III. Conservation Laws:

The reactions in elementary particles & their decay appear to obey certain conservation laws & selection rules. The usual & other conservation laws satisfied are:

	Strong Interaction	EM Interaction	Weak Interaction
1. Conservation law of Energy	yes	yes	yes
2. ………....Linear momentum	yes	yes	yes
3. ……….Angular momentum	yes	yes	yes
4. …………….....Charge (Q)	yes	yes	yes
5. ……………....Lepton no. (L)`	yes	yes	yes
6. …………...…Baryon No. (B)	yes	yes	yes
7. ……….Isospin magnitude (I)	yes	no	no
8. …….Isospin Z component (I_Z)	yes	yes	no
9. …..………Strangeness no. (S)	yes	yes	no
10. …………………….Parity (P)	yes	yes	no
11. …...…Charge conjugation (C)	yes	yes	no
12. …………....Time reversal (T)	yes	yes	yes
13. …………………..CPT	yes	yes	yes

1. Conservation of Lepton Number:

- Lepton no. is defined as L=1 for the lepton particles, L=-1 for lepton anti-particles and L=0 for all other particles.
- There are 3 types of leptons- e-type (e & ν_e), μ-type (μ & ν_μ) and τ-type (τ & ν_τ).
- Lepton no. for electrons and their associated neutrinos, lepton no. for μ meson and their associated neutrinos and lepton no. for τ meson and their associated neutrinos are separately conserved in all processes.
- Conservation law: *In any process, the lepton no. for electron type leptons, muon type leptons and tau type leptons must each remain constant.*

Example:

a] $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
Electron lepton no. $L_e: \ 0 \ = +1 - 1 \ + 0$
Muon lepton no. $L_\mu: \ 1 \ = +0 + 0 \ + 1$
Conserved

b] $K^0 \rightarrow \pi^+ + e^- + \bar{\nu}_e$
$L_e: \ 0 \ = +0 + 1 \ + (-1)$
Conserved

2. Conservation of Baryon Number:

- Baryon number is defined as B=+1 for baryon particles and B= -1 for baryon antiparticles. B=0 for all other particles.
- For any reaction or decay, total baryon number is conserved.

Example:

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

B: 0 + 1 = 1 + 0 + 0

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

B : 1 = 1 + 0 + 0

3. Conservation of Isospin and Isospin z component:

- Mesons and Baryons occur in groups or multiplets of like masses.
- The particles of a particular group differ in charge
- They interact with each other by means of strong interaction.
- Because of the charge independence of strong interactions, all the particles of a group interact with another particle strongly in the same way. However, e-m interaction causes a small difference.
- This charge independence has led to introduction of another quantum no. called Isotopic spin (I)
- It is defined in such a way that 2I+1 gives the no. of particles in a particular group
- It is a vector quantity with magnitude $\sqrt{I(I+1)}$
- It is a dimensionless quantity.

➢ The z component of Isospin, I_Z is quantized by the rule I_Z=I, I-1, I-2 ….. –I assigned in order of decreasing charge.
Example:
  - Pions: π^+, π^0, π^- all have a mass of about 140MeV & I=1 with I_Z= +1, 0, -1 respectively.
  - Nucleons: p,n, I= $\frac{1}{2}$, $I_Z = \frac{1}{2}$ [p], $-\frac{1}{2}$ [n]
  - Σ: I=1; Ξ: I=$\frac{1}{2}$; Λ & Ω: I=0 (singlet); Kaons (K^+, K^0): I=$\frac{1}{2}$.

➢ Antiparticle multiplets have the same isotopic spin as that of particles but I_Z is the negative of that the particle.

- Strong reaction: I (added as a vector) & I_Z are conserved.
- Weak reaction: I & I_Z are not conserved.
- EM reaction: I is not conserved but I_Z is conserved.

Example:

a] Strong Reaction

	π^0	p	π^+	n
I:	1	$\frac{1}{2}$	1	$\frac{1}{2}$
I_Z:	0	$\frac{1}{2}$	1	$-\frac{1}{2}$
Σ I:	$\frac{3}{2}$,	$\frac{1}{2}$	$\frac{3}{2}$,	$\frac{1}{2}$

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

Conserved

b] Weak Decay

	K^0	π^0	π^0
I:	$\frac{1}{2}$	1	1
I_Z:	$-\frac{1}{2}$	0	0
Σ I:	$\frac{1}{2}$	2, 1, 0	

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

Not conserved

4. Conservation of Strangeness number:

- It is found experimentally that kaon & the hyperons, Λ, Σ, Ξ, Ω are always produced in pairs in strong interactions, a phenomenon known as associated production, but they decay in weak interaction.
- To explain this strange phenomenon, a new quantum no. S, called strangeness no. is introduced.
- The particles with S≠0 are the strange particles.
- The strangeness of a particle is an integer.
- Strangeness of an antiparticle have the opposite sign of that of associated particle.
- The total strangeness number (Added as a scalar) is conserved in strong and e-m interaction but violated in weak interaction [ΔS=0, +1, -1]

Example:

Strong Reaction:

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

	π^+	p	Σ^+	K^+
S:	0	0	-1	+1

Conserved

Weak Reaction:

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

	Λ^0	π^+	p	
S:	-1	0	0	ΔS=+1

Violated

- The strangeness no. of a particle can be expressed in terms of charge no. Q, baryon no. B and the Z component of isotopic spin I_Z as

$$Q = I_Z + \frac{B+S}{2}$$

This is called **Gellmann-Nishijima** relation.
Y=B+S is called hypercharge.

5. Conservation of Parity:

- Symmetry operations: Parity, Charge conjugation and Time reversal
- It is a property of wave function that describes a system under mirror of co-ordinates, i.e. x,y,z⟶-x, -y, -z
- If the wave function changes sign the reaction or the system has the odd parity.
- If it is not, the parity is even.
- Parity is conserved in strong reaction but it is violated in weak interaction.

6. Charge Conjugation Transformation [C]:

- If a physical law or a reaction for particles also holds for anti-particles corresponding to particles, then the reaction is said to be invariant under the charge conjugation [C].
- It is valid for e-m and strong reactions but not for weak reaction.

7. Time reversal [T]:

- The time reversal transformation is a process in which the time variable describing the system or a wave function is replaced by its negative values. If a physical law is invariant with respect to such a transformation then it is invariant with respect to time reversal T. t⟶-t
- It preserves the helicity.
- It is obeyed in strong and e-m reaction but not true for the weak interaction (1%).

8. The CPT theorem:

- The CPT theorem states that the result of successively carrying out the charge conjugation C, the parity P and the time reversal T operation is to leave the essential description of the behavior of the interaction unchanged.
- This is an exact conservation law and is valid for all types of interactions.
- As a consequence of this theorem, the observed violation of parity in the weak interaction requires that C or T is also violated in the weak reaction.

❖ **Residual Coulomb interaction (A correction term):** It is a corrective electric interaction in atoms having many optically active electrons, that compensate the average spherically symmetric potential [Hatree Potential] on each optically active electron and describes the average effective coulomb interaction of an electron with other optically active electron. For atom with many optical electrons, the Coulomb potential is not spherically symmetric because the sub-shells are partially closed.

IV. Resonance Particles

- Weak decays have lifetimes of the order 10^{-10}s.
- Electromagnetic decays have much shorter lifetimes, about 10^{-16}-10^{-19}s.
- Particles decayed by strong force have lifetimes of the order 10^{-23}s.
- Their lifetimes are so short that they can't be detected before decaying.
- Their existence is inferred only from the decay products.
- These particles are known as Resonance Particles.
- First resonance particle was observed by Fermi during collision of π^+ and protons.
- After that many such particles were discovered.

V. The Quark Model

- In 1964 Gellman and G. Zweig independently proposed that all strongly interacting particles are built up of the unitary triplet of three new particles.
- These new particles are known as Quarks.
- Each quark have different flavor with fractional charge and fractional Baryon number.
- They are Fermions with spin$\frac{1}{2}$.
- There are three types of quark- u [up], d [down], s [strange].
- U, d belong to isospin doublet I= $\frac{1}{2}$ with S=0 where s belongs to iso-spin singlet I=0 with S=-1
- These quarks obey Gellman-Nishijima relation as the particles do.
  Example:
  For u quark, $Q=I_Z + (B+S)/2 = ½ + (1/3 + 0)/2 = 2/3$ similarly for others.

	I	I_Z	S	B	Q	Mass (GeV)
u	½	+ ½	0	$^1/_3$	$^2/_3$	0.39
d	½	- ½	0	$^1/_3$	$-^1/_3$	0.39
s	0	0	-1	$^1/_3$	$-^1/_3$	0.51
Three more heavy quarks proposed after 1976 are-						
c (charm)	0	0	0	$^1/_3$	$^2/_3$	1.55
b (bottom)	0	0	0	$^1/_3$	$-^1/_3$	5
t (top)				$^1/_3$	$^2/_3$	180

Anti-quarks of u, d, s etc have I_Z, S, B, Q negative of quark.
These 6 quarks are clubbed into three-

$$\begin{pmatrix} u \\ d \end{pmatrix} ; \begin{pmatrix} c \\ s \end{pmatrix} ; \begin{pmatrix} t \\ b \end{pmatrix} = \begin{pmatrix} \frac{2}{3}e \\ -\frac{1}{3}e \end{pmatrix}$$

Each quark carries another quantum no. called color and it has 3 values – r, b, g.

Example:

Combination of quarks gives hadrons:

$u\bar{d}$ pair: $Q = \frac{2}{3}\ e + \frac{1}{3}\ e = \ +1e, B = \frac{1}{3} - \frac{1}{3} = 0$, S=0+0=0

These values are in agreement with the values for π^+-meson. Hence π^+-meson is considered as $u\bar{d}$ pair.

$$K^+ = u\bar{s}\ with\ Q = 1, B = 0, S = +1$$

Neutron $n = ddu\ with\ Q = -\frac{e}{3} - \frac{e}{3} + \frac{2e}{3} = 0, B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = +1$, S=0+0+0=0

Combination of quarks gives mesons:

Quarks have spin half, but spin of meson is zero. Mesons with spin 1 have been detected also. Hence two quarks with opposite spins can form a meson. Baryon number of two combined quarks is 1/3+1/3=2/3 but baryon no. of meson is zero. Hence a quark and an anti-quark combination has to be taken to form a meson.

Table: Quark Composition of selected Hadrons

Mesons	Quark composition	Baryons	Quark Composition
π^+	$u\bar{d}$	p	uud
π^-	$\bar{u}d$	n	udd
π^0	$u\bar{u}$	Λ^0	uds
K^+	$u\bar{s}$	Σ^+	uus
K^-	$\bar{u}s$	Σ^0	uds
K^0	$d\bar{s}$	Ξ^0	uss
		Ξ^-	dss