Generation Of Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix} \begin{matrix} \longrightarrow + \dfrac{2e}{3} \\ \longrightarrow - \dfrac{1e}{3} \end{matrix}$$

(I) (II) (III)

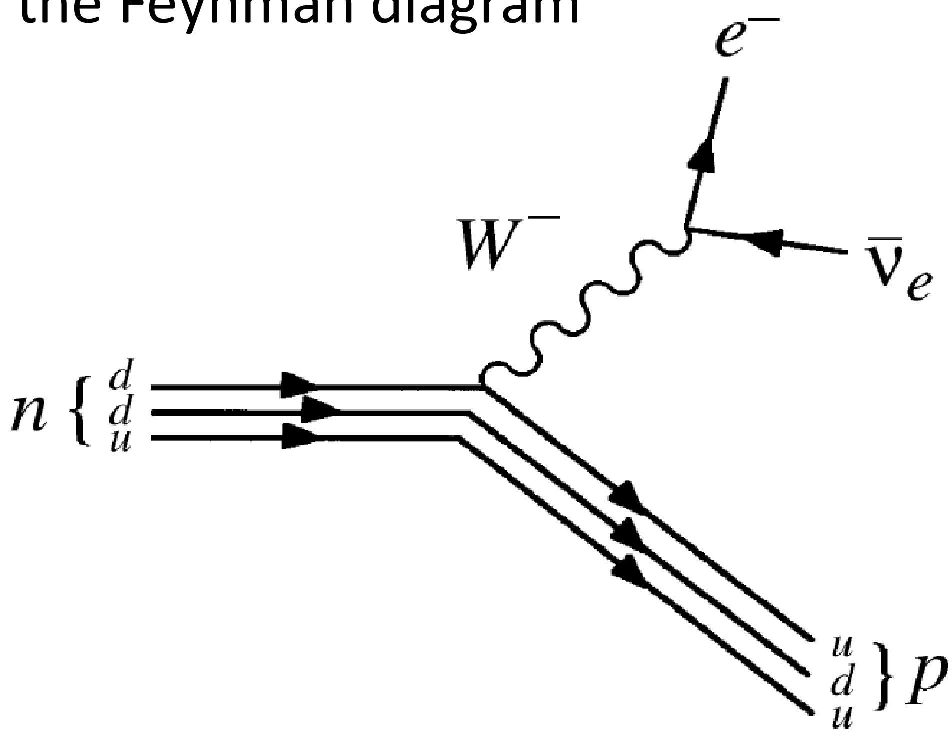
$$\begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix} \qquad \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix} \qquad \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix} \begin{matrix} \longrightarrow + \dfrac{1e}{3} \\ \longrightarrow - \dfrac{2e}{3} \end{matrix}$$

Properties of Quarks: All have spin ½

Name	Symbol	Mass GeV/c^2	Q	Lifetime (s)	Major decays
Down	d	$m_d \approx 0.3$	$-1/3$		
Up	u	$m_u \approx m_d$	$2/3$		
Strange	s	$m_s \approx 0.5$	$-1/3$	10^{-8}–10^{-10}	$s \to u + X$
Charmed	c	$m_c \approx 1.5$	$2/3$	10^{-12}–10^{-13}	$c \to s + X$
					$c \to d + X$
Bottom	b	$m_b \approx 4.5$	$-1/3$	10^{-12}–10^{-13}	$b \to c + X$
Top	t	$m_t = 180 \pm 12$	$2/3$	$\sim 10^{-25}$	$t \to b + X$

X denotes other particle

- The decay of quarks always takes place within a hadron, with the other bound quarks acting as spectators i.e. not taking part in the interaction.
- It is assumed that the exchanged particle interacts with only one constituent quark in the nucleons. This is the essence of the spectator model. For example: Neutron decay at the quark level is shown by the Feynman diagram



Spectator model quark Feynman for the decay n → p + e^- + $\overline{\upsilon_e}$

- In strong and em – interactions, quarks can be created or destroyed as particle – anti – particle pairs. For example,

$e^+ + e^- \longrightarrow c + \bar{c}$ is allowed

$e^+ + e^- \longrightarrow c + \bar{u}$ is not allowed

Moreover, it implies the conservation of each of the six quark numbers,

$$N_f = N(f) - N(\bar{f})$$

(f = u, d, s, c, b, t)

Where $N(f)$ is the number of quarks of flavor of present and $N(\overline{f})$ is the number of antiquarks of flavor $\overline{f}$ present.

For ex: for single – particle states; $N_c = 1$ for the c – quark; $N_c = -1$ for the c antiquark and $N_c = 0$ for all other particles.

- In weak interactions, more general possibilities are allowed, and only the total quark number is conserved

$$N_q = N(q) - N(\overline{q})$$

Where $N(q)$ and $N(\bar{q})$ are the total no. of quarks and antiquarks irrespective of their flavor.

- For example, the main decay mode of the charmed quark,

$$c \rightarrow s + u + \bar{d}$$

Where conservation of individual quark numbers N_c, N_s, N_u and N_d are violated but the total quark number N_q is conserved.

- It is convenient to replace the quark number Nq by the Baryon Number B, defined by,

$$B = Nq/3 = [N(q) - N(\bar{q})]/\ 3$$

Quark Model Spectroscopy

- In the quark model of hadrons the baryons are assumed to be bound states of three quarks (qqq), antibaryons are assumed to be bound states of three anti-quantities (q’q’q’) and mesons are assumed to be bound states of a quark and an antiquark (q q’).
- Mesons are a type of hadrons that have integral spin. Pions are the lightest known mesons with masses π^{+}(140) and π^{o}(135).

- Charged pions have unique composition while the neutral pion is composed of both uu’ and dd’ pairs in equal amounts. Pions are produced in high–energy collisions by strong interaction processes such as $p + p \quad p + n + \pi$.
- Kaons are completely different mesons that have non zero values for strangeness quantum number. Strangeness is conserved in strong and electromagnetic interactions, but not necessarily conserved in weak interactions.
- The strangeness S, apart from a sign is the strangeness quark number, i.e. $S = - N_s$

- The lightest strange baryon is the lambda, with the quark composition $\Lambda = uds$.
- The charm and bottom quantum numbers are defined as

  $C = N_C = N(C) – N(C')$, $B' = - N_b = - [N(b) – N(b')]$
- **We could construct all the mesons states of the form qq', where q can be any of the six quark flavors. Each of these is labeled by its spin and its intrinsic parity P.**
- The simplest states would have the spins of the quark and the antiquark antiparallel with no orbital angular momentum between them and so have spin parity $J^P = 0^-$.

- If we consider those states composed of just u, d, and s quarks there will be nine such mesons and they have a quantum number which may be identified with the mesons (k^o,k^+), ($\bar{k}^0$, k^-), ($\pi^\pm$, π^0) and two neutral particles, which are called η and η'.
- The supermultiplet is shown as a plot of Y, the hypercharge is defined as,

$$Y = B + S + C + B' + T$$

- The Simplest meson state is $J^P = 0^-$ (the spins of the quark and the antiquark antiparallel with no orbital angular momentum between them).

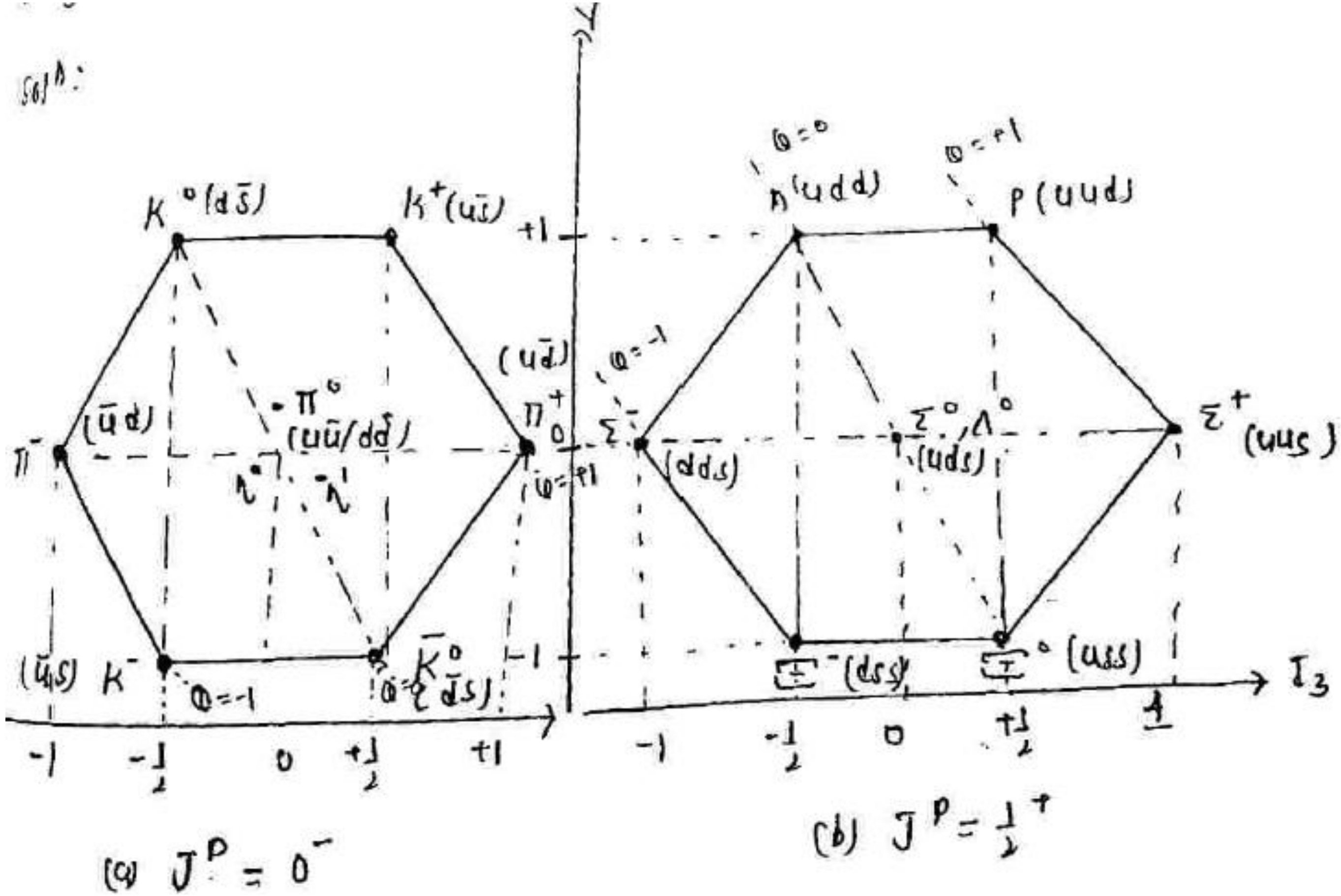
Considering those states composed of just u, d, and s quarks there will be nine such mesons. The hypercharge for this meson state is Y = S

- Similarly the lowest lying 3 quarks (q q q) states and the lowest lying supermultiplet consists of the eight ($J^P = \frac{1}{2}^+$) baryons as shown below.

For $J^P = \frac{1}{2}^+$ state Y = S + B.

Some examples of baryons and mesons, with their major decay modes masses are in MeV/c^2

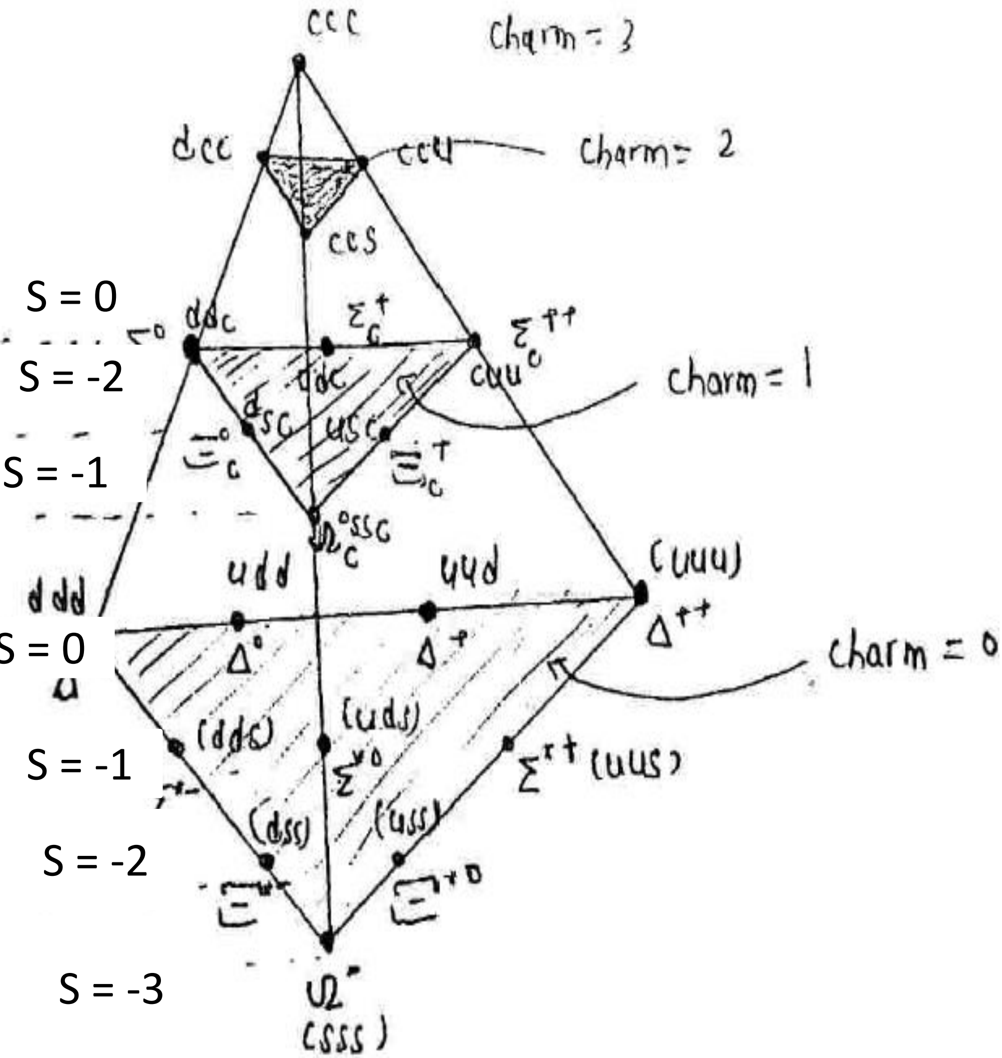
Particle	Mass	Lifetime (s)	Major decays
$\pi^+(u\bar{d})$	140	2.6×10^{-8}	$\mu^+\nu_\mu$ (~100%)
$\pi^0(u\bar{u}, d\bar{d})$	135	8.4×10^{-17}	$\gamma\gamma$ (~100%)
$K^+(u\bar{s})$	494	1.2×10^{-8}	$\mu^+\nu_\mu$ (64%)
			$\pi^+\pi^0$ (21%)
$K^{*+}(u\bar{s})$	892	$\sim 1.3 \times 10^{-23}$	$K^+\pi^0$, $K^0\pi^+$ (~100%)
$D^-(d\bar{c})$	1869	1.1×10^{-12}	Several seen
$B^-(b\bar{u})$	5278	1.6×10^{-12}	Several seen
$p(uud)$	938	Stable	None
$n(udd)$	940	887	$pe^-\bar{\nu}_e$ (100%)
$\Lambda(uds)$	1116	2.6×10^{-10}	$p\pi^-$ (64%)
			$n\pi^0$ (36%)
$\Delta^{++}(uuu)$	1232	$\sim 0.6 \times 10^{-23}$	$p\pi^+$ (100%)
$\Omega^-(sss)$	1672	0.8×10^{-10}	ΛK^- (68%)
			$\Xi^0\pi^-$ (24%)
$\Lambda_c^+(udc)$	2285	2.1×10^{-13}	Several seen

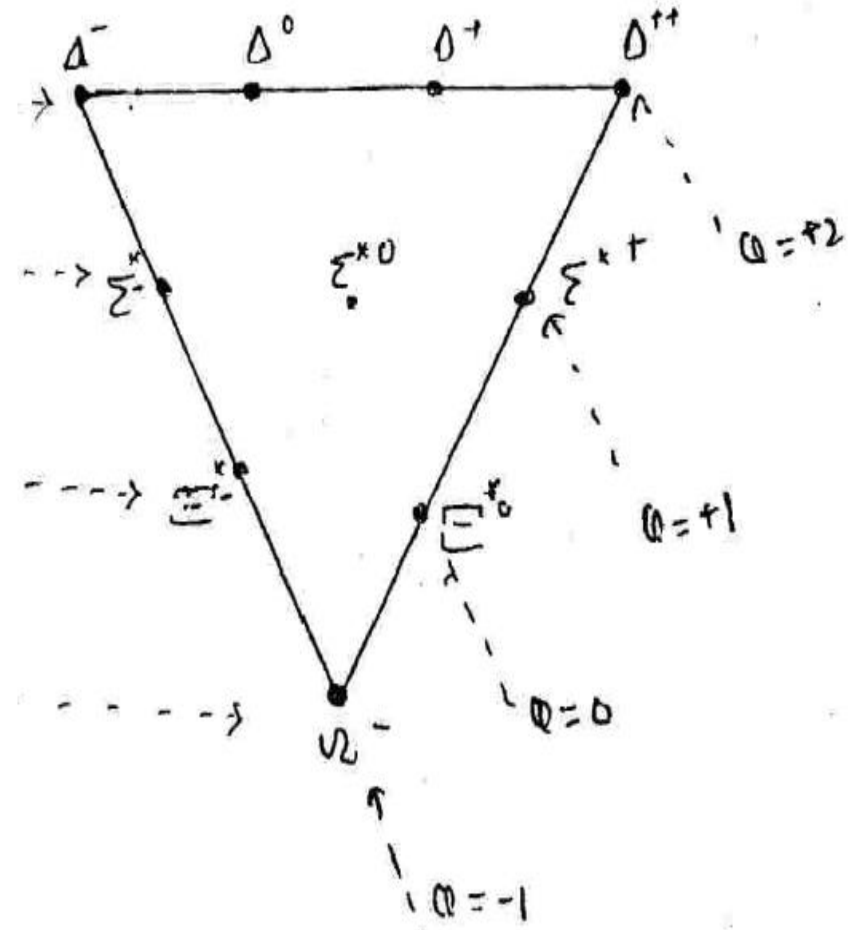


The lowest – lying states with (a) $J^p = 0^-$ and (b) $J = \frac{1}{2}^+$ that are composed of u, d and s quarks

In the above diagrams, particles along the same horizontal line share the same strangeness q. no. (S), while those on the same vertical, line share the same I_3 and those on the same diagonals share the same charge.

- The scheme may also be extended to more quark flavors, although the diagrams become increasingly complex.
- For example, figure below shows the predicted $J^P = \frac{3}{2}^+$ baryon states formed from u, d, and s quarks when all the three quarks have their spins aligned, but still with zero orbital angular momentum between them.
- In the baryon decuplet the particles indicated with an **asterisk are excited states** of corresponding particles in Baryon octet. These excited states have higher mass and spin.





The J = $\frac{3}{2}^{+}$ baryon states composed of u, d, s and c quarks

Hadronic Magnetic moments:

Magnetic moments have been measured only for the $\frac{1}{2}^{+}$ octet states composed of u, d and s quarks. In this supermultiplet, the quarks have zero orbital angular momentum and so the hadronic magnetic moments are just the sums of contribution from the constituent quark magnetic moments.

If we assume the quark magnetic moments are of the Dirac form then

$$\mu_q = < q, S_z = \frac{1}{2} \mid \mu_z \mid q, S_z = \frac{1}{2} >$$

$$= e_q \frac{e\hbar}{2mq} = e_q \frac{Mp\mu_N}{m_q} \text{...... (1)}$$

Where, e_q is the quark change in units of e and $\mu_N = \frac{e\hbar}{2mq}$ is the nuclear magneton.

Thus, $\mu_u = \frac{2Mp\mu_N}{3m_q}$, $\mu_d = \frac{-1Mp\mu_N}{3m_d}$, $\mu_s = \frac{-1Mp\mu_N}{3m_s}$,

For example, in the case of Λ= uds, the u d pair in a spin-0 state and no contribution to the Λ spin or magnetic moment. Thus we have the predicted

$$\mu_\Lambda = \mu_s = \frac{-1Mp\mu_N}{3m_q}$$