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# Search for New Physics in reactor and accelerator experiments

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**Summary.** — We consider two scenarios of New Physics: the Large Extra Dimensions (LED), where sterile neutrinos can propagate in a $(4 + d)$-dimensional space-time, and the Non Standard Interactions (NSI), where the neutrino interactions with ordinary matter are parametrized at low energy in terms of effective flavour-dependent complex couplings $\varepsilon_{\alpha\beta}$. We study how these models have an impact on oscillation parameters in reactor and accelerator experiments.

## 1. – Details of the models

In both models we can consider the effect of New Physics (NP) as a perturbation of the Standard Model (SM) neutrino oscillation amplitude $\mathcal{A}(\nu_\alpha \to \nu_\beta) = \mathcal{A}_{\rm SM}(\nu_\alpha \to \nu_\beta) + \delta\mathcal{A}(\nu_\alpha \to \nu_\beta)$. In the case of LED model this is due to the presence of a tower of massive extra sterile neutrinos that can mix with the ordinary SM neutrinos

$$\mathcal{A}_{\rm LED}(\nu_\alpha \to \nu_\beta) = \sum_{j=1}^{3}\sum_{k=0}^{\infty} U_{\alpha j}U^*_{\beta j}\left[W_j^{(k)}\right]^2 \exp\left[\frac{i(\lambda_j^{(k)})^2 L}{2ER^2}\right], \tag{1}$$

where $\lambda_j^{(0)} \simeq m_j R$, $\lambda_j^{(k)} \simeq k + m_j^2 R^2/k$ are the mass eigenstates and $(W_j^{(0)})^2 \simeq 1$, $(W_j^{(k)})^2 \simeq 2m_j^2 R^2/k^2$ are the matrix elements that connect the SM neutrino to the Kaluza-Klein modes, $U$ is the PMNS matrix, $m_j$ are the light neutrino masses and $R$ is the radius of the largest compactified extra dimension. For the NSI scenario the correction to the SM amplitude is due to the fact that neutrinos at source and detector are a linear superposition of physical neutrino eigenstates

$$\mathcal{A}_{\rm NSI}(\nu_\alpha \to \nu_\beta) = \left[\langle\nu|(1+\varepsilon^d)\right]_{\beta\rho}\left[e^{-iHL}\right]_{\rho\sigma}\left[(1+\varepsilon^s)|\nu\rangle\right]_{\sigma\alpha}, \tag{2}$$

where $H$ is the evolution operator, which in the mass basis neglecting matter effects reads $H_{\alpha\beta} = U_{\alpha j}{\rm diag}\{0, \Delta m^2_{21}, \Delta m^2_{31}\}_{jk}\,(U^\dagger)_{k\beta}/2E$.

 

TABLE I. – *Best fit ($\pm 1\sigma$) and $3\sigma$ errors of the standard parameters obtained in the fit of T2K $\oplus$ Daya Bay data, using the SM, LED and NSI probabilities. If two values are given, the upper one corresponds to Normal Ordering and the lower one to Inverted Ordering.*

| | SM | | LED | | NSI | |
|---|---|---|---|---|---|---|
| Parameter | Best-fit | $3\sigma$ range | Best-fit | $3\sigma$ range | Best-fit | $3\sigma$ range |
| $\lvert\Delta m^2_{31}\rvert/10^{-3}\,\mathrm{eV}^2$ | $2.51^{+0.06}_{-0.06}$ | 2.34–2.69 | $2.53^{+0.07}_{-0.05}$ | 2.37–2.73 | $2.56^{+0.06}_{-0.09}$ | 2.31–2.74 |
| | $2.54^{+0.06}_{-0.06}$ | 2.37–2.73 | $2.54^{+0.07}_{-0.07}$ | 2.35–2.71 | $2.56^{+0.09}_{-0.08}$ | 2.32–2.77 |
| $\sin^2\theta_{23}/10^{-1}$ | $5.3^{+0.4}_{-0.6}$ | 4.0–6.3 | $5.3^{+0.4}_{-0.5}$ | 4.1–6.3 | $5.2^{+0.6}_{-0.8}$ | 3.8–6.5 |
| | $5.3^{+0.4}_{-0.5}$ | 4.1–6.2 | $5.3^{+0.4}_{-0.5}$ | 4.1–6.3 | $5.2^{+0.6}_{-0.8}$ | 3.9–6.5 |
| $\sin^2\theta_{13}/10^{-2}$ | $2.3^{+0.3}_{-0.2}$ | 1.6–3.0 | $2.3^{+0.2}_{-0.4}$ | 1.4–3.0 | $3.9^{+0.4}_{-2.6}$ | 0.7–5.1 |
| | $2.4^{+0.2}_{-0.3}$ | 1.6–3.0 | $2.2^{+0.1}_{-0.1}$ | 1.3–2.9 | $3.8^{+0.5}_{-2.6}$ | 0.7–5.1 |
| $\delta/\pi$ | $1.53^{+0.33}_{-0.37}$ | — | $1.47^{+0.35}_{-0.31}$ | — | $1.65^{+0.55}_{-0.78}$ | — |
| | $1.48^{+0.36}_{-0.35}$ | — | $1.59^{+0.30}_{-0.36}$ | — | $1.35^{+0.75}_{-0.49}$ | — |

## 2. – Statistical analysis and results

We use the T2K (28 events in channel $\nu_\mu \to \nu_e$ and 120 events in $\nu_\mu \to \nu_\mu$ [1]) and 217 days of $\bar{\nu}_e \to \bar{\nu}_e$ Daya Bay data [2] in order to: study how the standard oscillation parameters are modified by the NP and constrain the parameter space of the LED and NSI models [3]. The statistical analysis of the data has been performed using a modified version of the `GLoBES` software [4]. We consider the effects of experimental systematics with a pull method in the $\chi^2$ analysis. The SM quantities $\theta_{13}$, $\theta_{23}$, $\delta$ and $\Delta m^2_{31}$ are unconstrained, whereas for the solar angle and the solar mass difference we define gaussian priors: $\sin^2\theta_{12} = (3.08 \pm 20\%) \times 10^{-1}$ and $\Delta m^2_{21} = (7.54 \pm 5\%) \times 10^{-5}\,\mathrm{eV}^2$.

While the impact of LED on the best fit values and $1\sigma$ errors of the standard oscillation parameters is almost negligible, this is not the case for the NSI scenario, where the allowed values of $\theta_{13}$ and $\delta$ are different from the SM determination, see table I. In fact the $1\sigma$ confidence region for $\theta_{13}$ is roughly six as large as in the SM case. The situation is similar for the phase $\delta$, where the presence of new phases from the NSI complex couplings reduces the sensitivity and also the hints for a maximal CP violation.

As for the bounds on the parameters of the LED and NSI models at $2\sigma$ CL (1 dof), we have found the following results:

- in the combined analysis of the T2K $\oplus$ Daya Bay data we obtain $R \leq 0.60\,\mu\mathrm{m}$ for Normal Ordering and $R \leq 0.17\,\mu\mathrm{m}$ for Inverted Ordering,

- for $\lvert\varepsilon_{e\mu}\rvert < 4.85 \times 10^{-3}$ and $\lvert\varepsilon^s_{\mu e}\rvert < 6.28 \times 10^{-3}$ (for $\delta = 0$); $\lvert\varepsilon_{e\mu}\rvert < 9.94 \times 10^{-3}$ and $\lvert\varepsilon^s_{\mu e}\rvert < 9.96 \times 10^{-3}$ (for $\delta = \pi$).

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