Neutrino mixing and baryogenesis via leptogenesis from complex scaling

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We propose a complex extension of the scaling ansatz on the neutrino Majorana mass matrix M_ν derived with a type-1 seesaw and three singlet hierarchical heavy Majorana neutrinos of masses $M_{1,2,3}$. A nonzero mass for each of the three light neutrinos is now allowed as well as a nonvanishing θ_{13}. Leptonic Dirac CP violation must be maximal while atmospheric neutrino mixing need not be exactly maximal. Each of the two Majorana phases, to be probed by the search for $0\nu\beta\beta$ decay, has to be zero or π and a normal neutrino mass hierarchy is allowed. Realistic baryogenesis via leptogenesis is shown to be feasible only for the mass regime $10^9\ \mathrm{GeV} < T \sim M_1 < 10^{12}\ \mathrm{GeV}$ with a normal light neutrino mass ordering.

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Introduction

Focus on neutrino mixing, not so much the dynamical generation of neutrino masses

Flavor eigenstates ν_ℓ $(\ell = e, \mu, \tau)$

Supposition 1: $\exists$ only 3 left-chiral neutrinos: $\Updownarrow$ related by U

$\nu_i = U_{i\ell}\nu_\ell$ Mass eigenstates ν_i $(i = 1, 2, 3)$

$U^T M_\nu U = M_\nu^d \equiv \mathrm{diag}\,(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3)$. $M_{ch} = \mathrm{diag}\,(\mathrm{m_e}, \mathrm{m}_\mu, \mathrm{m}_\tau)$

Supposition 2: all 3 light neutrinos are Majorana particles

$-\mathcal{L}_D = f^N_{i\alpha}\overline{N}_{Ri}\tilde{\phi}^\dagger \not{L}_\alpha + h.c.,\ \tilde{\phi} = (\phi^{0*}\ \ -\phi^-)^T,\ <\phi>= (<\phi^0>\ \ 0)^T$

$-\mathcal{L}^{\nu,N}_{mass} = \bar{N}_{iR}(m_D)_{i\alpha}\nu_{L\alpha} + \frac{1}{2}\bar{N}_{iR}(M_R)_i\delta_{ij}N^C_{jR} + \mathrm{h.c.}$ with

$(m_D)_{i\alpha} = f^N_{i\alpha} < \phi^0 >$ Type-I seesaw: $M_\nu = -m_D^T M_R^{-1} m_D$

Effectively: $-\mathcal{L}^\nu_{mass} = \frac{1}{2}\bar{\nu}^C_l (M_\nu)_{lm}\nu_m + h.c.$ with $M_\nu^* \neq M_\nu = M_\nu^T$

Leptonic mixing matrix using PDG convention,

$$U \equiv U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & e^{i\frac{\alpha}{2}} s_{12}c_{13} & s_{13}e^{-i(\delta-\frac{\beta}{2})} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & e^{i\frac{\alpha}{2}}(c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta}) & c_{13}s_{23}e^{i\frac{\beta}{2}} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & e^{i\frac{\alpha}{2}}(-c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta}) & c_{13}c_{23}e^{i\frac{\beta}{2}} \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij} \text{ and } \theta_{ij} = [0, \pi/2]; \quad \underbrace{\delta, \alpha, \beta}_{CP-violation} = [0, 2\pi]$$

Neutrino factfile: 3σ ranges

Gonzalez-Garcia et al. (2016)

$\Delta m^2_{21} \equiv m^2_2 - m^2_1$: $7.02 \times 10^{-5}\ \mathrm{eV}^2 - 8.09 \times 10^{-5}\ \mathrm{eV}^2$

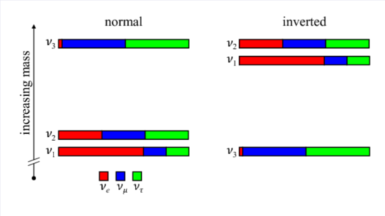
$|\Delta m^2_{31}| \equiv m^2_3 - m^2_1$: $2.32 \times 10^{-3}\ \mathrm{eV}^2 - 2.59 \times 10^{-3}\ \mathrm{eV}^2$

$\Sigma_\nu m_\nu < 0.23$ eV $\Longleftarrow$ PLANCK (2015)

θ_{12}: 31.29^o–35.91^o

θ_{23}: 38.3^o–53.3^o

θ_{13}: 7.87^o–9.11^o



The problematic Simple Real Scaling

Lavoura (2000), Mohapatra, Rodejohann (2007).

$M_\nu^{SRS} = \begin{pmatrix} x & -Yk & Y \\ -Yk & Zk^2 & -Zk \\ Y & -Zk & Z \end{pmatrix}$ from simple real scaling.

x, Y, Z mass dimensional quantities, x real and Y, Z complex

$$\frac{(M_\nu^{SRS})_{e\mu}}{(-M_\nu^{SRS})_{e\tau}} = \frac{(M_\nu^{SRS})_{\mu\mu}}{(-M_\nu^{SRS})_{\mu\tau}} = \frac{(M_\nu^{SRS})_{\tau\mu}}{(-M_\nu^{SRS})_{\tau\tau}} = k$$

k: Real dimensional constant. $k = 1 \rightarrow \mu\tau$ interchange symmetry plus $M^\nu_{\mu\mu}$ = - $M^\nu_{\mu\tau}$. Sign convention to match with PDG form of U_{PMNS}.

$\det \mathrm{M}_\nu^{\mathrm{SRS}} = 0 \Rightarrow$ one null eigenvalue. Large $\theta_{12}, \theta_{23} \Rightarrow$ eigenvector= 3rd column of U.

$\theta_{13} = 0$ and inverted mass ordering ($m_3 = 0 \longleftrightarrow$ does not survive extension)

$$C_3^{SRS} = \begin{pmatrix} 0 \\ (1+k^2)^{-\frac{1}{2}} e^{i\frac{\beta}{2}} \\ k(1+k^2)^{-\frac{1}{2}} e^{i\frac{\beta}{2}} \end{pmatrix} \Rightarrow s_{23} = \frac{1}{\sqrt{1+k^2}},\ c_{23} = \frac{k}{\sqrt{1+k^2}},\ \underbrace{\tan\theta_{23} = k^{-1}}$$

$\Uparrow$

survives extension

Now, with arbitrary θ_{12},

$$U^{SRS} = \begin{pmatrix} c_{12} & s_{12} e^{i\frac{\alpha}{2}} & 0 \\ -k(1+k^2)^{-\frac{1}{2}} s_{12} & k(1+k^2)^{-\frac{1}{2}} c_{12} e^{i\frac{\alpha}{2}} & (1+k^2)^{-\frac{1}{2}} e^{i\frac{\beta}{2}} \\ k(1+k^2)^{-\frac{1}{2}} s_{12} & -k(1+k^2)^{-\frac{1}{2}} c_{12} e^{i\frac{\alpha}{2}} & k(1+k^2)^{-\frac{1}{2}} e^{i\frac{\beta}{2}} \end{pmatrix}.$$

$\rightarrow \theta_{13} = 0$, excluded by expt. at 10σ. (Daya Bay, 2015)

Residual flavor symmetry and $\mathbb{Z}_2$ Scaling

Lam(2003)
Gupta, Joshipura, Patel (2012)

Flavor symmetry of M_ν implemented by unitary G: $\nu_{L\alpha} \to (G)_{\alpha\beta}\nu_{L\beta}$

$$G^T M_\nu G = M_\nu$$

$\longrightarrow$ G has eigenvalues ± 1 and

$U^\dagger G U = d$, $d^2 = I$, $d_{lm} = \pm\delta_{lm}$. Of 8 possible d's, $d = \pm I$ trivial, rest 6 split into $\{d_i\}$ and $\{-d_i\}$

Finally, 3 remaining $\{d_i\}$, i=1,2,3

Each $d \to$ one G but only two independent: $G_a = \epsilon_{abc} G_b G_c$

Take $G_{2,3}$: $G_2 \longleftrightarrow d_2 = \mathrm{diag}\,(-1, 1, -1)$
$G_3 \longleftrightarrow d_3 = \mathrm{diag}\,(-1, -1, 1)$

$U^\dagger G U = d \Rightarrow$ Similarity transformation

There is a residual symmetry $\mathbb{Z}_2 \times \mathbb{Z}_2$

$\mathbb{Z}_2$: $G_2^T M_\nu G_2 = M_\nu$ (Lam, 2003)

$\mathbb{Z}_2$: $G_3^T M_\nu G_3 = M_\nu$

Identify second $\mathbb{Z}_2$ as with $\mathbb{Z}_2^{scaling}$ and propose its generator as

$$G_3^{\text{scaling}} = U^{SRS} d_3 U^{SRS\dagger}$$

$$\rightarrow G_3^{\text{scaling}} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & \frac{1-k^2}{1+k^2} & \frac{2k}{1+k^2} \\ 0 & \frac{2k}{1+k^2} & -\frac{1-k^2}{1+k^2} \end{pmatrix} = (G_3^{\text{scaling}})^T$$

Residual flavor symmetry and complex scaling

Lam (2003)
Gupta, Joshipura, Patel (2012)
Samanta, Roy, Ghosal (2016)

We implement a complex-extended flavor invariance by unitary $G_{L,R}$ with CP-transformed linear transformations

$$\nu_{L\alpha} \to i(G_L)_{\alpha\beta}\gamma^0\nu^C_{L\beta}, \quad N_{Ri} \to i(G_R)_{ij}\gamma^0 N^C_{Rj}$$

and demanding $G_R^\dagger m_D G_L = m_D^*, \quad G_R^\dagger M_R G_R^* = M_R^*$

which imply $G_L^T M_\nu G_L = M_\nu^*$.

Similar complex-extension used earlier for $\mu\tau$ interchange symmetry.

Now $U^\dagger G U = d, \qquad d_{\alpha\beta} = \pm\delta_{\alpha\beta}$

Only a pair nontrivially independent:

$$d_2 = \mathrm{diag}\,(-1, 1, 1)$$

$$d_3 = \mathrm{diag}\,(-1, -1, 1)$$

Choose $G_L = G_3^{\rm scaling} = U^{SRS} d_3 (U^{SRS})^\dagger = (G_3^{scaling})^T$

$$\rightarrow G_3^{\rm scaling} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & (1-k^2)(1+k^2)^{-1} & 2k(1+k^2)^{-1} \\ 0 & 2k(1+k^2)^{-1} & -(1-k^2)(1+k^2)^{-1} \end{pmatrix}$$

The most general form of M_ν satisfying complex scaling:

$$M_\nu^{CES} = \begin{pmatrix} x & -y_1 k + i y_2 k^{-1} & y_1 + i y_2 \\ -y_1 k + i y_2 k^{-1} & z_1 - w k^{-1}(k^2-1) - i z_2 & w - i z_2 (2k)^{-1}(k^2-1) \\ y_1 + i y_2 & w - i z_2 (2k)^{-1}(k^2-1) & z_1 + i z_2 \end{pmatrix}$$

6 real parameters: x, $y_{1,2}$, $z_{1,2}$, w.

Using $G_3^{\rm scaling} U^* = U \tilde{d}$, one can show that

$$\tan\theta_{23} = k^{-1}, \;\; \sin\alpha = \sin\beta = \cos\delta = 0$$

Majorana phases 0 or π. Dirac phase $\pi/2$ or $3\pi/2$. Dirac CP violation maximal.

Common source of CP violation and nonzero θ_{13}. If Im M_ν^{CES}, i.e. CP violation, vanishes, θ_{13} vanishes too.

Turning to G_R, the only form compatible with scaling symmetry $\rightarrow$

$G_R = \mathrm{diag}\,(-1,-1,-1)$

$\Rightarrow m_D G_L = -m_D^*.$

$$\rightarrow m_D^{CES} = \begin{pmatrix} a & b_1 + ib_2 & -b_1/k + ib_2 k \\ e & c_1 + ic_2 & -c_1/k + ic_2 k \\ f & d_1 + id_2 & -d_1/k + id_2 k \end{pmatrix}$$

Relation with parameters of M_ν^{CES} (taking $M_3 >> M_{1,2}$)

Table: Parameters of M_ν^{CES} in terms of the parameters of m_D and M_R.

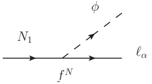
$$x = -\left(\frac{a^2}{M_1} + \frac{e^2}{M_2} + \frac{f^2}{M_3}\right)$$
$$y_1 = \frac{1}{k}\left(\frac{ab_1}{M_1} + \frac{ec_1}{M_2} + \frac{fd_1}{M_3}\right)$$
$$y_2 = k\left(\frac{ab_2}{M_1} + \frac{ec_2}{M_2} + \frac{fd_2}{M_3}\right)$$
$$z_1 = -\frac{1}{k^2}\left(\frac{b_1^2}{M_1} + \frac{c_1^2}{M_2} + \frac{d_1^2}{M_3}\right) + k^2\left(\frac{b_2^2}{M_1} + \frac{c_2^2}{M_2} + \frac{d_2^2}{M_3}\right)$$
$$z_2 = \frac{2b_1 b_2}{M_1} + \frac{2c_1 c_2}{M_2} + \frac{2d_1 d_2}{M_3}$$
$$w = \frac{1}{k}\left(\frac{b_1^2}{M_1} + \frac{c_1^2}{M_2} + \frac{d_1^2}{M_3}\right) + k\left(\frac{b_2^2}{M_1} + \frac{c_2^2}{M_2} + \frac{d_2^2}{M_3}\right)$$

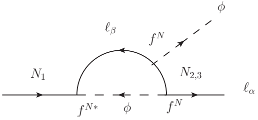
Baryogenesis via leptogenesis

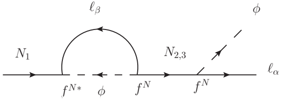
Calculation of CP symmetry parameter ε_i^α. First recall $\not{L}_\alpha = (\nu_{L_\alpha}\ \ell^-_{L\alpha})^T$ and $\tilde{\phi} = (\phi^{0*}\ \ -\phi^-)^T$.

Now $$\varepsilon_i^\alpha = \frac{\Gamma(N_i \to \not{L}_\alpha \phi) - \Gamma(N_i \to \not{L}^C_\alpha \phi^\dagger)}{\Gamma(N_i \to \not{L}_\alpha \phi) + \Gamma(N_i \to \not{L}^C_\alpha \phi^\dagger)}$$

calculated from







Final result is $\varepsilon_1^e = 0$, $\varepsilon_1^\mu = -\varepsilon_1^\tau \neq 0-$ explicitly given in terms of M_i/M_j and the parameters of m_D.

Since $M_1 << M_2 << m_3$ assumed, reasonable to suppose that leptogenesis occurs at $T \sim M_1$.

3 regimes:

• $T \sim M_1 < 10^9$ GeV : all lepton flavors separately active in ε_i^α. But $\varepsilon_1^e = 0$, $\varepsilon_1^\mu = -\varepsilon_1^\tau$ in our model simplify situation.

• $10^9 \text{ GeV} < T \sim M_1 < 10^{12} \text{ GeV}$: here only τ- flavor can be identified separately, e. μ act together, but we just have ε_1^μ and $\varepsilon_1^\tau = -\varepsilon_1^\mu$.

• $T \sim M_1 > 10^{12} \text{ GeV}$: here all flavors act indistinguishably so that we just have $\varepsilon_1^e + \varepsilon_1^\mu + \varepsilon_1^\tau$ which vanishes in our model so that there is no leptogenesis in this regime.

For the two allowed regimes, we have numerically studied the thermal evolution via Boltzmann equations of the yield $Y_\lambda = \frac{n_L^\lambda - n_{\bar{L}}^\lambda}{s} = \frac{n_\gamma}{s}\eta_L^\lambda$ of the active leptonic flavor λ ($n=$ no. density, $s=$ entropy density) from $T \sim M_1$ to electroweak temperatures and the sphaleronic conversion of the lepton asymmetry into a baryon asymmetry keeping $\Delta_\lambda \equiv \frac{1}{3}B - L^\lambda$ conserved. Our finding is that a realistic baryon asymmetry parameter

$$Y_B = (n_B - n_{\bar{B}})/s \simeq (8.7 \pm 0.1) \times 10^{-11}$$

can be generated only for the regime $10^9 \text{ GeV} < T \sim M_1 < 10^{12} \text{ GeV}$ and not for $T \sim M_1 < 10^9$ GeV.

Phenomenological discussion

Numerical run with six parameter M_ν using quoted input values : θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, $|\Delta m_{31^2}|$ and $\Sigma_i m_i$

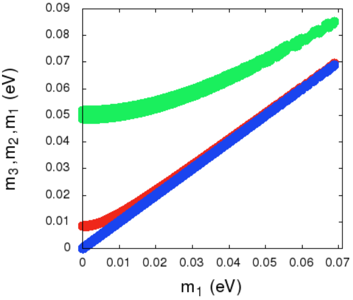
Table: Output values obtained for normal mass ordering

x eV	y_1 eV	y_2 eV	z_1 eV	z_2 eV	w eV
-0.20 – $+0.21$	-0.12 – $+0.11$	-0.05 – $+0.05$	-0.17 – $+0.17$	-0.18 – $+0.17$	-0.16 – $+0.15$
m_1 eV		m_2 eV		m_3 eV	
9.2×10^{-5} – 0.071		0.01 – 0.077		0.051 – 0.082	

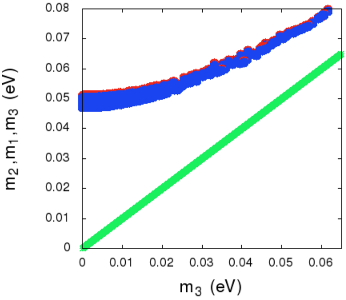
Table: Output values obtained for inverted mass ordering

x eV	y_1 eV	y_2 eV	z_1 eV	z_2 eV	w eV
-0.44 – $+0.46$	-0.16 – $+0.16$	-0.14 – $+0.14$	-0.01 – $+0.01$	-0.01 – $+0.01$	-0.05 – $+0.06$
m_1 eV		m_2 eV		m_3 eV	
0.051 – 0.085		0.049 – 0.079		8.2×10^{-5} – 0.068	

Neutrino mass bands for normal and inverted ordering



Normal

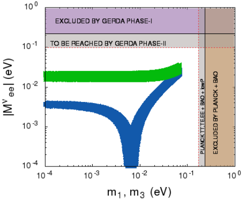


Inverted

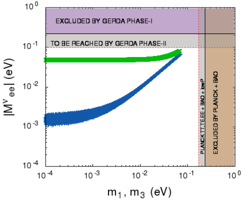
Neutrinoless double beta ($\beta\beta0\nu$) decay

$$(M_\nu)_{ee} = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i(\beta - 2\delta)}$$

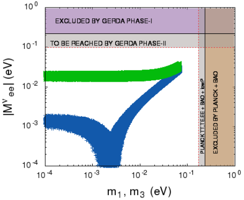
$\tilde{d}_a = \mathrm{diag}\,(-1, +1, +1)$



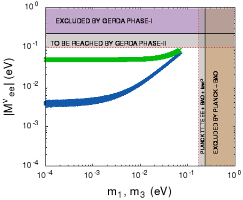
$\tilde{d}_c = \mathrm{diag}\,(-1, -1, +1)$



$\tilde{d}_b = \mathrm{diag}\,(-1, +1, -1)$



$\tilde{d}_d = \mathrm{diag}\,(-1, -1, -1)$



Conclusions

- Proposed complex scaling on the basis of $G_3 M_\nu G_3 = M_\nu^*$
- obtained 6-parameter form of $M_\nu =$

$$M_\nu^{CES} = \begin{pmatrix} x & -y_1 k + i\frac{y_2}{k} & y_1 + iy_2 \\ -y_1 k + i\frac{y_2}{k} & z_1 - w\frac{k^2-1}{k} - iz_2 & w - i\frac{k^2-1}{2k}z_2 \\ y_1 + iy_2 & w - i\frac{k^2-1}{2k}z_2 & z_1 + iz_2 \end{pmatrix}$$

- Consequences :

  $\alpha, \beta = 0$ or π : NO MAJORANA CP-VIOLATION

  $\cos\delta = o$, i.e. $\delta = \frac{\pi}{2}$ or $\frac{3\pi}{2}$: MAXIMAL DIRAC CP-VIOLATION

- Each neutrino mass can be nonzero; can be generated from type-I seesaw.
- Either mass ordering, normal or inverted, possible
- Hierarchical neutrinos for most values of the neutrino mass-sum; quasidegenerate only when latter approaches the cosmological upper bound ~ 0.23 eV
- Interesting predictions on $|(M_\nu)_{ee}|$ parameter for future experiments.

• Realistic baryogenesis via leptogenesis possible for
10^9 GeV $< T \sim M_1 < 10^{12}$ GeV and normal light neutrino mass ordering.