Non-unitary Neutrino Mixing and CP Violation in the Minimal Inverse Seesaw Model

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Non-unitary Lepton Mixing in Neutrino Oscillations

Suppose the neutrinos entering the charged current (CC) interactions are in general not a mere unitary admixture of three light mass eigenstates. There can be other components present which do not enter charged currents.

\[ \langle \nu_\alpha \rangle = \sum_{i=1}^{3} V_{\alpha i} \langle \nu_i \rangle + \ldots \]

\[ (V^\dagger V)_{ij} \neq \delta_{ij} \]

\[ (VV^\dagger)_{\alpha \beta} \neq \delta_{\alpha \beta} \]

Assuming the extra states are dynamically inaccessible one can effectively consider only three light mass eigenstates are relevant for oscillations of the three flavours. Technically, one has to canonically normalize the light fields when the heavy sector effectively decouples.

The standard oscillation formalism then yields the vacuum transition probability in the form:

\[
P_{\alpha \to \beta} = \sum_{i,j} F_{\alpha \beta}^i F_{\alpha \beta}^{j*} - 4 \sum_{i>j} \text{Re}(F_{\alpha \beta}^i F_{\alpha \beta}^{j*}) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} \text{Im}(F_{\alpha \beta}^i F_{\alpha \beta}^{j*}) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)
\]

Ohlsson, Zhang, 2008, ....

\[ V \equiv (1 - \eta) U \]

Altarelli, Meloni 2009

\[ \eta \] is a (small) hermitean matrix characterizing the departure from a unitary \( U \), which can be at leading order parametrized by means of the measured neutrino mixing parameters.
Non-unitarity Effects in “Canonical” Seesaw Models

Type-I seesaw:
In the canonical type-I seesaw, the non-unitarity effects are suppressed because the same structure \((F)\) that makes the light neutrino masses to fall into the sub-eV region enters \(\eta\):

\[
m_\nu = FM_R F^T \quad \text{where} \quad F = M_D M_R^{-1}
\]

\[
\eta = \frac{1}{2} FF^\dagger
\]

Thus, the non-unitarity due to the quasi-decoupled heavy sector is tiny unless one invokes a fine-tuning.

Type-II seesaw:
In the canonical type-II seesaw there is nothing extra that could admix into the flavour eigenstates.

Type-III seesaw:
The situation is analogous to the type-I case.

Thus, there is a need to disentangle the lightness of the neutrino masses from the typical magnitude of the \(M_D M_R^{-1}\) structure.

Expected bonus: since \(M_D\) is to be kept around the electroweak scale (being a Dirac mass) there is another virtue in scenarios with potentially large (\%) non-unitary effects - a heavy sector in few TeV range, perhaps observable at the LHC (?).
Inverse seesaw scenario (ISS)

Due to the presence of an extra singlet sector, the traditional 6x6 neutrino mass matrix is enlarged, typically to a 9x9 structure.

\[
M_\nu = \begin{pmatrix}
0 & M_D & 0 \\
M_T^T & 0 & M_T^T \\
0 & M_R & \mu
\end{pmatrix}
\]

Mohapatra, Valle 1986

The RH sector is arranged to be pseudo-Dirac with a tiny \( \mu \ll M_R \) mass difference providing the only source of lepton number violation. Light neutrino masses are driven by an interplay of two different scales.

\[
m_\nu = M_D M_R^{-1} \mu (M_R^T)^{-1} M_D^T = F \mu F^T
\]

Malinsky, Ohlsson, Zhang, 2009

One can keep the right-handed sector sizably admixed into the flavour eigenstates entering the CC by keeping \( F \) relatively large (at the %-level) whilst dynamically decoupling the light neutrinos from the heavy ones so that the three mass-eigenstate mixing approximation makes sense. In other words, the mixing (driving the non-unitarity parameters) is potentially large due to the proximity of \( M_R \) and the electroweak scale, while the light neutrino mass scale is suppressed due to an extra freedom in choosing \( \mu \).

Virtues of the ISS:
+ Naturalness of the setting
+ Similarity to the type-I/III, but very different in the amount of lepton number violation
+ Non-unitarity effects not suppressed by the smallness of the neutrino masses, simple form of \( \eta \) gives rise to correlations between various entries (better than mere Schwarz inequality)
+ LFV effects also not suppressed, non-vanishing even for zero neutrino masses

Thus, ISS is a very plausible framework providing accessible (at least in principle) new physics without unnatural fine-tuning
Minimal Inverse Seesaw Scenario (MISS)

ISS in the usual formulation is not very predictive, but it is not minimall either, one can have even simpler model, yet compatible with the oscillation data.

Employing only two heavy pseudo-Dirac neutrinos makes the correlations between the various $\eta_{\alpha\beta}$ ’s even more stringent than in the ISS case and the model is testable.

In particular, one typically obtains a structure like

$$\eta \propto \begin{pmatrix} -\cos \theta_{23} x \star & -\cos \theta_{23} x \star & \sin \theta_{23} x \star \\ -\cos \theta_{23} x & \cos^2 \theta_{23} & \pm \cos \theta_{23} \sin \theta_{23} \\ \sin \theta_{23} x & \pm \cos \theta_{23} \sin \theta_{23} & \sin^2 \theta_{23} \end{pmatrix}$$

Thus, only the $\eta_{\mu\tau}$ off-diagonal can be sizeable, yielding a specific pattern of would-be extra CP violation entering the oscillation formulae, c.f. Figure 1.

Moreover, CP effects can be sizeable only for normal hierarchy, see Figure 2.

Future experimental sensitivity to $\eta_{\mu\tau}$:

There is a certain chance to observe an effect at future facilities like a neutrino factory only before the standard oscillations take over (note the different dependence on the oscillation length).

An OPERA-like near detector within few tens of kilometers would be an ideal tool to do that, see Figure 3.

Malinsky, Ohlsson, Xing, Zhang, 2009