First LHC School Lecture#2

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Space Time Symmetries

- Bilateral Symmetry (Space Reflection Invariance) is not universal; it is violated by fundamental laws governing weak interactions, while respected by all other interactions (electromagnetic, strong, gravitational).
- We have positively charged proton and negatively charged electron in nature. Negative proton and positive electron do not exist in nature.
- Dirac, by unifying the special theory of relativity with quantum mechanics, predicted the existence of antimatter viz. negatively charged antiproton and positively charged antielectron.
- Invariance under Charge Conjugation (particle $\rightleftarrows$ antiparticle) is also violated by weak interactions but respected by all other interactions.

- To understand the preponderance of matter in the universe is a subject actively pursued in cosmology with input from particle physics.
- Time is measured while passing, we have present, present past and present future. There is no evidence that time reversal is violated by the fundamental laws of nature. Still in our consciousness, we distinguish between past and future. Past is known, future is unknown, uncertain.
- Our present actions determine the future but still uncertainty is there.
- The first person who ever thought about time was Saint Augustine in the 4th century. He asked himself the question, “What was God doing before he created the universe?” His answer was: God dwells in eternity. Nothing moves into the past; all was present, there was no before. Time begins with the creation of universe - an answer not different from the one given by big bang theory.

Continuous Symmetries

The rotational symmetry in geometry is formulated in terms of group of rotations around a point O in a plane or around an axis in space. In plane geometry, finite groups of rotations are of two kinds:

- The group consisting of the reptititions of a single proper rotation by an angle $\theta = \frac{360}{n}$ $(n = 1, 2, 3...)$ called the cyclic group C_n.
- The group of these rotations combined with the reflections in n axes forming angles $\theta/2$ called dihedral group D_n.

For ornamental pattern in art as well as in crystals, there are no other rotational symmetries except those of order 2, 3, 4 and 6. Some examples of these symmetries are shown in the following figures. However, one can find pentagonal symmetries in organic world.

Symmetries of Laws of Nature

The structure of space-time is also revealed by the symmetries of laws of nature. In quantum mechanics, a transformation is associated with an operator (unitary):

$$UU^\dagger = 1 = U^\dagger U, \quad U^\dagger = U^{-1}$$

U can be written as $U = e^{i\epsilon\hat{F}}$. Unitarity of U implies $\hat{F}$ is Hermitian: $\hat{F}^\dagger = F$.

Fundamental law of Quantum Mechanics is given by the Schrodinger equation:

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = H|\psi(t)\rangle$$

A formal solution of this equation is

$$|\psi(t)\rangle = e^{-iHt/\hbar}|\psi(0)\rangle$$

Average value of an operator $\hat{A}$ is defined as:

$$\begin{aligned}\bar{a}_{\psi(t)} &= \langle\psi(t)|\hat{A}|\psi(t)\rangle \\ &= \langle\psi(t)|e^{+iHt/\hbar}\hat{A}e^{-iHt/\hbar}|\psi(t)\rangle \\ &= \langle\psi|\hat{A}(t)|\psi\rangle = \bar{a}_{\psi}(t) \\ \hat{A}(t) &= e^{+iHt/\hbar}\hat{A}(0)e^{-iHt/\hbar} \\ \text{In particular} \quad H(t) &= e^{+iHt/\hbar}H(0)e^{-iHt/\hbar} = H(0) = H \\ i\hbar\frac{\partial}{\partial t}\hat{A}(t) &= [\hat{A}(t), H]\end{aligned}$$

This is the Heisenberg *picture*. We can move from one picture to the other picture by unitary transformation. $\hat{A}(t)$: Time Translated Operator.

If $[\hat{A}(t), H] = 0$, then $\hat{A}$ is time independent and its eigenvalues are constant of motion. Since eigenvalues are possible result of measurement, this implies that an experiment done now or in the past would give the same result under same conditions. (Translational Symmetry in Time: Conservation of Energy $H(t) = H$)

We formulate the invariance principle in a general way. Consider a transition from an initial state $|i\rangle$ to a final state $|f\rangle$. This transition is described by matrix elements $\langle f|S|i\rangle$:

$$\langle f|S|i\rangle = \langle f|U^\dagger USU^\dagger U|i\rangle = \langle f^u|USU^\dagger|i^u\rangle$$

$|i^u\rangle$ and $|f^u\rangle$ are transferred states: Above equation is an identity. However, if

$$USU^\dagger = S \quad \text{then} \quad \langle f|S|i\rangle = \langle f^u|S|i^u\rangle$$

This implies that the result of experiment remains unchanged when the states are transformed (invariance principle):

$$USU^\dagger = S \Rightarrow [U, S] = 0 \quad \text{or} \quad [U, H] = 0$$

i.e. S matrix commutes with U. For infinitesimal unitary transformation,

$$U = 1 + i\epsilon\hat{F} \Rightarrow [\hat{F}, S] = 0$$

Invariance means that generator of transformation commutes with S-matrix or the Hamiltonian. $\hat{F}$ is Hermitian and thus observable. Its eigenvalues are real.

$$\hat{F}|F_i\rangle = F_i|F_i\rangle$$
$$\langle F_f|[S, \hat{F}]|F_i\rangle = (F_i - F_f)\langle F_f|S|F_i\rangle = 0$$

Hence $F_i = F_f$ if $\langle F_f|S|F_i\rangle \neq 0$.
Invariance implies conservation law, i.e. eigenvalues of $\hat{F}$ remain unchanged.

Example 1: Translation in Space

For simplicity, we consider one dimensional case. The generalization to 3D is straightforward. Consider the translation $x \to x + a$. Associated with this translation is a unitary operator $U_T = e^{i\hat{p}a/\hbar}$.

$$U_T|x\rangle = |x - a\rangle, \quad U_T^\dagger|x\rangle = |x + a\rangle$$

$U_T|\psi\rangle = |\psi^T\rangle$.

$$\begin{aligned} \psi^T(x) &= \langle x|\psi^T\rangle = \langle x|U_T|\psi\rangle \\ &= \langle x + a|\psi\rangle = \psi(x + a) \end{aligned}$$

$$\begin{aligned} \psi^T(x) = \langle x|\psi^T\rangle &= \psi(x) + a\frac{\partial}{\partial x}\psi(x) \\ &= \langle x|\psi\rangle + a\frac{\partial}{\partial x}\langle x|\psi\rangle \end{aligned}$$

But

$$\langle x|\psi^T\rangle = \langle x|U_T|\psi\rangle = \langle x|\psi\rangle + \langle x|\frac{i\hat{p}a}{\hbar}|\psi\rangle$$

$$\hat{p} = -i\hbar\frac{\partial}{\partial x}$$

Hence momentum operator is generator of the translation.

$$U_D\hat{x}U_D^\dagger = \hat{x} + a$$

If $[\hat{p}, H] = 0$ or $[\hat{p}, S] = 0$, then momentum is conserved, i.e. translational invariance implies conservation of momentum. In 3D,

$$U_D\hat{\vec{x}}U_D^\dagger = \hat{\vec{x}} + \vec{a}$$

Thus we have

$$\hat{A}(\vec{x} + \vec{a}) = e^{+i\hat{\vec{p}}\cdot\vec{a}/\hbar}\hat{A}(\vec{x})e^{-i\hat{\vec{p}}\cdot\vec{a}/\hbar}$$

We have already noted that $\hat{A}(t+\tau) = e^{+iH\tau/\hbar}\hat{A}(t)e^{-iH\tau/\hbar}$.
Introduce 4-vector ($\hbar = c = 1$)

$$P^\mu = (H, \hat{\vec{p}}), \qquad P_\mu = (H, -\hat{\vec{p}})$$

$$e^{iP^\mu a_\mu} = e^{iH\tau} e^{-i\hat{\vec{p}}\cdot\vec{a}}$$

$$\hat{A}(x+a) = e^{+iP\cdot a/\hbar}\hat{A}(x)e^{-iP\cdot a/\hbar}$$

For any field operator $\phi(x)$, we have

$$\phi(x) = e^{iP.x}\phi(0)e^{-iP.x}$$

$$i\partial^\mu\phi(x) = [\phi(x), P^\mu], \qquad P^\mu = \text{Generator of Spacetime Translation}$$

Example 2: Rotation in Space

Under rotation $x_i = R_{ij} x_j$

The length of a vector remains unchanged. Then,

$$\begin{aligned}\vec{x}'^2 = x_i' x_i' &= R_{ij} R_{ik} x_j x_k \\ &= (R^T)_{ki} (R)_{ij} x_j x_k \\ &= x_j x_j = \vec{x}^2\end{aligned}$$

provided

$$(R^T)_{ki} (R)_{ij} = \delta_{ij}$$

$$R^T R = R R^T = 1 \qquad \text{(Orthogonal transformation)}$$

For infinitesimal rotation $\vec{\omega}$:

$$\vec{x}' = \vec{x} - \vec{\omega} \times \vec{x}$$

$$x_i' = x_i - \epsilon_{ijk} \omega_k x_k$$

Corresponding to rotation, there is a unitary operator U_R:

$$
\begin{aligned}
U_R|\psi\rangle &= |\psi^R\rangle \\
U_R|\vec{x}\rangle &= |\vec{x} + \vec{\omega} \times \vec{x}\rangle \\
\psi_R(\vec{x}) &= \langle \vec{x}|U_R|\psi\rangle = \langle \vec{x} - \vec{\omega} \times \vec{x}|\psi\rangle \\
&= \psi(\vec{x} - \vec{\omega} \times \vec{x}) \\
&= \psi(\vec{x}) - \vec{\omega} \cdot (\vec{x} \times \nabla)\psi(\vec{x}) \\
&= (1 - i\vec{\omega} \cdot \vec{L}/\hbar)\psi(\vec{x}) \\
U_R &= e^{-i\vec{\omega}\cdot\vec{L}/\hbar}
\end{aligned}
$$

Hence the angular momentum is generator of rotation. In general,

$$U_R = e^{-i\vec{\omega}\cdot\vec{J}/\hbar}$$

where angular momentum $\vec{J}$ satisfies the commutation relation

$$[J_i, J_j] = i\hbar\epsilon_{ijk}J_k, \qquad J_\pm = J_1 \pm iJ_2$$

$$[J_+, J_-] = 2\hbar J_3, \qquad [J^2, J_3] = 0, \qquad [J_3, J_\pm] \qquad = \pm\hbar J_\pm$$

$$J^2 = J_x^2 + J_y^2 + J_z^2$$

$\vec{J}$ is the generator of rotation group O_3. Rotational invariance means $[\vec{J}, H] = 0$, $[\vec{J}, S] = 0$. Hence, rotational invariance implies conservation of angular momentum.

Lorentz Transformation

Contravariant Vector: $x^\mu = (x^0, x^i) = (ct, \vec{x})$
Covariant Vector: $x_\mu = (x_0, x_i) = (ct, -\vec{x})$

$$x^\mu = g^{\mu\nu} x_\nu, \qquad x_\mu = g_{\mu\nu} x^\nu$$
$$g_{\mu\nu} = g^{\mu\nu} = diag(+1, -1, -1, -1), \qquad g_{ij} = -\delta_{ij}$$

Lorentz Transformations

$$x'^\mu = \Lambda^\mu_\nu x^\nu, x'_\mu = \Lambda^\nu_\mu x_\nu$$

leave

$$x_\mu x^\mu = x^0 x_0 + x^i x_i = c^2 t^2 - \vec{x}^2$$

invariant, i.e. $x'^\mu x'_\mu = x^\mu x_\mu$.

$$\Lambda^\mu_\nu \Lambda^\lambda_\mu = \delta^\lambda_\nu$$
$$g_{\mu\nu} \Lambda^\mu_\lambda \Lambda^\nu_\sigma = g_{\lambda\sigma}$$

For infinitesimal Lorentz transformations,

$$\Lambda^\mu_\nu = \delta^\mu_\nu + \epsilon^\mu_\nu$$

$$\epsilon^\mu_\nu = g^{\mu\lambda}\epsilon_{\lambda\nu}, \qquad \epsilon_{\mu\nu} = g_{\mu\lambda}\epsilon^\lambda_\mu, \qquad \epsilon_{\mu\nu} = -\epsilon_{\nu\mu}$$

$$\epsilon^0_i = \nu_i = \nu^i = -\epsilon^i_0$$

$$\epsilon^i_j = g^{i\lambda}\epsilon_{\lambda j} = \epsilon_{ij}$$

$$= -\epsilon_{ijk}\omega^k = \epsilon^{ijk}\omega^k$$

Associated with Lorentz transformation there is a unitary operator: $U = e^{i/2\epsilon_{\mu\nu}M^{\mu\nu}}$. $M^{\mu\nu}$ are generators of Lorentz group and $M_{\mu\nu} = -M_{\nu\mu}$.

There are six generators in total:

- 3 correspond to rotations.
- 3 correspond to Lorentz boosts.

$$M^{ij} = -\epsilon^{ijk} J_k = \epsilon^{ijk} J^k$$

$$M_{ij} = \epsilon_{ijk} J_k = M^{ij}$$

$$M^{oi} = K^i = -M^{io}$$

$$\epsilon_{\mu\nu} M^{\mu\nu} = -2\vec{\nu} \cdot \vec{K} - 2\vec{\omega} \cdot \vec{J}$$

$$U = e^{-i\vec{\omega}\cdot\vec{J} - i\vec{\nu}\cdot\vec{K}}$$

Rotation group is subgroup of Lorentz group.

Basic equations incorporating physical laws can be expressed in covariant form so that form of equation is frame independent.

Relativistic Quantum Mechanics

Under Lorentz transformation, a field operator transforms as:

$$\begin{aligned}\psi(x) \rightarrow \psi'(x') &= S\psi(x) \\ &= S\psi(\Lambda^{-1}x') \\ \psi'(x) &= S\psi(\Lambda^{-1}x) \\ \psi'(x) = U\psi(x)U^{\dagger} &= S\psi(\Lambda^{-1}x)\end{aligned}$$

Using infinitesimal transformation:

$$\begin{aligned}U &= 1 + \frac{i}{2}\epsilon^{\mu\nu}M_{\mu\nu} \\ S &= 1 - \frac{i}{2}\epsilon^{\mu\nu}\Sigma_{\mu\nu}\end{aligned}$$

we get

$$[M_{\mu\nu}, \psi(x)] = -[L_{\mu\nu} + \Sigma_{\mu\nu}]\psi(x)$$

where

$$L_{\mu\nu} = i(x_\mu \partial_\nu - x_\nu \partial_\mu) \qquad \text{(Orbital Part)}$$

$$\Sigma_{\mu\nu} = \frac{1}{2}\sigma_{\mu\nu} \qquad \text{(for Dirac Spinor)}$$

For Dirac spinor,

$$[M_{\mu\nu}, \psi(x)] = -[L_{\mu\nu} + \frac{1}{2}\sigma_{\mu\nu}]\psi(x)$$

Dirac equation: $(i\gamma^\mu \partial_\mu - m)\psi(x) = 0.$

Dirac spinor ψ describes the spin 1/2 particle along with its antiparticle. γ^μs are 4 x 4 Dirac matrices:

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu} \qquad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 \qquad \gamma^5\gamma^\mu + \gamma^\mu\gamma^5 = 0$$

$$S = 1 - \frac{i}{4}\epsilon_{\mu\nu}\sigma^{\mu\nu} \qquad S^{-1} \neq S^\dagger$$

$$\bar{\psi} = \psi^\dagger\gamma^0 \qquad \psi'(x) = S\psi(\Lambda^{-1}x)$$

$$\bar{\psi}'(x') = \bar{\psi}(x)S^{-1} \qquad \psi'(x') = S\psi(x)$$

Dirac bilinears are:

$$\bar{\psi}\psi, \bar{\psi}\gamma^\mu\psi, \bar{\psi}i\gamma^5\psi, \bar{\psi}\gamma^\mu\gamma^5\psi, \bar{\psi}\sigma^{\mu\nu}\psi$$

In the Weyl representation of γ matrices,

$$\gamma_5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \gamma_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

$$\psi(x) = \frac{1-\gamma^5}{2}\psi + \frac{1+\gamma^5}{2}\psi = \psi_L(x) + \psi_R(x) = \begin{pmatrix} \psi_L(x) \\ \psi_R(x) \end{pmatrix}$$

$$S = \begin{pmatrix} S_L & 0 \\ 0 & S_R \end{pmatrix}$$

$$S_L = 1 + \frac{i}{2}\vec{\omega}\cdot\vec{\sigma} + \frac{1}{2}\vec{\nu}\cdot\vec{\sigma}$$

$$S_R = 1 + \frac{i}{2}\vec{\omega}\cdot\vec{\sigma} - \frac{1}{2}\vec{\nu}\cdot\vec{\sigma}$$

Fundamental representation of Lorentz group:

$$(1/2, 0):\ [\vec{J}, \psi_L] = -\frac{1}{2}\vec{\sigma}\psi_L, \quad [\vec{K}, \psi_L] = \frac{i}{2}\vec{\sigma}\psi_L$$

$$(0, 1/2):\ [\vec{J}, \psi_R] = -\frac{1}{2}\vec{\sigma}\psi_R, \quad [\vec{K}, \psi_R] = -\frac{i}{2}\vec{\sigma}\psi_R$$

Discrete Symmetries

Space Reflection, P: $\vec{x} \to -\vec{x}$

$$\psi(\vec{x}, t) \to \psi'(-\vec{x}, t) = \gamma^0 \psi(\vec{x}, t)$$
$$\bar{\psi}(\vec{x}, t) \to \bar{\psi}'(-\vec{x}, t) = \bar{\psi}(-\vec{x}, t)$$

Charge Conjugation, C: *particle* $\to$ *antiparticle*

$$\psi \to \psi^c = C\bar{\psi}^T, \qquad \bar{\psi} \to \bar{\psi}^c = -\psi^T C^{-1}$$
$$(\gamma^\mu)^T = -C^{-1}\gamma^\mu C, \qquad C = -i\gamma^2\gamma^0, \qquad CC^\dagger = 1,\ C^2 = -1$$

Under C, P and CP, Dirac bilinears transform as:

Transformation	Vector	Axial vector
	$\bar{\Psi}_i\gamma^\mu\Psi_j$	$\bar{\Psi}_i\gamma^\mu\gamma^5\Psi_j$
P	$\eta(\mu)\,\bar{\Psi}_i\gamma^\mu\Psi_j$	$-\eta(\mu)\,\bar{\Psi}_i\gamma^\mu\gamma^5\Psi_j$
C	$-\bar{\Psi}_j\gamma^\mu\Psi_i$	$\bar{\Psi}_j\gamma^\mu\gamma^5\Psi_i$
CP	$-\eta(\mu)\,\bar{\Psi}_j\gamma^\mu\Psi_i$	$-\eta(\mu)\,\bar{\Psi}_j\gamma^\mu\gamma^5\Psi_i$

Thus both vector and axial vector currents transform the same way under CP.

Lee and Yang in 1956, suggested that there is no experimental evidence for parity conservation in weak interaction. They suggested number of experiments to test the validity of space reflection invariance in weak decays. One way to test this is to measure the helicity of outgoing muon in the decay:

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

The helicity of muon comes out to be negative, showing that parity conservation does not hold in this decay. In the rest frame of the pion, since μ^+ comes out with negative helicity, the neutrino must also come out with negative helicity because of the spin conservation. Thus confirming the fact that neutrino is left handed.

$$\pi^+ \rightarrow \mu^+(-) + \nu_\mu$$

Under charge conjugation,

$$\pi^+ \xrightarrow{C} \pi^- \qquad \mu^+ \xrightarrow{C} \mu^- \qquad \nu_\mu \xrightarrow{C} \bar{\nu}_\mu$$

Helicity $\mathcal{H} = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$ under C and P transforms as

$$\mathcal{H} \xrightarrow{C} \mathcal{H}, \qquad \mathcal{H} \xrightarrow{P} -\mathcal{H}$$

Invariance under C gives,

$$\Gamma_{\pi^+ \to \mu^+ (-) \nu_\mu} = \Gamma_{\pi^- \to \mu^- (-) \bar{\nu}_\mu}$$

Experimentally,

$$\Gamma_{\pi^+ \to \mu^+ (-) \nu_\mu} >> \Gamma_{\pi^- \to \mu^- (-) \bar{\nu}_\mu}$$

showing that C is also violated in weak interactions. However, under CP

$$\Gamma_{\pi^+\to\mu^+(-)\nu_\mu} \xrightarrow{CP} \Gamma_{\pi^-\to\mu^-(+)\bar{\nu}_\mu}$$

which is seen experimentally. Thus, CP conservation holds in weak interaction.

In the Standard Model, the fermions for each generation in their left handed chirality state belong to the representation,

$$\begin{array}{rcl} \begin{pmatrix} u_i \\ d_i \end{pmatrix}_{1/3} & : & q(3,2,1/3) \\ \bar{u}_i & : & (3,1,-4/3) \\ \bar{d}_i & : & (\bar{3},1,2/3) \\ \begin{pmatrix} \nu_{e^-} \\ e_i^- \end{pmatrix} & : & l(1,2,-1/2) \\ e_i^+ & : & (1,1,1) \end{array}$$

of the electroweak unification group $SU_C(3) \times SU_L(2) \times U_Y(1)$. Hence, the weak interaction Lagrangian for the charged current in the Standard Model is given by,

$$\mathcal{L}_W = \bar{\psi}_i \gamma^\mu (1 - \gamma^5) \psi_j W^+_\mu + h.c.$$

where ψ_i is any of the left-handed doublet (i is the generation index). We note that the weak eigenstates d', s' and b' are not equal to the mass eigenstates d, s and b. They are related to each other by a unitarity transformation,

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1}$$

where V is called the CKM matrix.

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ub} = |V_{ub}|e^{-i\gamma}, \qquad V_{td} = |V_{td}|e^{-i\beta}, \qquad \alpha + \beta + \gamma = \pi$$

The Lagrangian transforms as:

$$\begin{aligned} \mathcal{L}_W &= \bar{\psi}_i \gamma^\mu (1-\gamma^5)\psi_j W^+_\mu + h.c. \\ &\overset{CP}{\rightarrow} -\eta(\mu)\bar{\psi}_j \gamma^\mu (1-\gamma^5)\psi_i (-\eta(\mu)) W^-_\mu + h.c. \end{aligned}$$

We conclude that the weak interaction Lagrangian in the Standard Model is *CP* invariant and since *CP* violation has been observed in hadronic sector (only in B, B_s and K decays) and not in leptonic sector, it is a consequence of mismatch between weak and mass eigenstates (i.e. the phases in *CKM* matrix) and/or the mismatch between *CP*-eigenstates,

$$|X^0_{1,2}\rangle = \frac{1}{\sqrt{2}}\left[|X^0\rangle \mp |\bar{X}^0\rangle\right];\ CP\,|X^0_{1,2}\rangle = \pm\,|X^0_{1,2}\rangle \qquad (2)$$

and the mass eigenstates i.e. CP-violation in the mass matrix. CP-violation due to mass mixing and in the decay amplitude has been experimentally observed in K^0 and B_d^0. For B_s decays, the CP-violation in the mass matrix is not expected in the Standard Model. In fact time dependent CP-violation asymmetry gives a clear way to observe direct CP-violation in B and B_s decays.

Conclusion-I

- No evidence that space-time symmeries are violated by fundamental laws of nature. Both translational and rotational symmetries hold in nature.

  Translational Symmetry $\Rightarrow$ Energy Momentum Conservation
  Rotational Symmetry $\Rightarrow$ Angular Momentum Conservation

- If we examine light emitted by a distant object billions of light years away, we find that atoms have been following the same laws as they are here and now. (Translation Symmetry)

Conclusion-II

- Discrete Symmetries are not universal; both C and P are violated in the weak interaction but repsected by electromagnetic and strong interactions. There is no evidence for violation of time reversal invariance by any of the fundamental laws of nature.
- Basic weak interaction Lagrangian is CP conserving. CP violation in weak interactions is a consequence of mismatch between mass eigenstates and CP eigenstates and or mismatch between weak and mass eigenstates at quark level. There is no evidence of CP violation in Lepton sector.
- CP violation in weak decays is an example where basic laws are CP invariant but states at quark level violate CP.

Conclusion-III

- The fundamental interaction governing the atoms and molecules is the electromagnetic interaction which does not violate bilateral symmetry (left-right symmetry). In nature we find organic molecules in asymmetric form, i.e. left handed or right handed. This is another example where the basic laws governing these molecules are bilateric symmetric but states are not. (Asymmetric intial conditions?)
- **Baryon Asymmetry of the Universe: Baryogenesis** No evidence for existence of antibaryons in the universe. $\eta = n_B/n_\gamma \sim 3 \times 10^{-10}$. The universe started with a complete matter antimatter symmetry in big bang picture. In subsequent evolution of the universe, a net baryon number was generated. This is possible provided
  1. There exists a baryon number violating interaction.

Conclusion-IV

2. There exist C and CP violation to introduce the asymmetry between particle and antiparticle processes.
3. Departure from thermal equilibrium of X-particles which mediate the baryon number violating interactions.

- Key question is understanding the nature of discrete symmetries violation at a fundamental level.