Spontaneous CP violation, nonzero θ_{13} and leptogenesis in Type-II seesaw

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based on: Biswajit Karmakar and A.S., PRD 93 (2016) 013006

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Outline

Introduction

Questions :

(a) Why lepton mixing is so different from the that of the quarks?:
[hint toward a new symmetry in the lepton sector]

(b) Smallness of neutrino mass:
[hint toward a new scale: seesaw mechanism]

(c) Origin of CP violation in lepton sector:
[can there be a spontaneous CP violation?]

Neutrino Parameters : where do we stand

Neutrino flavor eigenstates and mass eigenstates are related by

- $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$

Pontecorvo-Maki-Nakagawa-Sakata parametrization

$$U_{PMNS} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{bmatrix}$$

here $C_{ij} = \cos\theta_{ij}$ and $S_{ij} = \sin\theta_{ij}$. PDG, Chin. Phys. C 38, 090001 (2014)

Neutrino Parameters

- Three mixing angles (θ_{12}, θ_{23} and θ_{13})
- Two mass squared differences, namely solar mass-squared difference ($\Delta m^2_\odot$) and atmospheric mass-squared difference (Δm^2_A). At-least, two different neutrino mass spectrum is possible: Normal hierarchy (NH) [$m_1 < m_2 < m_3$] and inverted hierarchy (IH) [$m_3 < m_1 < m_2$]
- Dirac phase (δ)
- Two Majorana phases (α_{21} and α_{31})

- **Neutrino Oscillation Parameters:** Forero et al., PRD 90 (2014) 9, 093006

Parameter	Best Fit	1σ range	3σ range
$\Delta m^2_{\odot}$ $[\times 10^{-5} eV^2]$	7.60	7.42 – 7.79	7.11 – 8.18
$\lvert\Delta m^2_A\rvert$ $[\times 10^{-3} eV^2]$	2.48 2.38	2.41 – 2.53 2.32 – 2.43	2.30 – 2.65 2.20 – 2.54
$\sin^2\theta_{12}$	0.323	0.307 – 0.339	0.278 – 0.375
$\sin^2\theta_{23}$	0.567 0.573	0.439 – 0.599 0.530 – 0.598	0.392 – 0.643 0.403 – 0.640
$\sin^2\theta_{13}$	0.0234 0.0240	0.0214 – 0.0254 0.0221 – 0.0259	0.0177 – 0.0294 0.0183 – 0.0297
δ/π	1.34 1.48	0.96 – 1.98 1.16 – 1.82	0 – 2 0 – 2

There is a recent hint for Dirac CP Phase $\rightarrow$ $\boxed{\delta \approx 270^\circ}$

- Absolute neutrino mass : $\sum_i m_{\nu_i} < 0.23$ eV (95% CL) PLANCK Collaboration, 1303:5076

- $|m_{ee}| < (0.14 - 0.28)$ eV KamLAND-Zen, arXiv:1409.0077
  $< (0.19 - 0.45)$ eV EXO-200, arXiv:1402.6956

A discrete roadmap towards lepton masses and mixing

Prior to 2012 : Tribimaximal(TBM) mixing and $\theta_{13} = 0$

Global analysis of neutrino oscillation data suggests $\sin^2\theta_{12} = 1/3$ and $\sin^2\theta_{23} = 1/2$. With $\theta_{13} = 0$, neutrino mixing matrix takes the form

$$U_{TB} = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Harrison, Perkins, Scott, hep-ph/9904297

2012 and afterwards: $\sin\theta_{13} \approx 0.155 \rightarrow \theta_{13} \approx 9^o$ [from result of Daya Bay , DOUBLE-CHOOZ, RENO, T2K]

Origin of TBM structure:

• Non-Abelian discrete symmetry: they have multi-dimensional representation and hence can relate one flavor to another.

• A_4 turns out to be simplest possibility to accommodate 3-families as it has 4-irreducible representations: $1, 1^{'}, 1^{''}, 3$. Ma,Rajasekharan PRD64; Altarelli,Feruglio NPB741

The basic set-up

Neutrino masses and mixing

1. A genral Type-II seesaw mechanism
2. Standard Model + 3 RH neutrinos (gauge singlets) + **only one scalar triplet**(Δ)
3. pure type-I seesaw provides TBM and **scalar triplet contribution generates** θ_{13}

CP violation

1. Source of CP violation : **Spontaneous CP violation** Branco, Parada, Rebelo hep-ph/0307119
2. This unique source of CP violation generates Dirac , Majorana CP phases and CP violation required for matter-antimatter asymmetry of the universe

   Branco, Felipe, Joaquim, Rev. Mod. Phys 84 (2012); Branco, Felipe, Joaquim, Serodio, PRD 86 (2012)
3. Complex vev of a single flavon serves the purpose

   [A] magnitude of complex vev $\Longrightarrow$ adequate θ_{13}
   [B] phase of complex vev $\Longrightarrow$ ensures CP violation of the theory

Leptogenesis

1. Decay of RH neutrinos only: lepton asymmetry vanishes
2. Decay of scalar triplet ($M_R > M_\Delta$) : RH neutrinos in loop $\Rightarrow$ successful leptogenesis scenario
3. Decay of RH neutrinos ($M_\Delta > M_R$) : Triplets in loop $\Rightarrow$ constrained leptogenesis scenario

   Hambye,Senjanovic, PLB 582, 73 (2004)

- **Generic Type-II seesaw:**

$$m_\nu = m_\nu^I + m_\nu^{II} = -m_D^T M_R^{-1} m_D + m_\nu^{II}$$

- **Symmetries and Particle Content**

Field	e_R	μ_R	τ_R	L	N_R	H	Δ	ϕ_S	ϕ_T	ξ	ξ'	S
A_4	1	$1''$	$1'$	3	3	1	1	3	3	1	$1'$	1
Z_4	-1	-1	-1	i	i	1	$-i$	-1	$-i$	-1	i	-1
Z_3	ω	ω	ω	ω	ω	1	ω^2	ω	1	ω	ω^2	1

- **A_4 multiplication rule:**

$3 \times 3 = 1 + 1' + 1'' + 3_A + 3_S; 1' \times 1' = 1''; 1' \times 1'' = 1; 1'' \times 1'' = 1'$

If (a_1, a_2, a_3) and (b_1, b_2, b_3) are two triplets under A_4, then
$1 \sim a_1 b_1 + a_2 b_3 + a_3 b_2, 1' \sim a_3 b_3 + a_1 b_2 + a_2 b_1, 1'' \sim a_2 b_2 + a_3 b_1 + a_1 b_3$
$3_S = \frac{1}{3}(2a_1 b_1 - a_2 b_3 - a_3 b_2, 2a_3 b_3 - a_1 b_2 - a_2 b_1, 2a_2 b_2 - a_1 b_3 - a_3 b_1)$ and
$3_A = \frac{1}{2}(a_2 b_3 - a_3 b_2, a_1 b_2 - a_2 b_1, a_3 b_1 - a_1 b_3)$

- **Diagonal Charged Lepton Sector:**

$$\mathcal{L}_l = \frac{y_e}{\Lambda}(\bar{L}\phi_T)He_R + \frac{y_\mu}{\Lambda}(\bar{L}\phi_T)'H\mu_R + \frac{y_\tau}{\Lambda}(\bar{L}\phi_T)''H\tau_R,$$

Λ : cut-off scale of the theory, $\langle\phi_S\rangle = (u_S, u_S, u_S)$ and $\langle\phi_T\rangle = (u_T, 0, 0)$

- **Type-I seesaw contribution**

$$\mathcal{L}_{\mathcal{I}} = y\bar{L}\widetilde{H}N_R + x_A \xi \overline{N_R^c} N_R + x_B \phi_S \overline{N_R^c} N_R,$$

$$m_D = Y_D v = yv \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}; M_R = \begin{pmatrix} a+2b/3 & -b/3 & -b/3 \\ -b/3 & 2b/3 & a-b/3 \\ -b/3 & a-b/3 & 2b/3 \end{pmatrix}$$

$$a = 2x_A\langle\xi\rangle = 2x_A u_\xi, \, b = 2x_B u_S$$

$$\begin{aligned} m_\nu^I &= -m_D^T M_R^{-1} m_D \\ &= -k \begin{pmatrix} \frac{3+\alpha}{3(1+\alpha)} & \frac{\alpha}{3(1+\alpha)} & \frac{\alpha}{3(1+\alpha)} \\ \frac{\alpha}{3(1+\alpha)} & -\frac{\alpha(2+\alpha)}{3(1-\alpha^2)} & \frac{3+\alpha-\alpha^2}{3(1-\alpha^2)} \\ \frac{\alpha}{3(1+\alpha)} & \frac{3+\alpha-\alpha^2}{3(1-\alpha^2)} & -\frac{\alpha(2+\alpha)}{3(1-\alpha^2)} \end{pmatrix} \text{ where } \alpha = b/a \text{ and } k = v^2y^2/a \end{aligned}$$

- **TBM Mixing:**

Here, m_ν^I can be diagonalized by TBM Mixing matrix

$$U_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}.$$

- U_{TB} also diagonalizes M_R

$$M_R^{\rm diag} = U_R^T M_R U_R = {\rm diag}(a+b, a, |a-b|) \quad \text{with} \quad U_R = U_{TB}$$

- **Triplet contribution : Type-II seesaw**

$$\mathcal{L}_{\mathcal{II}} = \frac{1}{\Lambda^2}\Delta L^T L(x_1 S + x_1' S^*)\xi'$$

$$\text{with } \langle\xi'\rangle = u_{\xi'},\ \boxed{\langle S\rangle = v_S e^{i\alpha_S}} \Leftarrow \text{Only source of CP violation}$$

$$\Downarrow$$

$$\text{Yukawa matrix for triplet : } Y_\Delta = h\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \quad h = \frac{1}{\Lambda^2}u_{\xi'}v_S(x_1 e^{i\alpha_S} + x_1' e^{-i\alpha_S})$$

- **Complete Scalar Potential:**

$$V = V_S + V_H + V_\Delta + V_{SH} + V_{S\Delta} + V_{\Delta H},$$

where

$$\begin{aligned}
V_S &= \mu_S^2(S^2 + S^{*2}) + m_S^2 S^* S + \lambda_1(S^4 + S^{*4}) + \lambda_2 S^* S(S^2 + S^{*2}) + \lambda_3(S^* S)^2, \\
V_H &= m_H^2 H^\dagger H + \lambda_4(H^\dagger H)^2, \\
V_\Delta &= M_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5[\mathrm{Tr}(\Delta^\dagger\Delta)]^2, \\
V_{SH} &= \lambda_6(S^* S)H^\dagger H + \lambda_7(S^2 + S^{*2})(H^\dagger H), \\
V_{S\Delta} &= \mathrm{Tr}(\Delta^\dagger\Delta)[\lambda_8(S^2 + S^{*2}) + \lambda_9 S^* S], \\
V_{\Delta H} &= \lambda_{10}(H^\dagger H)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_{11}(H^\dagger\Delta^\dagger\Delta H) + \left(-\frac{\mu}{\Lambda}\widetilde{H}^T\Delta\widetilde{H}\phi_S\phi_T + h.c.\right).
\end{aligned}$$

- **After Minimizating of Scalar Potential:**

$$\langle \Delta^0 \rangle \equiv u_\Delta = \eta \frac{v^2}{M_\Delta^2} \quad \text{and} \quad \eta = \frac{\mu}{\Lambda} u_S u_T$$

- **Triplet contribution:**

$$m_\nu^{II} = \begin{pmatrix} 0 & 0 & d \\ 0 & d & 0 \\ d & 0 & 0 \end{pmatrix}, \quad d = 2h u_\Delta = 2h\eta \frac{v^2}{M_\Delta^2}.$$

- **Effective Neutrino Mass Matrix:**

$$m_\nu = m_\nu^I + m_\nu^{II} = -k \begin{pmatrix} \frac{3+\alpha}{3(1+\alpha)} & \frac{\alpha}{3(1+\alpha)} & \frac{\alpha}{3(1+\alpha)} \\ \frac{\alpha}{3(1+\alpha)} & -\frac{\alpha(2+\alpha)}{3(1-\alpha^2)} & \frac{3+\alpha-\alpha^2}{3(1-\alpha^2)} \\ \frac{\alpha}{3(1+\alpha)} & \frac{3+\alpha-\alpha^2}{3(1-\alpha^2)} & -\frac{\alpha(2+\alpha)}{3(1-\alpha^2)} \end{pmatrix} + \begin{pmatrix} 0 & 0 & d \\ 0 & d & 0 \\ d & 0 & 0 \end{pmatrix}.$$

- **Diagonalization of Effective Neutrino Mass Matrix:**

$$m_\nu' = U_{TB}^T m_\nu U_{TB} = \begin{pmatrix} -\frac{d}{2} - \frac{k}{(1+\alpha)} & 0 & \frac{\sqrt{3}d}{2} \\ 0 & d-k & 0 \\ \frac{\sqrt{3}d}{2} & 0 & \frac{d}{2} + \frac{k}{(1-\alpha)} \end{pmatrix}$$

- **To diagonalize m'_ν : Additional rotation required $\Longrightarrow$** $\boxed{U_1^T m'_\nu U_1 = m_\nu^{\rm diag}}$

$$\text{with} \qquad U_1 = \begin{pmatrix} \cos\theta & 0 & \sin\theta e^{-i\psi} \\ 0 & 1 & 0 \\ -\sin\theta e^{i\psi} & 0 & \cos\theta \end{pmatrix}$$

- Effectively:

$$(U_{TB}U_1)^T m_\nu U_{TB} U_1 = {\rm diag}(m_1 e^{i\gamma_1}, m_2 e^{i\gamma_2}, m_3 e^{i\gamma_3})$$

$m_{i=1,2,3}$: real and positive eigenvalues, $\gamma_{i=1,2,3}$: phases associated to these mass eigenvalues.

- **Diagonalizing Matrix:** $U_\nu \Longleftrightarrow U_{PMNS}$

$$U_\nu = U_{TB} U_1 U_m = \begin{pmatrix} \sqrt{\frac{2}{3}}\cos\theta & \frac{1}{\sqrt{3}} & \sqrt{\frac{2}{3}} e^{-i\psi}\sin\theta \\ -\frac{\cos\theta}{\sqrt{6}} + \frac{e^{i\psi}\sin\theta}{\sqrt{2}} & \frac{1}{\sqrt{3}} & -\frac{\cos\theta}{\sqrt{2}} - \frac{e^{-i\psi}\sin\theta}{\sqrt{6}} \\ -\frac{\cos\theta}{\sqrt{6}} - \frac{e^{i\psi}\sin\theta}{\sqrt{2}} & \frac{1}{\sqrt{3}} & \frac{\cos\theta}{\sqrt{2}} - \frac{e^{-i\psi}\sin\theta}{\sqrt{6}} \end{pmatrix} U_m$$

$$\text{with} \quad U_m = {\rm diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$$

- **Majorana Phases**

$$\boxed{\alpha_{21} = (\gamma_1 - \gamma_2) \text{ and } \alpha_{31} = (\gamma_1 - \gamma_3)}$$

Evaluation of neutrino mixing parameter

Comparing U_ν and U_{PMNS}

$$\sin\theta_{13} = \sqrt{\frac{2}{3}}\,|\sin\theta|\,, \quad \sin^2\theta_{12} = \frac{1}{3(1-\sin^2\theta_{13})}\,,$$
$$\sin^2\theta_{23} = \frac{1}{2} + \frac{1}{\sqrt{2}}\sin\theta_{13}\cos\delta, \quad \delta = \arg[(U_1)_{13}]$$

Connection of triplet contribution with nonzero θ_{13}

- Triplet contribution $= d = |d|e^{i\phi_d}$ where $\beta = |d|/k$ and $k = v^2y^2/a$

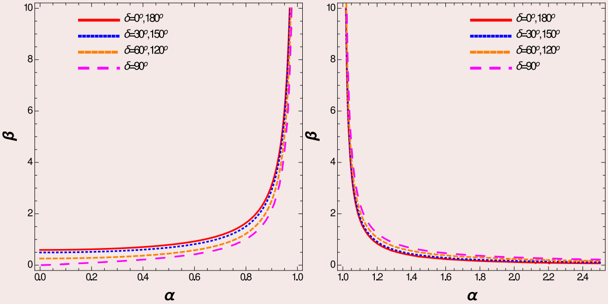
$$\tan 2\theta = \frac{\sqrt{3}}{\alpha}\,\frac{\left[1-(1-\alpha^2)\cos^2\phi_d\right]^{1/2}}{\frac{2}{\beta(1-\alpha^2)}+\cos\phi_d} \quad \text{and} \quad \tan\delta = \tan\psi = (\tan\phi_d)/\alpha.$$

$$\Uparrow$$

$$\langle S\rangle = v_S e^{i\alpha_S} \qquad \Longrightarrow \qquad \tan\phi_d = \frac{(x_1 - x_1')}{(x_1 + x_1')}\tan\alpha_S,$$

- θ_{13} and δ : depends on α, β, ϕ_d
- Cases A: $\alpha < 1$ and Cases B: $\alpha > 1$

Contour plots for $\sin^2\theta_{13} = 0.0234$ in the $\alpha - \beta$ plane for various δ



- Typical contour plot for $\sin^2\theta_{13}$ with a specific δ value coincides with $|\pi - \delta|$ values.
- Example: $\delta = 30^\circ$ is repeated for $\delta = 150^\circ, 210^\circ, 330^\circ$.

Light neutrino masses and Majorana phase

- **Real, positive light neutrino masses:**

$$m_1 = k\left[\left(\frac{\alpha}{(1-\alpha^2)}-\frac{p}{k}\right)^2+\left(\frac{q}{k}\right)^2\right]^{1/2},$$

$$m_2 = k\left[1+\beta^2-2\beta\cos\phi_d\right]^{1/2},$$

$$m_3 = k\left[\left(\frac{\alpha}{(1-\alpha^2)}+\frac{p}{k}\right)^2+\left(\frac{q}{k}\right)^2\right]^{1/2},$$

where p and q are defined as,

$$\left(\frac{p}{k}\right)^2=\frac{1}{2}\left(\frac{A}{k^2}+\sqrt{\frac{A^2}{k^4}+\frac{B^2}{k^4}}\right) \quad , \quad \left(\frac{q}{k}\right)^2=\frac{1}{2}\left(-\frac{A}{k^2}+\sqrt{\frac{A^2}{k^4}+\frac{B^2}{k^4}}\right);$$

$$\frac{A}{k^2}=\beta^2\cos 2\phi_d+\beta\frac{\cos\phi_d}{1-\alpha^2}+\frac{1}{(1-\alpha^2)^2} \quad , \quad \frac{B}{k^2}=\beta^2\sin 2\phi_d+\beta\frac{\sin\phi_d}{1-\alpha^2}.$$

- **Majorana phases:**

$$\alpha_{21} = \tan^{-1}\left[\frac{q/k}{p/k+\frac{\alpha}{(\alpha^2-1)}}\right]-\tan^{-1}\left[\frac{\beta\sin\phi_d}{\beta\cos\phi_d-1}\right],$$

$$\alpha_{31} = \pi+\tan^{-1}\left[\frac{q/k}{p/k+\frac{\alpha}{(\alpha^2-1)}}\right]-\tan^{-1}\left[\frac{q/k}{p/k+\frac{\alpha}{(1-\alpha^2)}}\right].$$

Constraining Parameters Involved

- Parameters α, β can be constrained by low energy neutrino oscillation data through ratio of solar and atmospheric mass squared difference defined as

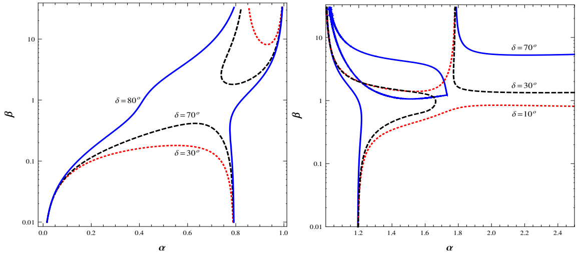
$$r = \frac{\Delta m^2_{\odot}}{|\Delta m^2_A|} \simeq 0.03, \quad \Delta m^2_{\odot} = \Delta m^2_{21} \equiv m_2^2 - m_1^2 = 7.6 \times 10^{-5} eV^2,$$

$$|\Delta m^2_A| = |\Delta m^2_{31}| \equiv |m_3^2 - m_1^2| = 2.48 \times 10^{-3} eV^2.$$

- Hence using above relations we get

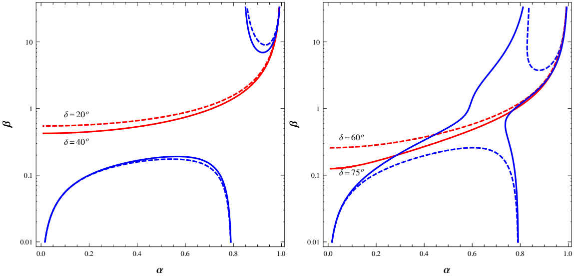
$$r = \frac{(1-\alpha^2)}{4\alpha}\frac{k}{p}\left[1+\beta^2 - 2\beta\cos\phi_d - \left(\frac{\alpha}{(1-\alpha^2)} - \frac{p}{k}\right)^2 - \left(\frac{q}{k}\right)^2\right].$$

- Contour plots for $r = 0.03$ in the $\alpha - \beta$ plane for various δ for $\alpha < 1$ and $\alpha > 1$



Constraining Parameters Involved: $\alpha < 1$

- Getting solutions for α and β by plotting $\sin^2\theta_{13} = 0.0234$ and $r = 0.03$ contours together



- α, β values at the intersection points of the r and $\sin^2\theta_{13}$ contours

δ	α	β	$\sum m_i$(eV)
$20^\circ(160^\circ, 200^\circ, 340^\circ)$	0.99	28.26	0.0714
$40^\circ(140^\circ, 220^\circ, 320^\circ)$	0.99	20.94	0.0709
$60^\circ(120^\circ, 240^\circ, 300^\circ)$	0.98	11.16	0.0701
$75^\circ(105^\circ, 255^\circ, 285^\circ)$	0.94	3.70	0.0691
	0.77	0.93	0.0734
	0.29	0.20	0.1333
$80^\circ(100^\circ, 260^\circ, 280^\circ)$	0.16	0.11	0.1835
$82^\circ(98^\circ, 262^\circ, 278^\circ)$	0.12	0.09	0.2137
$85^\circ(95^\circ, 265^\circ, 275^\circ)$	0.07	0.05	0.2827

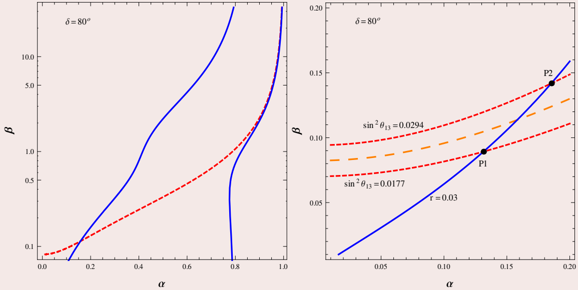
Constraining Parameters Involved: $\alpha < 1$

- **Each δ values are repeated at $|\pi - \delta|$**
- **Accepted solutions :** $\alpha, \beta < 1$

$\Downarrow$

Allowed Dirac CP phases: $72^\circ - 82^\circ$, $98^\circ - 108^\circ$, $252^\circ - 262^\circ$, $278^\circ - 288^\circ$ **out of** $0 - 360^\circ$

$\delta = 80^\circ (\equiv 100^\circ, 260^\circ, 280^\circ)$ and Neutrino Parameters

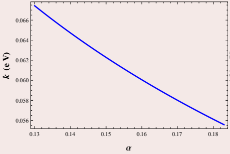


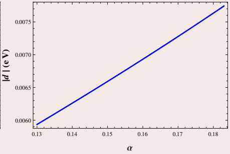
Reference Point P1 $(\alpha, \beta) = (0.13, 0.09)$
Reference Point P2 $(\alpha, \beta) = (0.18, 0.14)$

Prediction of neutrino parameters: $\alpha < 1$

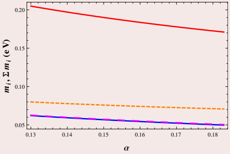
- **We solve for δ, β from $\sin^2\theta_{13} = 0.0234$ and $r = 0.03$ constraints**
- **To find d and k, we must satisfy $|\Delta m^2_{atm}|$ and $\Delta m^2_{\odot}$ independently**

k vs α and $|d|$ vs α plots for $\delta = 80°(\equiv 100°, 260°, 280°)$





Light neutrino masses vs α plots for $\delta = 80°(\equiv 100°, 260°, 280°)$

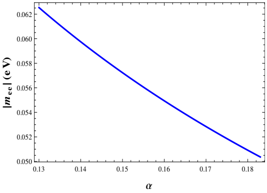


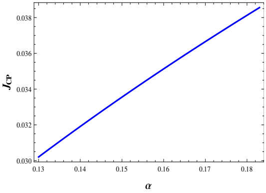
m_1 = blue continuous, m_2 = magenta large dashed, m_3= orange dashed and Σm_i = red continuous line

Prediction of neutrino parameters: $\alpha < 1$

- Effective neutrino mass parameter $|m_{ee}|$ and Jarlskog invariant for $\delta = 80^\circ$

$$\begin{aligned} |m_{ee}| &= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31} - 2\delta)} \right|. \\ J_{CP} &= \mathrm{Im}[U_{\mu 3} U_{e3}^* U_{e2} U_{\mu 2}^*] \\ &= \frac{1}{8} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta. \end{aligned}$$





Predictions: $0.050 \le |m_{ee}| \le 0.062$ eV and $0.03 < |J_{CP}| < 0.04$

Case B: $\alpha > 1$

Solutions for different δ

δ	α	β	$\sum m_i$(eV)
$10^\circ(170^\circ, 190^\circ, 350^\circ)$	1.43	0.36	0.0791
$30^\circ(150^\circ, 210^\circ, 330^\circ)$	1.39	0.45	0.0798
$40^\circ(140^\circ, 220^\circ, 320^\circ)$	1.36	0.53	0.0799
$50^\circ(130^\circ, 230^\circ, 310^\circ)$	1.32	0.64	0.0794
$60^\circ(120^\circ, 240^\circ, 300^\circ)$	1.26	0.83	0.0776
$70^\circ(110^\circ, 250^\circ, 290^\circ)$	1.17	1.13	0.0739
$73^\circ(107^\circ, 253^\circ, 287^\circ)$	1.07	3.02	0.0696

$$\boxed{\delta = 0^\circ - 63^\circ,\ (117^\circ - 180^\circ,\ 180^\circ - 243^\circ,\ 297^\circ - 360^\circ)}$$

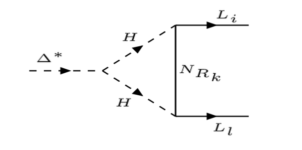
Leptogenesis

Possible Scenarios

1. Decay of RH neutrinos only: lepton asymmetry vanishes
2. Option (I), decay of scalar triplet ($M_R > M_\Delta$) : RH neutrinos in loop $\Rightarrow$ successful leptogenesis scenario
3. Option (II), decay of RH neutrinos ($M_\Delta > M_R$) : Triplets in loop $\Rightarrow$ constrained leptogenesis scenario

Hambye,Senjanovic, PLB 582, 73 (2004)

Option (I): decay of scalar triplet ($M_R > M_\Delta$)



Leptogenesis

- **Decay of Scalar Triplet:**

$$\begin{aligned}\Gamma_T &= \Gamma_{\Delta^* \to LL} + \Gamma_{\Delta^* \to HH} \\ &= \frac{M_\Delta}{8\pi}\left[\sum_{ij}\left|(Y_\Delta)_{ij}\right|^2 + \frac{|\eta|^2}{M_\Delta^2}\right].\end{aligned}$$

- **Lepton Asymmetry Parameter:** O'Donnell,Sarkar, PRD 49, 2118 (1994);Hambye,Senjanovic, PLB 582, 73 (2004)

$$\begin{aligned}\epsilon_\Delta &= 2\frac{\Gamma(\Delta^* \longrightarrow L+L) - \Gamma(\Delta \longrightarrow \bar{L}+\bar{L})}{\Gamma(\Delta^* \longrightarrow L+L) + \Gamma(\Delta \longrightarrow \bar{L}+\bar{L})}, \\ &= \frac{1}{8\pi}\sum_k M_{Rk}\frac{\sum_{il}\mathrm{Im}[(\hat{Y}_D^*)_{ki}(\hat{Y}_D^*)_{kl}(Y_\Delta)_{il}\eta^*]}{\sum_{ij}|(Y_\Delta)_{ij}|^2 M_\Delta^2 + |\eta|^2}\log(1 + M_\Delta^2/M_{Rk}^2).\end{aligned}$$

Here i,j denote the flavor indices, $\hat{Y}_D = U_R^T Y_D$ in the basis where RH neutrino mass matrix is diagonal

- **Masses of RH neutrinos:**

$$\begin{aligned}M_{R_1} &= \frac{v^2 y^2}{k}(1+\alpha), \\ M_{R_2} &= \frac{v^2 y^2}{k}, \\ M_{R_3} &= \left|\frac{v^2 y^2}{k}(1-\alpha)\right|.\end{aligned}$$

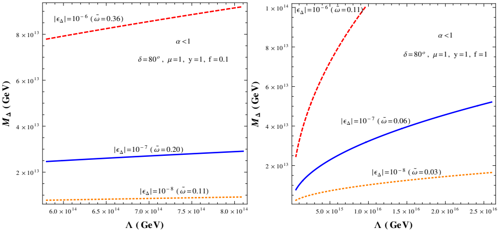
Leptogenesis: for $\delta = 80^\circ$ and $\alpha < 1$

- **Lepton Asymmetry Parameter: Our Estimation (with $M_\Delta < M_{Ri} < \Lambda$)**

$$\epsilon_\Delta = -\frac{M_\Delta^2}{8\pi v^2}\frac{\alpha^2}{(1-\alpha^2)}\frac{k\mu\tilde{\omega}^3 v_S(x_1 - x_1')\sin\alpha_S}{\left[3\tilde{\omega}^2\frac{v_S^2}{\Lambda^2}\left(x_1^2 + x_1'^2 + 2x_1x_1'\cos 2\alpha_S\right)M_\Delta^2 + (\mu\tilde{\omega}^2\Lambda)^2\right]}$$

- Here $\tilde{\omega} = v_f/\Lambda$, where v_f is considered to be the common vev of all flavons except S-field's vev $\langle S\rangle = v_S e^{i\alpha_S}$.
- α_S is the only source of CP-violation.
- Defining $v_S/\Lambda = f\tilde{\omega}$ where f serves as a relative measure of the vevs, the asymmetry parameter (becomes $\tilde{\omega}$ independent) ,

$$\epsilon_\Delta = -\frac{\alpha^2}{8\pi v^2(1-\alpha^2)}\frac{kf(x_1 - x_1')\sin\alpha_S(\mu\Lambda/M_\Delta^2)}{\left[(3f^2/M_\Delta^2)\left(x_1^2 + x_1'^2 + 2x_1x_1'\cos 2\alpha_S\right) + (\mu\Lambda/M_\Delta^2)^2\right]}.$$



with $x_1 = 0.5$, $x_1' = 1$ and $|d| = 2fv^2\tilde{\omega}^4\frac{\mu\Lambda}{M_\Delta^2}(x_1 + x_1')\cos\alpha_S \sec\phi_d$.

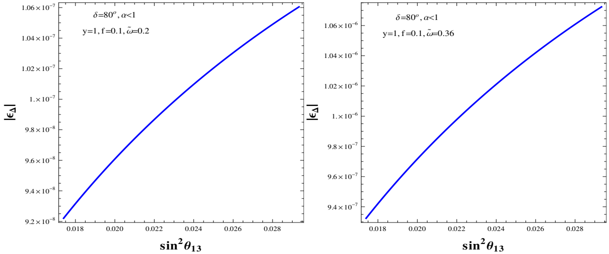
Leptogenesis: for $\delta = 80^\circ$ and $\alpha < 1$

ϵ_Δ vs $\sin^2\theta_{13}$ for $\delta = 80^\circ$ and $\alpha < 1$

- **Approximated Lepton Asymmetry Parameter :** For $M_\Delta < \Lambda$

$$\epsilon_\Delta \simeq -\frac{\alpha^2}{8\pi v^2(1-\alpha^2)} kf(x_1 - x_1') \sin\alpha_S \frac{M_\Delta^2}{\mu\Lambda}$$

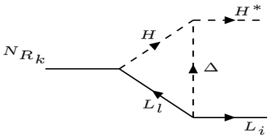
- Substituting $\mu\Lambda/M_\Delta^2$ from $|d|$ in ϵ_Δ above



- Thus, in this frame work neutrino oscillation data imposes an upper bound on the lepton asymmetry
- We have performed similar analysis for $\alpha > 1$ case too.

Leptogenesis: Decay of RH Neutrinos

- **Decay of RH neutrinos:** $M_{R_i} < M_\Delta$



- **Lepton Asymmetry Parameter:**

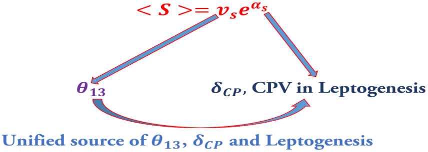
$$\begin{aligned}
\epsilon_{N_1} &= \frac{3}{16\pi v^2} M_{R_1} \frac{\sum_{il} \mathrm{Im}[(\hat{Y}_D)_{1i}(\hat{Y}_D)_{1l}(m_\nu^{II*})_{il}]}{\sum_i |(\hat{Y}_D)_{1i}|^2}, \\
&= \frac{3M_{R_1}}{2} \frac{1}{16\pi v^2} |d| \sin\phi_d, \\
\epsilon_{N_2} &= -3M_{R_2} \frac{1}{16\pi v^2} |d| \sin\phi_d \quad \text{and} \quad \epsilon_{N_3} = \mp \frac{3M_{R_3}}{2} \frac{1}{16\pi v^2} |d| \sin\phi_d, \ \text{`}+\text{'} \text{ for } \alpha > 1
\end{aligned}$$

- **Total Baryon Asymmetry:**

$$\left|\frac{n_B}{s}\right| = 1.48 \times 10^{-3} \sum_i \epsilon_{N_i} D_{N_i}, \text{ where } D_{N_i} : \text{ respective efficiency factor}$$

Due to specific flavor structure of M_{R_i} in our model, $\sum_i \epsilon_{N_i} = 0$, for same efficiency factor.

Unique Source of CP Violation



Conclusion

- We have adopted a generic Type-II seesaw with three RH neutrinos and only one scalar triplet
- A_4 symmetry helps in realizing desired flavor structure
- Spontaneous CP violation : turns out to be unique source of CP violation of the model
- Scalar triplet contribution generates desired amount nonzero θ_{13}
- Predictions on Dirac, Majorana phases and Jarlskog invariant
- Predictions on effective neutrino mass parameter and absolute neutrino masses
- Lepton asymmetry realized through decay of scalar triplets and connection with θ_{13}

Thank You