Relating Leptogenesis to Low Energy CP Violation

--- Can all CP violation come from a single source?

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Fermilab

Ref: M.-C. C and K.T. Mahanthappa, Phys. Rev. D71, 035001 (2005)

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Introduction

- CP violation in the quark sector is not sufficient to explain the observed matter-antimatter asymmetry in the Universe
- Neutrino oscillation opens up the possibility that CP violation in the lepton sector may be responsible, through leptogenesis, for the observed BAU
- Relating leptogenesis and low energy CPV is in general not possible due to extra mixing angles and phases in the heavy RH neutrino sector
- In minimal LR symmetric model with spontaneous CP violation, there exist very pronounced correlations between these high (10^16 GeV) and low energy processes

The minimal LR symmetric model

- Gauge symmetry: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$

$$\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \qquad Q = T_{3,L} + T_{3,R} + \tfrac{1}{2}(B-L)$$

- Particle content:

-- fermions:

$$Q_{i,L} = \begin{pmatrix} u \\ d \end{pmatrix}_{i,L} \sim (1/2,\ 0,\ 1/3) \qquad Q_{i,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{i,R} \sim (0,\ 1/2,\ 1/3)$$

$$L_{i,L} = \begin{pmatrix} e \\ \nu \end{pmatrix}_{i,L} \sim (1/2,\ 0,\ -1) \qquad L_{i,R} = \begin{pmatrix} e \\ \nu \end{pmatrix}_{i,R} \sim (0,\ 1/2,\ -1)$$

-- scalars:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (1/2,\ 1/2,\ 0)$$

$$\Delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_L^+ & \Delta_L^{++} \\ \Delta_L^0 & -\frac{1}{\sqrt{2}}\Delta_L^+ \end{pmatrix} \sim (1,\ 0,\ +2) \qquad \Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \sim (0,\ 1,\ +2)$$

Under P: $\psi_L \leftrightarrow \psi_R,\ \ \Delta_L \leftrightarrow \Delta_R,\ \ \Phi \leftrightarrow \Phi^+$

- In general,

$$\langle\Phi\rangle = \begin{pmatrix} \kappa e^{i\alpha_\kappa} & 0 \\ 0 & \kappa' e^{i\alpha_{\kappa'}} \end{pmatrix}, \ \langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\alpha_L} & 0 \end{pmatrix}, \ \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R e^{i\alpha_R} & 0 \end{pmatrix}$$

- To get realistic SM gauge boson masses, the bi-doublet VEV's must satisfy $\kappa^2 + \kappa'^2 \cong 2m_W^2 / g^2 \cong (174 GeV)^2$

- The two triplet VEVs are related by $v_L = \beta \frac{\kappa^2}{v_R}$

so v_L is seesaw suppressed => EW precision constraints OK

(small neutrino mass => v_R ~10^(15) GeV and v_L ~ 0.01 eV)

- The Lagrangian is invariant under the following unitary transformations,

$$U_L = \begin{pmatrix} e^{i\gamma_L} & 0 \\ 0 & e^{-i\gamma_L} \end{pmatrix}, \quad U_R = \begin{pmatrix} e^{i\gamma_R} & 0 \\ 0 & e^{-i\gamma_R} \end{pmatrix}$$

under which the fields transform as

$$\psi_L \to U_L \psi_L, \quad \psi_R \to U_R \psi_R$$

$$\Phi \to U_R \Phi U_L^+, \quad \Delta_L \to U_L^* \Delta_L U_L^+, \quad \Delta_R \to U_R^* \Delta_R U_R^+$$

$\Rightarrow$

$$\kappa \to \kappa e^{-i(\gamma_L - \gamma_R)}, \quad \kappa' \to \kappa' e^{i(\gamma_L - \gamma_R)}$$

$$v_L \to v_L e^{-2i\gamma_L}, \qquad v_R \to v_R e^{-2i\gamma_R}$$

Using these unitary transformations, we can rotate away two phases and are left with only two intrinsic phases

$$\langle \Phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha_{\kappa'}} \end{pmatrix}, \quad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\alpha_L} & 0 \end{pmatrix}, \quad \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

- Yukawa sector: quarks

$$-L_q = \overline{Q}_{i,R}(F_{ij}\Phi + G_{ij}\overline{\Phi})Q_{j,L} + h.c. \quad \text{where } \overline{\Phi} = \tau_2\Phi^*\tau_2$$

- Mass matrices

$$M_u = F_{ij}\kappa + G_{ij}\kappa' e^{-i\alpha_{\kappa'}}, \quad M_d = F_{ij}\kappa' e^{i\alpha_{\kappa'}} + G_{ij}\kappa$$

$\Rightarrow$ All Yukawa coupling constants are real as SCPV

$\Rightarrow$ $\alpha_{\kappa'}$ responsible for all CPV in the quark sector

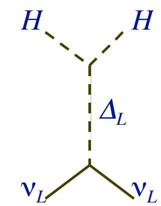
$\Rightarrow$ To suppress FCNC requires a large hierarchy in the bi-doublet VEV

$$\kappa/\kappa' \cong m_t/m_b >> 1$$

- Lepton sector: $-L_l = \overline{L}_{i,R}(P_{ij}\Phi + R_{ij}\overline{\Phi})L_{j,L} + f_{ij}(L^T_{i,L}\Delta_L L_{j,L} + L^T_{i,R}\Delta_R L_{j,R}) + h.c.$

$$M_e = P_{ij}\kappa' e^{i\alpha_{\kappa'}} + R_{ij}\kappa$$

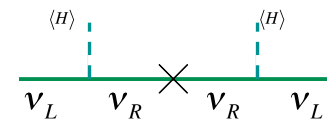
$$M_\nu^{Dirac} = P_{ij}\kappa + R_{ij}\kappa' e^{-i\alpha_{\kappa'}}, \quad M_\nu^{LL} = f_{ij}v_L e^{i\alpha_L}, \quad M_\nu^{RR} = f_{ij}v_R,$$



$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\begin{pmatrix} M_{LL} & M_{LR}^T \\ M_{LR} & M_{RR} \end{pmatrix} \quad \xrightarrow{\upsilon_R} SU(2)_L \times U(1)_Y \Rightarrow \begin{pmatrix} 0 & 0 \\ 0 & f\upsilon_R \end{pmatrix}$$

$$\xrightarrow{\upsilon_{ew}} U(1)_{EM} \Rightarrow \begin{pmatrix} f\upsilon_L & h\upsilon_{ew} \\ h\upsilon_{ew} & f\upsilon_R \end{pmatrix}$$



$$M_\nu^{eff} = M_\nu^{II} - M_\nu^{I} \approx (fe^{i\alpha_L} - \frac{1}{\beta}P^T f^{-1} P)\upsilon_L$$

$$M_\nu^{I} = (M_\nu^{Dirac})^T (M_\nu^{RR})^{-1} (M_\nu^{Dirac}) = (\kappa P + \kappa' e^{-i\alpha_{\kappa'}} R)^T (\upsilon_R f)^{-1} (\kappa P + \kappa' e^{-i\alpha_{\kappa'}} R) \approx \frac{\upsilon_L}{\beta} P^T f^{-1} P$$

$$M_\nu^{II} = \upsilon_L e^{i\alpha_L} f$$

⇒ The connection between CPV in quark sector and that in the lepton sector, which is made thru the phase $\alpha_{\kappa'}$, appear only at the sub-leading order $O(\kappa'/\kappa)$

⇒ Thus making these effects rather weak (will be neglected in this analysis)

- Leptonic mixing matrix (MNS matrix):

$$U_{MNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & e^{i\alpha_{21}/2} & \\ & & e^{i\alpha_{31}/2} \end{pmatrix}$$

- These three leptonic phases, which are functions of α_L , appear in the following processes:

(I) neutrino oscillation:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i})\sin^2(\Delta m^2_{ij}\tfrac{L}{4E}) + 2\sum_{i>j} J_{CP}\sin^2(\Delta m^2_{ij}\tfrac{L}{4E})$$

$$J_{CP} = -\frac{\mathrm{Im}(H_{12}H_{23}H_{31})}{\Delta m^2_{21}\Delta m^2_{32}\Delta m^2_{31}} \propto \sin\alpha_L, \qquad H \equiv M^{eff}_\nu (M^{eff}_\nu)^+$$

(II) neutrinoless double beta decay:

$$\left|\langle m_{ee}\rangle\right|^2 = m_1^2|U_{e1}|^4 + m_2^2|U_{e2}|^4 + m_3^2|U_{e3}|^4 + 2m_1m_2|U_{e1}|^2|U_{e2}|^2\cos\alpha_{21}$$
$$+ 2m_1m_3|U_{e1}|^2|U_{e3}|^2\cos\alpha_{31} + 2m_2m_3|U_{e2}|^2|U_{e3}|^2\cos(\alpha_{31} - \alpha_{21})$$

(III) Leptogenesis: two ways to generate lepton number asymmetry

(1) $N_1 \to \ell + H^*,$ $\qquad \varepsilon = \dfrac{\Gamma(N_1 \to \ell + H^*) - \Gamma(N_1 \to \bar{\ell} + H)}{\Gamma(N_1 \to \ell + H^*) + \Gamma(N_1 \to \bar{\ell} + H)}$

(2) $\Delta_L^* \to \ell + \ell,$ $\qquad \varepsilon = \dfrac{\Gamma(\Delta_L^* \to \ell + \ell) - \Gamma(\Delta_L \to \bar{\ell} + \bar{\ell})}{\Gamma(\Delta_L^* \to \ell + \ell) + \Gamma(\Delta_L \to \bar{\ell} + \bar{\ell})}$

- A natural scenario is that the SU(2)_L triplet Higgs is heavier than the lightest RH neutrino. If this is the case, then the decay of the lightest RH neutrino dominates => case (1)

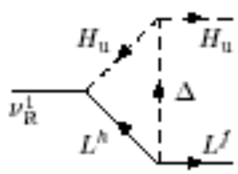
  two types of diagrams contribute to this asymmetry $\quad \mathrm{M}_D = O_R M_D$

(a)

(a) (b)

$$\varepsilon = \frac{3}{16\pi}\left(\frac{M_1}{\upsilon^2}\right)\frac{\mathrm{Im}(\mathrm{M}_D (M_\nu^I)^* \mathrm{M}_D^T)_{11}}{(\mathrm{M}_D \mathrm{M}_D^+)_{11}} = 0$$

(b)



(c)

$$\varepsilon = \frac{3}{16\pi}\left(\frac{M_1}{\upsilon^2}\right)\frac{\mathrm{Im}(\mathrm{M}_D (M_\nu^{II})^* \mathrm{M}_D^T)_{11}}{(\mathrm{M}_D \mathrm{M}_D^+)_{11}} \propto \sin\alpha_L$$

Independent of the choice of the unitary transformation $U_{L,R}$

- Out-of-equilibrium condition: To avoid the generated lepton number asymmetry from being washed out by the scattering processes, the decay rate of the RH neutrino must be smaller than the expansion rate of the Universe at temperature equal to the RH neutrino mass

$$\frac{\Gamma}{H|_{T=M_1}} = \frac{M_{Pl}}{(1.7)(32\pi)\sqrt{g_*}\upsilon^2} \cdot \frac{\left(\mathrm{M}_D \mathrm{M}_D^+\right)_{11}}{M_1} \approx \frac{1}{(0.01eV)} \cdot \frac{\left(\mathrm{M}_D \mathrm{M}_D^+\right)_{11}}{M_1} < 1$$

=> to satisfy this condition, M_1 cannot be too light

=> the hierarchy in RH neutrino mass matrix cannot be too large (usually the problem in conventional Type-I seesaw)

- The lepton number asymmetry then get converted into baryon number asymmetry:

  The observed BAU $n_b / s \sim 10^{-10}$ => $\varepsilon \sim 10^{-8}$

Specific Flavor Ansatz for Bi-large Mixing

$$M_\nu^{eff} = (f e^{i\alpha_L} - \frac{1}{\beta} P^T f^{-1} P)\upsilon_L \qquad P \propto \begin{pmatrix} m_u/m_t & & \\ & m_c/m_t & \\ & & 1 \end{pmatrix}$$

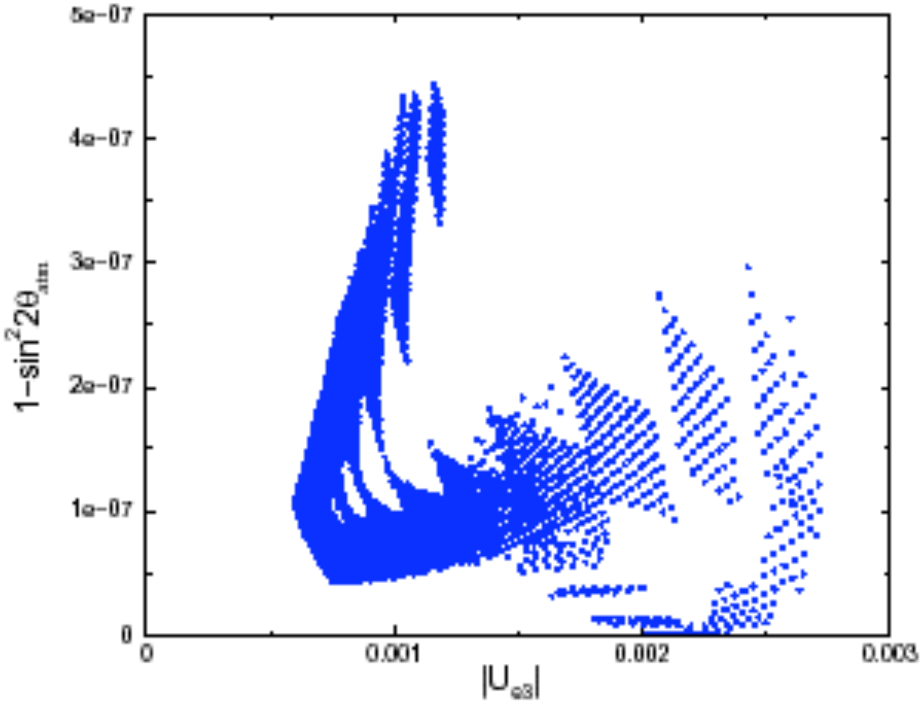
(I)

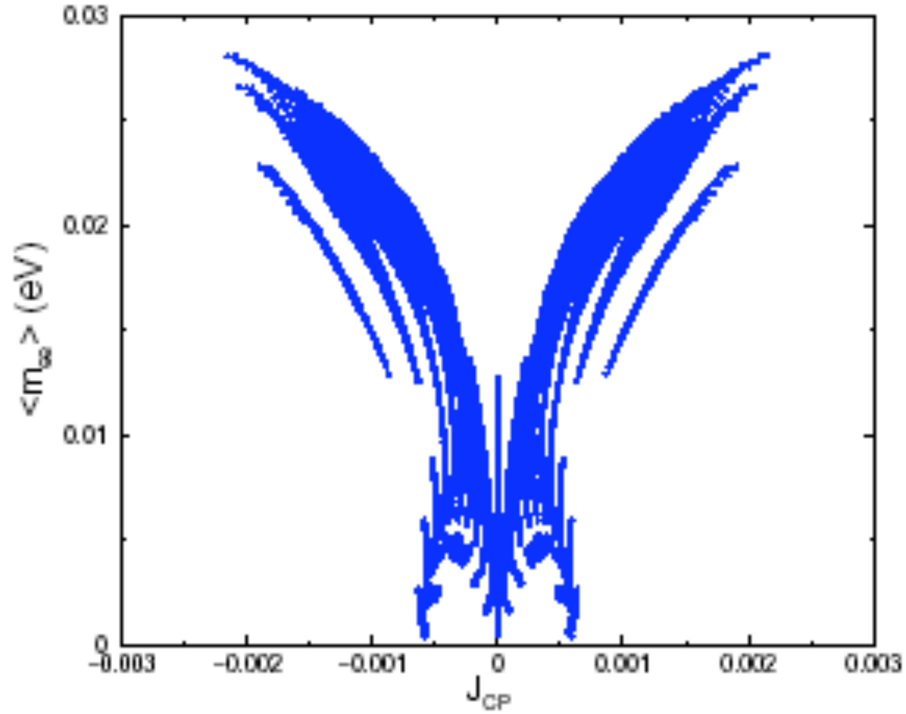
$$f_{ij} = \begin{pmatrix} t^2 & t & -t \\ t & 1 & 1 \\ -t & 1 & 1 \end{pmatrix} \qquad \frac{1}{\beta} P^T f^{-1} P = s \begin{pmatrix} 0 & \frac{1}{t}\frac{m_u m_c}{m_t^2} & -\frac{1}{t}\frac{m_u}{m_t} \\ \frac{1}{t}\frac{m_u m_c}{m_t^2} & 0 & \frac{m_c}{m_t} \\ -\frac{1}{t}\frac{m_u}{m_t} & \frac{m_c}{m_t} & 0 \end{pmatrix}$$

--may arise from U(1) horizontal symmetry

--deviation of atmospheric mixing angle from being maximal is negligible

$$J_{CP} = -\frac{2st^2(1-t^2)\upsilon_L^6}{\Delta m_{21}^2 \Delta m_{31}^2 \Delta m_{32}^2} \left(\frac{m_u}{m_t}\right) \sin\alpha_L$$

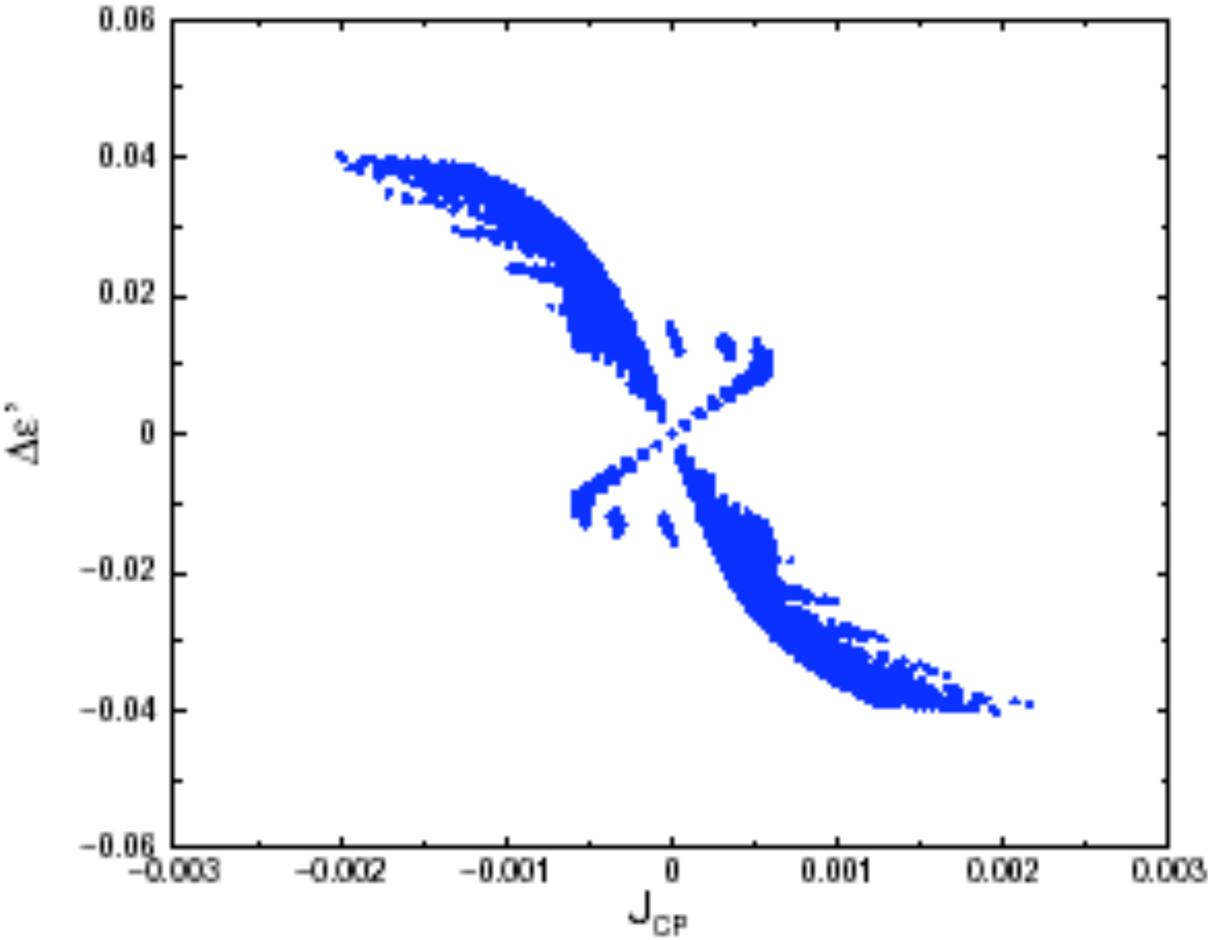




-- In the large J_CP region, strong correlation between J_CP and <m_ee>

-- J_CP ranges from 0 to 10^(-3)

-- <m_ee> ranges from 10^(-4) to 10^(-2) eV; current limit ~ 0.1eV



-- symmetry bt 2nd and 4th quadrants

-- In the large J_CP region, strong correlation between J_CP and lepton number asymmetry

-- total amount of lepton number asymmetry

$$\varepsilon = 10^{-2} \times \Delta\varepsilon' < (10^{-4} - 10^{-5})$$

-- no wash-out effect:

$$\frac{\Gamma}{H|_{T=M_1}} \approx \frac{1}{(0.01eV)} \cdot \frac{\left(\mathrm{M}_D \mathrm{M}_D^{+}\right)_{11}}{M_1} < 1$$

$$\frac{\left(\mathrm{M}_D \mathrm{M}_D^{+}\right)_{11}}{M_1} \sim \left(\frac{m_c}{m_t}\right)^2 \upsilon_L = 10^{-7} eV!!!$$

Even with a small amount of J_CP ~ 10^(-5), sufficient amount of BAU can be generated

$$\upsilon_R \sim (10^{12-13}) GeV, \;\; M_1 \sim 0.1 \upsilon_R$$

Conclusions

- In minimal LR symmetric model, there are only two intrinsic phases to account for ALL CPV observed in Nature, if CPV occurs spontaneously

- Due to the parity in the model, the LH and RH Majorana mass terms are proportional to each other

⇒ Pronounced relations between leptogenesis and low energy LFV processes exist

- CPV in quark sector and CPV in lepton sector are also related; nontheless, such connection is very weak due to the large hierarchy in the bi-doublet vev required by a realistic quark sector