Lambda^0 + \pi^0, \Lambda^0 \rightarrow p + \pi^- \qquad ...(18.8\text{-}6)$$

The mass of Ω^- estimated from the Q value of its decay is

$$m(\Omega^-) = 3272.4\, m_e$$

$$m\,(\Omega^-)\, c^2 = 1672.5\,\text{MeV}$$

The mean life of decay is

$$\tau\,(\Omega^-) = 1.3 \times 10^{-10}\text{s}$$

Other channels of decay are also known :

$$\Omega^- \rightarrow \Xi^- + \pi^0$$

$$\Omega^- \rightarrow \Lambda^0 + \text{K}^-. \qquad ...(18.8\text{-}7)$$

The spin parity of Ω^- is $(3/2^+)$. The Ω^- is an isospin singlet with $I = 0$, $I_3 = 0$.

All the hyperons discussed above are heavier than the nucleus . The hyperon decay schemes show that all of them have unit baryonic charge (see § 18.11) with baryon number $B = 1$. They have half-integral spins and even (+) intrinsic parity. Antiparticles of all these hyperons have been discovered.

The strangeness of Ω^- is $S = -3$