The remnant CP transformation

Felix Gonzalez Canales

Departamento de Física
CINVESTAV-IPN

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- Peng Chen, Gui-Jun Ding, FGC and J. W. F. Valle,
  Generalized $\mu - \tau$ reflection symmetry and leptonic CP violation
  Phys. Lett. B 753 (2016) 644-652

  arXiv:1512.01551

- Peng Chen, Gui-Jun Ding, FGC and J. W. F. Valle,
  Classifying CP transformations according to their texture zeros: theory and implications

  arXiv:1604.03510

Redefinition of lepton mixing matrix

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$$\mathbf{m}_l \equiv \text{diag}\left(m_e, m_\mu, m_\tau\right).$$

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- The lepton mixing matrix
$$\mathbf{U} = \mathbf{\Sigma}\, \mathbf{O}_{3\times 3}\, \mathbf{Q}_\nu,$$
$\mathbf{\Sigma}$ is the Takagi factorization matrix of $\mathbf{X}$ fulfilling $\mathbf{X} = \mathbf{\Sigma}\mathbf{\Sigma}^T$,
$$\mathbf{Q}_\nu = \mathrm{diag}\left(e^{-ik_1\pi/2}, e^{-ik_2\pi/2}, e^{-ik_3\pi/2}\right),$$
the entries of $\mathbf{Q}_\nu$ are ± 1 and $\pm i$ which encode the CP-parity or CP-signs of the neutrino states and it renders the light neutrino mass eigenvalues positive.

Redefinition of lepton mixing matrix

- The matrix $\mathbf{O}_{3\times 3} = \mathbf{O}_1\mathbf{O}_2\mathbf{O}_3$ is a generic three dimensional real orthogonal matrix, and it can be parameterized as

$$\mathbf{O}_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_1 & \sin\theta_1 \\ 0 & -\sin\theta_1 & \cos\theta_1 \end{pmatrix}, \mathbf{O}_2 = \begin{pmatrix} \cos\theta_2 & 0 & \sin\theta_2 \\ 0 & 1 & 0 \\ -\sin\theta_2 & 0 & \cos\theta_2 \end{pmatrix}$$

$$\mathbf{O}_3 = \begin{pmatrix} \cos\theta_3 & \sin\theta_3 & 0 \\ -\sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

The neutrino oscillation data

Parameter[1]	BFP$\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}\ \left[10^{-5}\ \mathrm{eV}^2\right]$	$7.60^{+0.19}_{-0.18}$	$7.26 - 7.99$	$7.11 - 8.18$
$\Delta m^2_{31}\ \left[10^{-3}\ \mathrm{eV}^2\right]$ (NH)	$2.48^{+0.05}_{-0.07}$	$2.35 - 2.59$	$2.30 - 2.65$
$\Delta m^2_{13}\ \left[10^{-3}\ \mathrm{eV}^2\right]$ (IH)	$2.38^{+0.05}_{-0.06}$	$2.26 - 2.48$	$2.20 - 2.54$
$\sin^2\theta_{12}/10^{-1}$	3.23 ± 0.16	$2.92 - 3.57$	$2.78 - 3.75$
$\sin^2\theta_{23}/10^{-1}$ (NH)	$5.67^{+0.32}_{-1.24}$	$4.14 - 6.23$	$3.93 - 6.43$
$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.73^{+0.25}_{-0.39}$	$4.35 - 6.21$	$4.03 - 6.40$
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.26 ± 0.12	$2.02 - 2.50$	$1.90 - 2.62$
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.29 ± 0.12	$2.05 - 2.52$	$1.93 - 2.65$
δ/π (NH)	$1.41^{+0.55}_{-0.40}$	$0.0 - 2.0$	$0.0 - 2.0$
δ/π (IH)	1.48 ± 0.31	$0.00 - 0.09$ & $0.86 - 2.0$	$0.0 - 2.0$

The allowed ranges of $|\left(\mathbf{U}_{\mathrm{PMNS}}\right)_{ij}|$ are explicitly given at the 3σ level:

NH

$$\begin{pmatrix} 0.780 - 0.842 & 0.520 - 0.607 & 0.137 - 0.162 \\ 0.207 - 0.555 & 0.395 - 0.714 & 0.618 - 0.794 \\ 0.226 - 0.566 & 0.420 - 0.731 & 0.590 - 0.772 \end{pmatrix}$$

IH

$$\begin{pmatrix} 0.779 - 0.842 & 0.520 - 0.607 & 0.139 - 0.163 \\ 0.207 - 0.554 & 0.397 - 0.710 & 0.626 - 0.792 \\ 0.229 - 0.566 & 0.426 - 0.729 & 0.592 - 0.765 \end{pmatrix}$$

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0.229 − 0.566	0.426 − 0.729	0.592 − 0.7

- ⋆ The $|U_{\mu i}| \simeq |U_{\tau i}|$ relation. Approximate $\mu - \tau$ relation.
- ⋆ Exact $\mu - \tau$ relation $|U_{\mu i}| = |U_{\tau i}|$. This equality holds if either of the following two sets of conditions can be satisfied.

$$|U_{\mu i}| = |U_{\tau i}| \Leftrightarrow \begin{cases} \theta_{23} = \frac{\pi}{4}\,, \theta_{13} = 0; \\ \theta_{23} = \frac{\pi}{4}\,, \delta_{\text{CP}} = \pm\frac{\pi}{2}. \end{cases}$$

It is clear that θ_{13} has already bee ruled out, but $\theta_{23} = \frac{\pi}{4}$ and $\delta_{\text{CP}} = -\frac{\pi}{2}$ are both allowed at the 1 or 2σ level (and $\delta_{\text{CP}} = \frac{\pi}{2}$ is also allowed at the 3σ).

The $\mu - \tau$ Flavor Symmetry

We claim that there must be a partial or approximate $\mu - \tau$ flavor symmetry behind the observed pattern of the PMNS matrix.
The $\mu - \tau$ symmetry gives the constraint that Lagrangian is invariant under transformation of μ and τ neutrinos states.

- **The $\mu - \tau$ permutation symmetry**
  The neutrino mass term is unchanged under the transformations;

$$\nu_e \longrightarrow \nu_e \,, \qquad \nu_\mu \longrightarrow \nu_\tau \,, \qquad \nu_\tau \longrightarrow \nu_\mu \,.$$

- **The $\mu - \tau$ reflection symmetry**
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$$\nu_e \longrightarrow \nu_e^c \,, \qquad \nu_\mu \longrightarrow \nu_\tau^c \,, \qquad \nu_\tau \longrightarrow \nu_\mu^c \,.$$

[2] The superscript c denotes the charged conjugation.

Generalized $\mu - \tau$ reflection

This interesting CP transformation takes the following form:

$$\mathbf{X} = \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta}\cos\Theta & ie^{i\frac{(\beta+\gamma)}{2}}\sin\Theta \\ 0 & ie^{i\frac{(\beta+\gamma)}{2}}\sin\Theta & e^{i\gamma}\cos\Theta \end{pmatrix},$$

where the parameters α, β, γ, and Θ are real.

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$$\mathbf{\Sigma} = \begin{pmatrix} e^{i\frac{\alpha}{2}} & 0 & 0 \\ 0 & e^{i\frac{\beta}{2}}\cos\frac{\Theta}{2} & ie^{i\frac{\beta}{2}}\sin\frac{\Theta}{2} \\ 0 & ie^{i\frac{\gamma}{2}}\sin\frac{\Theta}{2} & e^{i\frac{\gamma}{2}}\cos\frac{\Theta}{2} \end{pmatrix}.$$

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As a result the resulting lepton mixing angles are determined as

$$\sin^2\theta_{13} = \sin^2\theta_2, \quad \sin^2\theta_{12} = \sin^2\theta_3, \quad \sin^2\theta_{23} = \frac{1}{2}\left(1 - \cos\Theta\cos 2\theta_1\right),$$

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while the CP violation parameters are predicted as

$$J_{\rm CP} = \tfrac{1}{4}\sin\Theta\sin\theta_2\sin 2\theta_3\cos^2\theta_2\,, \quad \sin\delta_{\rm CP} = \frac{\sin\Theta\ {\rm sign}[\sin\theta_2\sin 2\theta_3]}{\sqrt{1-\cos^2\Theta\cos^2 2\theta_1}}\,,$$

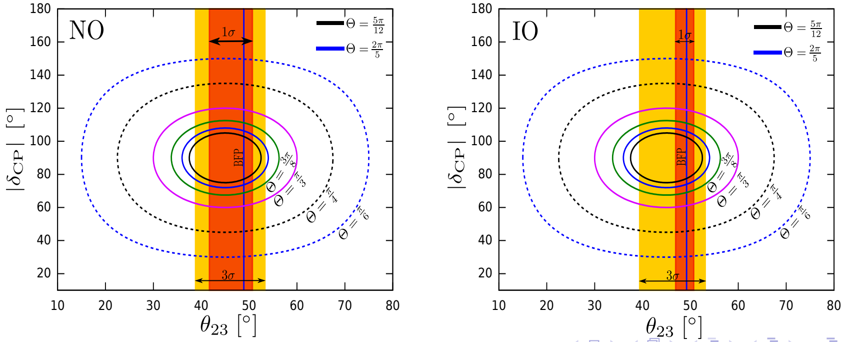
$$\tan\delta_{\rm CP} = \tan\Theta\csc 2\theta_1\,, \quad \phi_{12} = \tfrac{k_2-k_1}{2}\pi\,, \quad \phi_{13} = \tfrac{k_3-k_1}{2}\pi\,, \quad \delta_{\rm CP} = \tfrac{k_3-k_2}{2}\pi - \phi_{23}\,.$$

Generalized $\mu - \tau$ reflection

We have a correlation between $\delta_{\rm CP}$ and the atmospheric angle.

$$\sin^2 \delta_{\rm CP} \sin^2 2\theta_{23} = \sin^2 \Theta \,.$$

Taking $\Theta = \pm\frac{\pi}{2}$, both θ_{23} and $\delta_{\rm CP}$ are maximal, since the residual CP transformation $\mathbf{X}$ reduces to the standard $\mu - \tau$ reflection. When $\theta_1 = \pm\frac{\pi}{4}$, the atmospheric mixing angle θ_{23} is maximal and $\tan\delta_{\rm CP} = \pm\tan\Theta$.



Neutrinoless double beta decay

The rare decay $(A, Z) \to (A, Z+2) + e^- + e^-$ is the lepton number violating process "par excellence". In the symmetric parametrization, the amplitude for the decay is proportional to the effective mass parameter

$$|m_{ee}| = \left| m_1 \cos^2\theta_{12} \cos^2\theta_{13} + m_2 \sin^2\theta_{12} \cos^2\theta_{13} e^{-i2\phi_{12}} + m_3 \sin^2\theta_{13} e^{-i2\phi_{13}} \right| ,$$

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Within our scheme the Majorana phases are predicted as

$$\phi_{12} = \frac{k_2 - k_1}{2}\pi \quad \text{and} \quad \phi_{13} = \frac{k_3 - k_1}{2}\pi.$$

In other words, these phase factors are predicted to lie at their CP conserving values, which correspond to the CP signs of neutrino states. This implies that the two Majorana phases (ϕ_{12}, ϕ_{13}) can only take the following nine values

$$(0,0),\ (0,\pm\pi/2),\ (\pm\pi/2,0) \quad \text{and} \quad (\pm\pi/2,\pm\pi/2).$$

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The effective mass m_{ee} is an even function. This means that for each possible neutrino mass ordering, there are only four independent regions for the effective mass.

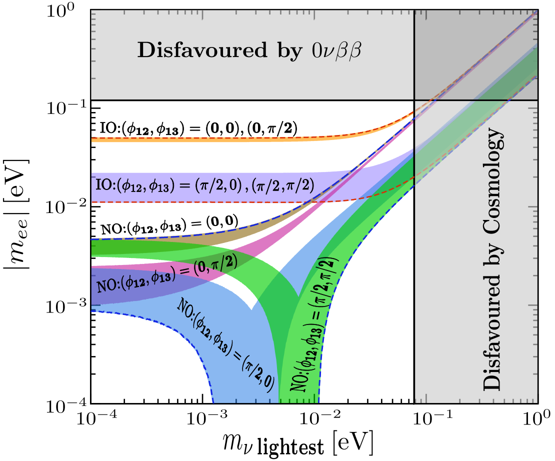
Neutrinoless double beta decay

Normal Ordering		
CP signs Q_ν	$(\phi_{12},\ \phi_{13})$	$\lvert m_{ee}\rvert$ $(10^{-2}$ eV$)$
$\mathrm{diag}(1,1,1)$	$(0,\ 0)$	$[\,0.32\,,7.22\,]$
$\mathrm{diag}(1,1,-i)$	$\left(0,\ \frac{\pi}{2}\right)$	$\left[9.50\times 10^{-2}\,,6.89\right]$
$\mathrm{diag}(1,-i,1)$	$\left(\frac{\pi}{2},\ 0\right)$	$[0\,,3.31]$
$\mathrm{diag}(1,-i,-i)$	$\left(\frac{\pi}{2},\ \frac{\pi}{2}\right)$	$[0\,,2.94]$

Inverted Ordering		
CP signs Q_ν	$(\phi_{12},\ \phi_{13})$	$\lvert m_{ee}\rvert$ $(10^{-2}$ eV$)$
$\mathrm{diag}\,(1,1,1)$ $\mathrm{diag}\,(1,1,-i)$	$(0,\ 0)$ $\left(0,\ \frac{\pi}{2}\right)$	$[\,4.59\,,8.20\,]$
$\mathrm{diag}\,(1,-i,1)$ $\mathrm{diag}\,(1,-i,-i)$	$\left(\frac{\pi}{2},\ 0\right)$ $\left(\frac{\pi}{2},\ \frac{\pi}{2}\right)$	$[1.10\,,3.45]$

The allowed ranges for the effective mass in for the case of normal and inverted ordering. Notice that in our generalized $\mu-\tau$ reflection scenario the Majorana phases can only be 0 and $\pm\pi/2$.

Neutrinoless double beta decay



The red and blue dashed lines indicate the regions currently allowed at 3σ by neutrino oscillation data. The most stringent upper bound $|m_{ee}| < 0.120$eV from EXO-200 in combination with KamLAND-ZEN. The upper limit on the mass of the lightest neutrino is derived from the lastest Planck result $\sum_i m_i < 0.230$eV at 95% level.

CP violation in neutrino oscillations

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- The transition probability $P(\nu_\mu \to \nu_e)$ in matter has the form

$$P\left(\nu_\mu \to \nu_e\right) \simeq P_{\rm atm} + P_{\rm sol} \pm 2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}} \cos\left(\Delta_{32} \pm \arcsin\left(\frac{\sin\Theta}{\sin 2\theta_{23}}\right)\right) .$$

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- The neutrino anti-neutrino asymmetry in matter is given by

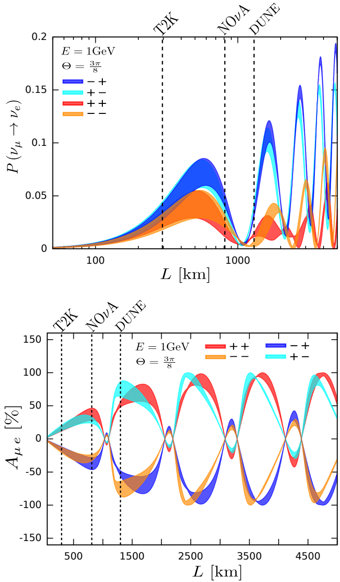
$$A_{\mu e} = \pm \frac{2\sqrt{P_{\mathrm{atm}}}\sqrt{P_{\mathrm{sol}}}\sin\Delta_{23}\sin\Theta}{\left(P_{\mathrm{atm}} + P_{\mathrm{sol}}\right)\sin 2\theta_{23} \pm 2\sqrt{P_{\mathrm{atm}}}\sqrt{P_{\mathrm{sol}}}\sqrt{\sin^2 2\theta_{23} - \sin^2\Theta}\,\cos\Delta_{23}},$$

where

$$\sqrt{P_{\mathrm{atm}}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}, \quad \sqrt{P_{\mathrm{sol}}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21},$$

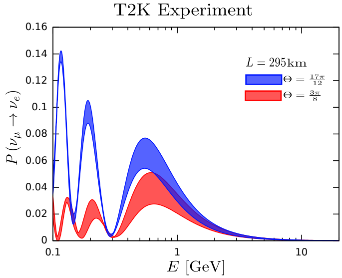
$\Delta_{kj} = \Delta m^2_{kj}L/(4E)$ with $\Delta m^2_{kj} = m^2_k - m^2_j$, L is the baseline, E is the energy of neutrino. $a = G_F N_e/\sqrt{2}$, G_F is the Fermi constant and N_e is the density of electrons, with $a \approx (3500\mathrm{km})^{-1}$ for $\rho Y_e = 3.0\mathrm{g\,cm}^{-3}$, where Y_e is the electron fraction.

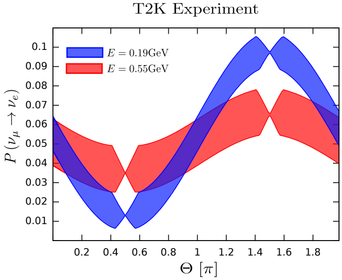
CP violation in neutrino oscillations



The mixing angle θ_{23} is taken within the 3σ range $0.393 \leq \sin^2\theta_{23} \leq 0.643$. The remaining neutrino oscillation parameters are fixed at their best fit values:
$\Delta m^2_{21} = 7.60 \times 10^{-5}\text{eV}^2$,
$|\Delta m^2_{31}| = 2.48 \times 10^{-3}\text{eV}^2$,
$\sin\theta_{12} = 0.323$ and
$\sin\theta_{13} = 0.0226$. The Θ parameter is fixed to the value $3\pi/8$. The figure corresponds to the case of normal ordering and the sign combinations.

CP violation in neutrino oscillations





The transition probability $P(\nu_\mu \to \nu_e)$ at a baseline of 295km which corresponds to the T2K experiment. The mixing angle θ_{23} is taken within the 3σ range $0.393 \leq \sin^2\theta_{23} \leq 0.643$. The remaining neutrino oscillation parameters are fixed at their best fit values: $\Delta m^2_{21} = 7.60 \times 10^{-5}\text{eV}^2$, $|\Delta m^2_{31}| = 2.48 \times 10^{-3}\text{eV}^2$, $\sin\theta_{12} = 0.323$ and $\sin\theta_{13} = 0.0226$.

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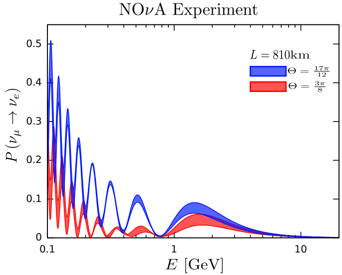
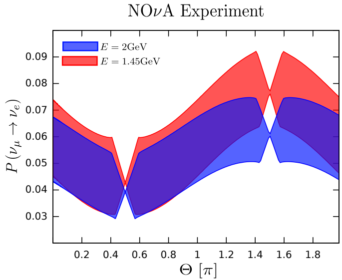
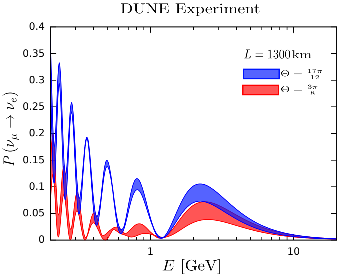
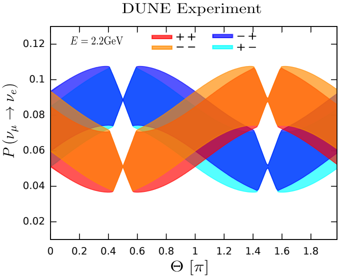




The transition probability $P(\nu_\mu \to \nu_e)$ at a baseline of 810km which corresponds to the NOνA experiment. The mixing angle θ_{23} is taken within the 3σ range $0.393 \leq \sin^2\theta_{23} \leq 0.643$. The remaining neutrino oscillation parameters are fixed at their best fit values: $\Delta m^2_{21} = 7.60 \times 10^{-5}\text{eV}^2$, $|\Delta m^2_{31}| = 2.48 \times 10^{-3}\text{eV}^2$, $\sin\theta_{12} = 0.323$ and $\sin\theta_{13} = 0.0226$.

CP violation in neutrino oscillations





The transition probability $P(\nu_\mu \to \nu_e)$ at a baseline of 1300km, which corresponds to the DUNE proposal. The mixing angle θ_{23} is taken within the 3σ range $0.393 \leq \sin^2\theta_{23} \leq 0.643$. The remaining neutrino oscillation parameters are fixed at their best fit values: $\Delta m^2_{21} = 7.60 \times 10^{-5}\mathrm{eV}^2$, $|\Delta m^2_{31}| = 2.48 \times 10^{-3}\mathrm{eV}^2$, $\sin\theta_{12} = 0.323$ and $\sin\theta_{13} = 0.0226$.

Conclusions

- We have proposed a generalized $\mu - \tau$ reflection scenario for leptonic CP violation and derived the corresponding restrictions on lepton flavor mixing parameters.
- In contrast with flavor symmetry schemes, our generalized CP symmetry approach can constrain not only the mixing angles but also the CP violating phases in function of four parameters.
- We found that the "Majorana" phases are predicted to lie at their CP-conserving values with important implications for the neutrinoless double beta decay amplitudes.
- We have obtained a new correlation between the atmospheric mixing angle θ_{23} and the "Dirac" CP phase $\delta_{\rm CP}$.
- We have also analysed the phenomenological implications of our scheme for present as well as upcoming neutrino oscillation experiments T2K, NOνA and DUNE.