Spontaneous leptonic CP violation and nonzero θ_{13}

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Work in collaboration with:
G.C.Branco, R. González Felipe, F.R. Joaquim, HS, arXiv:1203.2646

FLASY, Dortmund, 1 July 2012

Motivation

In the leptonic sector there are in general a large number of phases.

Not all are physical.

CP violation

- High energy: Leptogenesis
- Low energy: Dirac and/or Majorana

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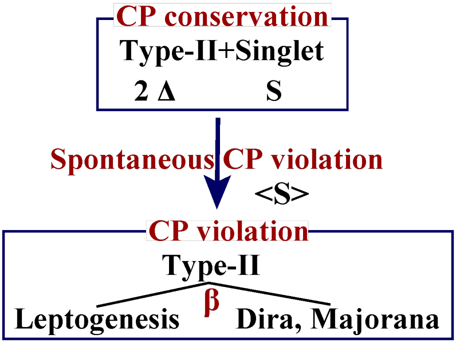

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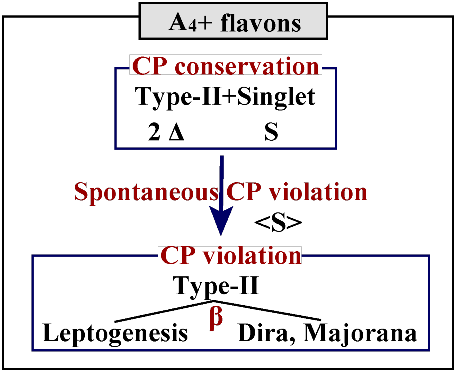

The scalar potential

$$Z_4: \quad S \to -S\,, \quad \phi \to i\phi\,, \quad \Delta_1 \to \Delta_1\,, \quad \Delta_2 \to -\Delta_2$$

$$V^{CP\times Z_4} = V_S + V_\phi + V_\Delta + V_{S\phi} + V_{S\Delta} + V_{\phi\Delta} + V_{S\phi\Delta}$$

$$\begin{aligned} V_S =& \mu_S^2\,(S^2 + S^{*2}) + m_S^2\,S^*S + \lambda'_S\,(S^4 + S^{*4}) \\ &+ \lambda''_S S^*S(S^2 + S^{*2}) + \lambda_S\,(S^*S)^2\,, \\ V_{\phi\Delta} =& \sum\nolimits_a \left[\xi'_a\,(\phi^\dagger\phi)\mathrm{Tr}\left(\Delta_a^\dagger\Delta_a\right) + \xi''_a\,(\phi^\dagger\Delta_a^\dagger\Delta_a\phi)\right] \\ &+ (\mu_2 M_2 \tilde{\phi}^T\Delta_2\tilde{\phi} + \mathrm{H.c.}) \\ V_{S\phi\Delta} =& \tilde{\phi}^T\Delta_1\tilde{\phi}\,(\lambda_1\,S + \lambda'_1\,S^*) + \mathrm{H.c.} \end{aligned}$$

The scalar potential

$$V_S = \mu_S^2 \left(S^2 + S^{*2}\right) + m_S^2\, S^* S + \lambda'_S \left(S^4 + S^{*4}\right) + \lambda''_S S^* S (S^2 + S^{*2}) + \lambda_S \left(S^* S\right)^2 , \quad \langle S \rangle = v_S e^{i\alpha}$$

Besides the trivial solution $v_S = 0$, which leads to $V_0 = 0$, there are other three possible solutions to the above system of equations:

$$\text{(i)} \quad v_S^2 = -\frac{m_S^2 + 2\mu_S^2}{2(\lambda_S + 2\lambda'_S + 2\lambda''_S)} , \quad \alpha = 0, \pm\pi;$$

$$\text{(ii)} \quad v_S^2 = \frac{-m_S^2 + 2\mu_S^2}{2(\lambda_S + 2\lambda'_S - 2\lambda''_S)} , \quad \alpha = \pm\frac{\pi}{2};$$

$$\text{(iii)} \quad v_S^2 = \frac{-2\lambda'_S m_S^2 + \lambda''_S \mu_S^2}{4\lambda_S \lambda'_S - 8\lambda'^2_S - \lambda''^2_S} , \quad \cos(2\alpha) = -\frac{\mu_S^2 + \lambda''_S v_S^2}{4\lambda'_S v_S^2} .$$

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Spontaneous CP violation

The model

$$\langle\Phi\rangle = (r,0,0)\ ,\ \langle\Psi\rangle = (s,s,s)$$

Field	L	e_R,μ_R,τ_R	Δ_1	Δ_2	ϕ	S	Φ	Ψ
A_4	$\mathbf{3}$	$\mathbf{1},\ \mathbf{1}',\ \mathbf{1}''$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$
$Z_4\times Z_4$	(i,i)	$(-i,i)$	$(1,1)$	$(-1,1)$	$(i,1)$	$(-1,-1)$	$(i,1)$	$(1,-1)$
$SU(2)_L\times U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(3,1)$	$(3,1)$	$(2,1/2)$	$(1,0)$	$(1,0)$	$(1,0)$

$$\mathcal{L} = \frac{y_e^\ell}{\Lambda}\left(\overline{L}\Phi\right)_{\mathbf{1}}\phi e_R + \frac{y_\mu^\ell}{\Lambda}\left(\overline{L}\Phi\right)_{\mathbf{1}''}\phi\mu_R + \frac{y_\tau^\ell}{\Lambda}\left(\overline{L}\Phi\right)_{\mathbf{1}'}\phi\tau_R$$
$$+\frac{y_2}{\Lambda}\Delta_2\left(L^T L\Psi\right)_{\mathbf{1}} + \frac{1}{\Lambda}\Delta_1\left(L^T L\right)_{\mathbf{1}}(y_1 S + y_1' S^*) + \text{H.c.}\,.$$

$$\mathbf{Y}^e = \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}, \mathbf{Y}^{\Delta_1} = y_{\Delta_1}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \mathbf{Y}^{\Delta_2} = \frac{y_{\Delta_2}}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix},$$

with

$$y_{e,\mu,\tau} = \frac{r}{\Lambda}y^\ell_{e,\mu,\tau}\,, \quad y_{\Delta_1} = \frac{v_S}{\Lambda'}\left(y_1 e^{i\alpha} + y_1' e^{-i\alpha}\right), \quad y_{\Delta_2} = \frac{y_2}{\Lambda}s.$$

Low-energy phenomenology

Mass matrix

$$\mathbf{m}_\nu = \mathbf{m}_\nu^{(1)} + \mathbf{m}_\nu^{(2)}\,, \quad \text{with} \quad \mathbf{m}_\nu^{(a)} = 2u_a \mathbf{Y}^{\Delta_a} \quad \text{and} \quad u_a = \mu_a^* v^2 / M_a$$

$$\mathbf{m}_\nu = \mathbf{U}^* \, \mathbf{d}_\nu \, \mathbf{U}^\dagger\,, \quad \mathbf{d}_\nu = \text{diag}\left(|z_1 e^{i\beta} + z_2|, z_1, |z_1 e^{i\beta} - z_2|\right)$$

$$z_a = 2|u_a y_{\Delta_a}|\,,$$

$$\beta = \arg(u_1 y_{\Delta_1})\,.$$

CP phase

Normal hierarchy ($\pi/2 < \beta < 3\pi/2$)

$$z_1 \simeq -\frac{1}{2\cos\beta}\sqrt{\frac{\Delta m_{31}^2}{2}}\,, \quad z_2 \simeq \sqrt{\frac{\Delta m_{31}^2}{2}}$$

$$\mathbf{U} = e^{-i\sigma_1/2} \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\gamma_1} & 0 \\ 0 & 0 & e^{i\gamma_2} \end{pmatrix}$$

Majorana phases: $\gamma_1 \simeq -\beta\,, \quad \gamma_2 \simeq -\frac{\beta}{2} - \frac{1}{2}\arctan\left(\frac{\tan\beta}{3}\right)$

Vacuum-alignment perturbations

Schwetz, Tortola, Valle, NJP (2011)

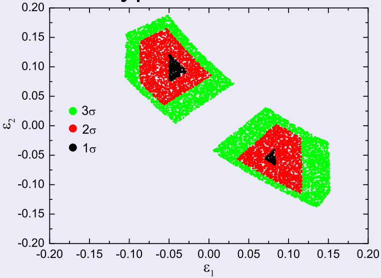
T2K and MINOS: $\sin^2\theta_{13} = 0.013^{+0.007}_{-0.005} \left(^{+0.015}_{-0.009}\right) \left[^{+0.022}_{-0.012}\right]$

Case A (charged leptons): $\langle\Phi\rangle = r(1, \epsilon_1, \epsilon_2)$

$$\mathbf{Y}^\ell = \begin{pmatrix} y_e & y_\tau\varepsilon_1 & y_\mu\varepsilon_2 \\ y_\tau\varepsilon_2 & y_\mu & y_e\varepsilon_1 \\ y_\mu\varepsilon_1 & y_e\varepsilon_2 & y_\tau \end{pmatrix}$$

Neutrino masses not affected

No Dirac-type CP-violation



$$\mathbf{U} = \mathbf{U}_\ell^\dagger \mathbf{U}_{TBM}$$

$$\sin^2\theta_{12} \simeq \frac{1}{3}\left[1 - 2(\epsilon_1 + \epsilon_2)\right]$$
$$\sin^2\theta_{23} \simeq \frac{1}{2}\left(1 + 2\epsilon_1\right)$$
$$\sin^2\theta_{13} \simeq \frac{(\epsilon_1 - \epsilon_2)^2}{2}$$

$$\sin^2\theta_{13} \simeq \frac{(4\sin^2\theta_{23} - 3\cos^2\theta_{12})^2}{8}$$

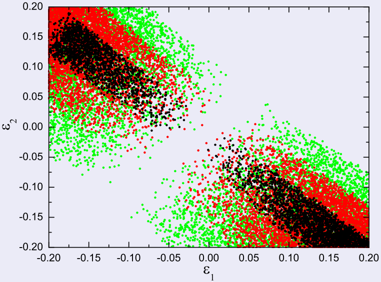
$0\nu2\beta$ decay $|m_{ee}|$

$$\frac{1}{3}\left|2\, m_1(1 + \varepsilon_1 + \varepsilon_2) + m_2\, e^{-2i\gamma_1}\right|$$

Vacuum-alignment perturbations

Case B (Neutrinos): $\langle\Psi\rangle = s(1, 1+\epsilon_1, 1+\epsilon_2)$

$$\mathbf{Y}^{\Delta_2} = \frac{y_{\Delta_2}}{3}\begin{pmatrix} 2 & -1-\varepsilon_2 & -1-\varepsilon_1 \\ -1-\varepsilon_2 & 2+2\varepsilon_1 & -1 \\ -1-\varepsilon_1 & -1 & 2+2\varepsilon_2 \end{pmatrix}$$



$$\sin^2\theta_{12} \simeq \frac{1}{3} + \frac{2}{9}(\epsilon_1 + \epsilon_2)$$
$$\sin^2\theta_{23} \simeq \frac{1}{2} + \frac{1}{6}(\epsilon 1 - \epsilon_2)$$
$$\sin^2\theta_{13} \simeq \frac{(\epsilon_1-\epsilon_2)^2}{72\cos^2\beta}$$

Dirac-type CP-violation

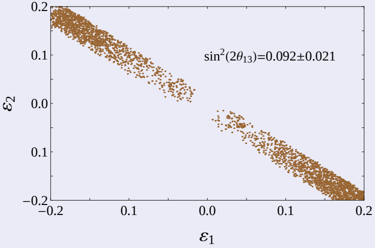
$$J_{\mathrm{CP}} = \mathrm{Im}\left[\mathbf{U}_{11}\mathbf{U}_{22}\mathbf{U}^*_{12}\mathbf{U}^*_{21}\right] \simeq \frac{\varepsilon_2-\varepsilon_1}{36}\tan\beta$$

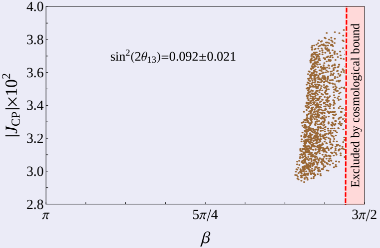
Neutrino masses suffers small corrections

Vacuum-alignment perturbations

Daya Bay: $\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$, 5.2σ

Only case B (Neutrinos) survives:

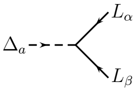


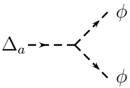


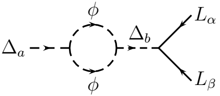
Predicts: $\frac{11}{8}\pi \lesssim \beta \lesssim \frac{3}{2}\pi$ with $0.03 \lesssim |J_{CP}| \lesssim 0.04$.
Neutrino spectrum near degenerated.

Leptogenesis

Ma, Sarkar, PRL (1998)







Tree-level decay

$$\mathcal{B}_a^L \, \Gamma_{\Delta_a} \equiv \sum_{\alpha,\beta} \Gamma(\Delta_a^* \to L_\alpha + L_\beta) = \frac{M_a}{8\pi} \mathrm{Tr}\, \mathbf{Y}^{\Delta_a \dagger} \mathbf{Y}^{\Delta_a},$$

$$\mathcal{B}_a^\phi \Gamma_{\Delta_a} \equiv \Gamma(\Delta_a^* \to \phi + \phi) = \frac{M_a}{8\pi} |\mu_a|^2 ,$$

One-loop decay

$$\epsilon_a^{\alpha\beta} = 2\frac{\Gamma(\Delta_a^* \to L_\alpha + L_\beta) - \Gamma(\Delta_a \to \bar{L}_\alpha + \bar{L}_\beta)}{\Gamma_{\Delta_a} + \Gamma_{\Delta_a^*}}$$

$$\simeq -\frac{g(x_b)}{2\pi} \frac{c_{\alpha\beta}\, \mathrm{Im}\left[\mu_a^* \mu_b \mathbf{Y}_{\alpha\beta}^{\Delta_a} \mathbf{Y}_{\alpha\beta}^{\Delta_b *}\right]}{\mathrm{Tr}\,(\mathbf{Y}^{\Delta_a \dagger} \mathbf{Y}^{\Delta_a}) + |\mu_a|^2}$$

$$c_{\alpha\beta} = \begin{cases} 2 - \delta_{\alpha\beta} & (\Delta_a^0, \Delta_a^{++}) \\ 1 & (\Delta_a^+) \end{cases}$$

$$g(x_b) = \frac{\sqrt{x_b}\,(1 - x_b)}{(x_b - 1)^2 + (\Gamma_{\Delta_b}/M_a)^2}$$

Hambye, Raidal, Strumia, PLB (2006)
Dorsner, Fileviez Perez, Gonzalez Felipe, NPB (2006)
Branco, Gonzalez Felipe, Joaquim, (2011)

Leptogenesis

In the hierarchical limit $M_a \ll M_b$

$$\epsilon_a^{\alpha\beta} \simeq \frac{M_a(\mathcal{B}_a^L\,\mathcal{B}_a^\phi)^{1/2}}{4\pi v^2}\,\frac{c_{\alpha\beta}\,\mathrm{Im}\left[\mathbf{m}_{\nu,\alpha\beta}^{(a)}\mathbf{m}_{\nu,\alpha\beta}^{*}\right]}{\left[\mathrm{Tr}\,\mathbf{m}_\nu^{(a)\dagger}\mathbf{m}_\nu^{(a)}\right]^{1/2}}\,,\ \epsilon_a \simeq \frac{M_a(\mathcal{B}_a^L\,\mathcal{B}_a^\phi)^{1/2}}{4\pi v^2}\,\frac{\mathrm{Im}\left[\mathrm{Tr}\,\mathbf{m}_\nu^{(a)}\mathbf{m}_\nu^{\dagger}\right]}{\left[\mathrm{Tr}\,\mathbf{m}_\nu^{(a)\dagger}\mathbf{m}_\nu^{(a)}\right]^{1/2}}$$

$$\epsilon_a^{\alpha\beta} = c_{\alpha\beta}\,\mathbf{P}_{\alpha\beta}^a\,\epsilon_a^0\,,\qquad \epsilon_a^0 = \frac{1}{3\pi}\,\frac{z_a\,z_b\,|u_a|^2\,M_a^2\,\sin\beta}{z_a^2\,t_a v^4 + 4\,|u_a|^4 M_a^2}\,,\qquad (t_1=3\,,\ t_2=2)$$

Case A:

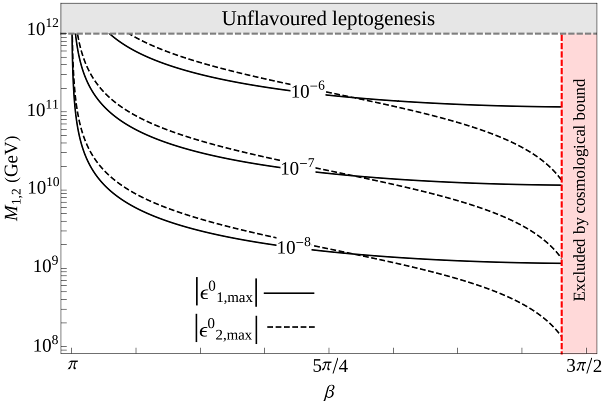
$$\mathbf{P}^a = \frac{(-1)^a}{2}\begin{pmatrix} -2(1+\varepsilon_1+\varepsilon_2) & \varepsilon_1-\varepsilon_2 & \varepsilon_2-\varepsilon_1 \\ \varepsilon_1-\varepsilon_2 & 4\left(\varepsilon_1+\varepsilon_2\,y_\mu^2/y_\tau^2\right) & 1+\varepsilon_1+\varepsilon_2 \\ \varepsilon_2-\varepsilon_1 & 1+\varepsilon_1+\varepsilon_2 & -4\left(\varepsilon_1+\varepsilon_2\,y_\mu^2/y_\tau^2\right) \end{pmatrix},$$

Case B:

$$\mathbf{P}^a = (-1)^a\left[\frac{1}{2}+\delta_{a2}\frac{v^4 z_2^2(\varepsilon_1+\varepsilon_2)}{18M_2^2u_2^4+9v^4z_2^2}\right]\begin{pmatrix} -2 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

Leptogenesis

Maximizing ϵ_a^0 with respect to the VEV of the decaying scalar triplet



$$\epsilon^0_{1,\max} \simeq \frac{M_1\sqrt{\Delta m^2_{31}}}{12\sqrt{6}\pi v^2}\sin\beta, \quad \epsilon^0_{2,\max} \simeq \frac{M_2\sqrt{\Delta m^2_{31}}}{48\pi v^2}\tan\beta\,.$$

Conclusion

- Model with spontaneous CP violation
- Single phase responsible for low and high energy CP violation
- Flavon vev corrections allow for the new Daya Bay results