A brief status of non-standard neutrino interactions

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Abstract

In this plenary talk, we review the status of non-standard neutrino interactions (NSIs). First, we give a brief introduction to neutrino flavor transitions with NSIs based on the standard paradigm of neutrino oscillations. Then, we discuss alternative scenarios for neutrino flavor transitions such as neutrino decoherence, neutrino decay, and NSIs. Second, we investigate NSIs with three neutrino flavors. In general, we introduce production and detection NSIs, including the so-called zero-distance effect, and matter NSIs. In addition, we study mappings and approximate formulas for NSIs. Third, we present a brief account of theoretical models for NSIs. Fourth and most important, we investigate in detail the phenomenology of NSIs based on different types of data from neutrino experiments. Fifth, we give some phenomenological bounds on both matter and production/detection NSIs as well as we present sensitivity and discovery reach of NSIs at future experiments. Finally, we present a summary and state our conclusions.

Keywords: non-standard neutrino interactions, neutrino flavor transitions, neutrino phenomenology, neutrino experiments

1. Introduction to NSIs

The phenomenon of neutrino oscillations is the leading description for neutrino flavor transitions. However, other mechanisms could be responsible for transitions on a sub-leading level. Therefore, we will phenomenologically study “new physics” effects due to non-standard neutrino interactions (NSIs).

In the standard paradigm of neutrino oscillations, leptonic flavor mixing is described as the mixing between weak interaction eigenstates $\{\nu_e, \nu_\mu, \nu_\tau\}$ and mass eigenstates $\{\nu_1, \nu_2, \nu_3\}$ [1–3]:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad (1)$$

where U is the leptonic mixing matrix. In the standard parametrization, U is given by

$$\begin{aligned} U &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \\ &\times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \\ &\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (2) \end{aligned}$$

where $c_{ij} \equiv \cos(\theta_{ij})$, $s_{ij} \equiv \sin(\theta_{ij})$, and the leptonic mixing parameters are the three mixing angles θ_{12} , θ_{13} , and θ_{23} as well as the Dirac CP-violating phase δ and the two Majorana CP-violating phases ρ and σ .

Next, the evolution of the neutrino vector of state

$$\nu = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}^T \quad (3)$$

describing neutrino oscillations in matter is described

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by a Schrödinger-like equation with a Hamiltonian H , viz.

$$i \frac{dv}{dt} = \frac{1}{2E} [MM^\dagger + \text{diag}(A, 0, 0)] v \equiv H v, \quad (4)$$

where E is the neutrino energy, $M = U \text{diag}(m_1, m_2, m_3) U^T$ is the neutrino mass matrix, and $A = 2\sqrt{2}EG_F N_e$ is the effective (ordinary) matter potential, which was studied in a seminal work by Wolfenstein [4].

Now, the present values of the fundamental neutrino parameters have been obtained in global fits of the current experimental neutrino data, which give (assuming normal mass ordering) [5]:

$$\begin{aligned} \Delta m_{21}^2 = m_2^2 - m_1^2 &= (7.50 \pm 0.185) \cdot 10^{-5} \text{ eV}^2, \\ |\Delta m_{31}^2| = |m_3^2 - m_1^2| &= (2.47^{+0.069}_{-0.067}) \cdot 10^{-3} \text{ eV}^2, \\ \sin^2 \theta_{12} &= 0.30 \pm 0.013, \\ \sin^2 \theta_{13} &= 0.023 \pm 0.0023, \\ \sin^2 \theta_{23} &= 0.41^{+0.037}_{-0.025}. \end{aligned}$$

See also Refs. [6, 7]. Thus, the currently unknown quantities are (i) the absolute neutrino mass scale m_1 , (ii) the sign of Δm_{31}^2 , i.e. $\text{sign}(\Delta m_{31}^2)$, (iii) the Dirac CP-violating phase δ , and (iv) the Majorana CP-violating phases ρ and σ .

Other descriptions for flavor transitions of neutrinos exist such as neutrino decoherence and neutrino decay (see Ref. [8] and references therein). However, such descriptions are now ruled out as the leading-order mechanism behind neutrino flavor transitions [9–13]. However, such descriptions could be sub-leading mechanisms and the origin of the NSIs, see e.g. Ref. [14]. In this context, we will discuss NSIs. Note that this talk is based on the review [8].

2. NSIs with three neutrino flavors

The phenomenological consequences of NSIs have been investigated in great detail in the literature. In general, NSI operators are given by [4, 15–17]

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ff'C} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_C f'), \quad (5)$$

where $\varepsilon_{\alpha\beta}^{ff'C}$ are NSI parameters. Using the NSI operators, we find that the effective NSI parameters follow

$$\varepsilon_{\alpha\beta} \propto \frac{m_W^2}{m_X^2}. \quad (6)$$

If the new physics scale, i.e., the NSI scale, is of the order 1(10) TeV, then one obtains

$$\varepsilon_{\alpha\beta} \sim 10^{-2}(10^{-4}). \quad (7)$$

Now, there are at least two different possibilities for NSIs: production/detection NSIs and matter NSIs. In the case of production and detection NSIs, neutrino states at sources and detectors can be written as superpositions of pure orthonormal flavor eigenstates [15, 18–20]:

$$\begin{aligned} |v_\alpha^s\rangle &= |v_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s |v_\beta\rangle = (1 + \varepsilon^s) U |v_m\rangle, \quad (8) \\ \langle v_\beta^d| &= \langle v_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle v_\alpha| = \langle v_m| U^\dagger [1 + (\varepsilon^d)^\dagger]. \end{aligned} \quad (9)$$

If the production and detection processes are the same, then $\varepsilon^s = (\varepsilon^d)^\dagger$. For production and detection NSIs, the neutrino transition probability is given by

$$\begin{aligned} P(v_\alpha^s \rightarrow v_\beta^d; L) &= \left| \sum_{\gamma,\delta,i} (1 + \varepsilon^d)_{\gamma\beta} (1 + \varepsilon^s)_{\alpha\delta} U_{\delta i} U_{\gamma i}^* e^{-i \frac{m_i^2 L}{2E}} \right|^2 \\ &= \sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*} \\ &\quad - 4 \sum_{i>j} \text{Re}(\mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) \\ &\quad + 2 \sum_{i>j} \text{Im}(\mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right) \end{aligned} \quad (10)$$

with $\mathcal{J}_{\alpha\beta}^i$ being some quantities.

What happens with this formula for the neutrino transition probability at $L = 0$? In this case, we obtain

$$P(v_\alpha^s \rightarrow v_\beta^d; L = 0) = \sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*} \quad (11)$$

with

$$\begin{aligned} \mathcal{J}_{\alpha\beta}^i &= U_{\alpha i}^* U_{\beta i} + \sum_{\gamma} \varepsilon_{\alpha\gamma}^s U_{\gamma i}^* U_{\beta i} \\ &\quad + \sum_{\gamma} \varepsilon_{\gamma\beta}^d U_{\alpha i} U_{\gamma i} + \sum_{\gamma,\delta} \varepsilon_{\alpha\gamma}^s \varepsilon_{\delta\beta}^d U_{\gamma i}^* U_{\delta i}. \end{aligned} \quad (12)$$

Thus, in general, the $\sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}$ is different from zero or one. This is known as the *zero-distance effect* [21]. (It could be measured with a near detector close to a source.) In the case that $\varepsilon^s = \varepsilon^d = 0$ (i.e., without NSIs), then

$$\sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*} = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* = \delta_{\alpha\beta}. \quad (13)$$

The three-flavor neutrino evolution equation with matter NSIs [cf. Eq. (4)] is given by [4, 22–24]

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} \left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}, \quad (14)$$

where $\varepsilon_{\alpha\beta}$'s are the effective matter NSI parameters. In general, this equation gives rise to rather cumbersome formulas for neutrino oscillation probabilities. Thus, we will not present any such general formulas for three neutrino flavors.

Instead, we discuss mappings between effective and fundamental parameters. In the case of neutrino masses, the mappings for the effective masses with NSIs are given by [25]

$$\tilde{m}_1^2 \simeq \Delta m_{31}^2 (\hat{A} + \alpha s_{12}^2 + \hat{A} \varepsilon_{ee}), \quad (15)$$

$$\tilde{m}_2^2 \simeq \Delta m_{31}^2 [\alpha c_{12}^2 - \hat{A} s_{23}^2 (\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}) - \hat{A} s_{23} c_{23} (\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*) + \hat{A} \varepsilon_{\mu\mu}], \quad (16)$$

$$\tilde{m}_3^2 \simeq \Delta m_{31}^2 [1 + \hat{A} \varepsilon_{\tau\tau} + \hat{A} s_{23}^2 (\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}) + \hat{A} s_{23} c_{23} (\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*)], \quad (17)$$

where $\hat{A} \equiv A/\Delta m_{31}^2$ and $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$, whereas in the case of leptonic mixing parameters, the mappings for the effective mixing matrix elements with NSIs are given by [25]

$$\tilde{U}_{e2} \simeq \frac{\alpha s_{12} c_{12}}{\hat{A}} + c_{23} \varepsilon_{e\mu} - s_{23} \varepsilon_{e\tau}, \quad (18)$$

$$\tilde{U}_{e3} \simeq \frac{s_{13} e^{-i\delta}}{1 - \hat{A}} + \frac{\hat{A} (s_{23} \varepsilon_{e\mu} + c_{23} \varepsilon_{e\tau})}{1 - \hat{A}}, \quad (19)$$

$$\tilde{U}_{\mu 2} \simeq c_{23} + \hat{A} s_{23}^2 c_{23} (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) + \hat{A} s_{23} (s_{23} \varepsilon_{\mu\tau} - c_{23}^2 \varepsilon_{\mu\tau}^*), \quad (20)$$

$$\tilde{U}_{\mu 3} \simeq s_{23} + \hat{A} [c_{23} \varepsilon_{\mu\tau} + s_{23} c_{23}^2 (\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}) - s_{23}^2 c_{23} (\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*)]. \quad (21)$$

These mappings are important for NSIs with long-baseline experiments, and indeed, the results are model independent. In Fig. 1, neutrino oscillation probabilities for the electron neutrino-muon neutrino channel are shown. As can be observed in this figure, there is an agreement between the numerical and approximate results to an extremely good precision. However, a singularity exists around 10 GeV due to the limitation of non-degenerate perturbation theory.

In some cases, approximate formulas for two neutrino flavors are sufficient. For example, for electron neutrino-tau neutrino oscillations with matter NSIs, the two-flavor neutrino oscillation probability formula is given by (see e.g. Ref. [26])

$$P(\nu_e \rightarrow \nu_\tau; L) = \sin^2(2\theta_M) \sin^2\left(\frac{\Delta m_M^2 L}{2E}\right) \quad (22)$$

with the effective parameters

$$\begin{aligned} (\Delta m_M^2)^2 &= [\Delta m^2 \cos(2\theta) - A(1 + \varepsilon_{ee} - \varepsilon_{\tau\tau})]^2 \\ &+ [\Delta m^2 \sin(2\theta) + 2A\varepsilon_{e\tau}]^2, \end{aligned} \quad (23)$$

$$\sin(2\theta_M) = \frac{\Delta m^2 \sin(2\theta) + 2A\varepsilon_{e\tau}}{\Delta m_M^2}. \quad (24)$$

See also Ref. [27] for a detailed discussion on approximate two-flavor neutrino formulas with NSIs.

3. Theoretical models for NSIs

How to realize NSIs in a more fundamental framework with some underlying high-energy physics theory, which would respect the SM gauge group $SU(3) \times SU(2) \times U(1)$? Using a toy model based on the SM and one heavy scalar field S , one has the following Lagrangian [28]

$$\mathcal{L}_{\text{int}}^S = -\lambda_{\alpha\beta} \bar{L}_\alpha^c i\sigma_2 L_\beta S + \text{h.c.} \quad (25)$$

Integrating out S generates a dimension-six operator at tree level [29]:

$$\mathcal{L}_{\text{NSI}}^{\text{d=6,as}} = 4 \frac{\lambda_{\alpha\beta} \lambda_{\delta\gamma}^*}{m_S^2} (\bar{\ell}_\alpha^c P_L \nu_\beta) (\bar{\nu}_\gamma P_R \ell_\delta^c). \quad (26)$$

Other examples of theoretical models for NSIs are different seesaw models, the Zee–Babu model, etc.

In general, theories beyond the SM must respect gauge symmetry invariance, which implies strict constraints on possible models for NSIs. See e.g. Ref. [30]. Therefore, if there is a dimension-6 operator on the form

$$\frac{1}{\Lambda^2} (\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta) (\bar{\ell}_\gamma \gamma_\rho P_L \ell_\delta),$$

it can lead to the NSI parameter $\varepsilon_{e\mu}^{ee}$. However, the dimension-6 operator must be a part of the more general form

$$\frac{1}{\Lambda^2} (\bar{L}_\alpha \gamma^\rho L_\beta) (\bar{L}_\gamma \gamma_\rho L_\delta),$$

which involves four charged-lepton operators. Thus, we have severe constraints from experiments on processes like $\mu \rightarrow 3e$, i.e., $\text{BR}(\mu \rightarrow 3e) < 10^{-12}$, which leads to the following upper bound on the above chosen NSI parameter $\varepsilon_{e\mu}^{ee} < 10^{-6}$.

Figure 1: Neutrino oscillations probabilities for the electron neutrino-muon neutrino channel. The solid curves are exact numerical results, the dashed curves are approximate results, and the dotted curves are results without NSIs. This figure has been adopted from Ref. [25].

4. Phenomenology of NSIs

In the case of NSIs with atmospheric neutrinos, one can use the two-flavor hybrid model [31], which has the two-flavor muon neutrino survival probability

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\mu; L) &= 1 - P(\nu_\mu \rightarrow \nu_\tau; L) \\ &= 1 - \sin^2(2\Theta) \sin^2\left(\frac{\Delta m^2 L}{4E} R\right), \end{aligned} \quad (27)$$

where

$$\begin{aligned} \sin^2(2\Theta) &= \frac{1}{R^2} \left[\sin^2(2\theta) + R_0^2 \sin^2(2\xi) \right. \\ &\quad \left. + 2R_0 \sin(2\theta) \sin(2\xi) \right], \end{aligned} \quad (28)$$

$$\begin{aligned} R &= \left\{ 1 + R_0^2 + 2R_0 \left[\cos(2\theta) \cos(2\xi) \right. \right. \\ &\quad \left. \left. + \sin(2\theta) \sin(2\xi) \right] \right\}^{1/2} \end{aligned} \quad (29)$$

with

$$R_0 = \sqrt{2} G_F N_e \frac{4E}{\Delta m^2} \sqrt{|\varepsilon|^2 + \frac{\varepsilon'^2}{4}}, \quad (30)$$

$$\xi = \frac{1}{2} \arctan\left(\frac{2\varepsilon}{\varepsilon'}\right). \quad (31)$$

Using the two-flavor hybrid model together with atmospheric neutrino data from the Super-Kamiokande

I (1996–2001) and II (2003–2005) experiments, the Super-Kamiokande collaboration has obtained the following results at 90 % C.L. [32]

$$|\varepsilon_{\mu\tau}| < 0.033 \quad \text{and} \quad |\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}| < 0.147.$$

Thus, the Super-Kamiokande collaboration has found no evidence for matter NSIs in its atmospheric neutrino data, see Fig. 2.

In the case of NSIs with accelerator neutrinos, studies include searches for matter NSIs with the K2K, MINOS, OPERA, T2K, and T2KK. For the MINOS experiment, the important NSI parameters are $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$, and $\varepsilon_{\tau\tau}$ and one of the interesting transition probabilities is (assuming $\theta_{23} = 45^\circ$) [33]

$$P(\nu_\mu \rightarrow \nu_\mu; L) \simeq 1 - \sin^2\left(\left|\frac{\Delta m_{31}^2}{4E} - \varepsilon_{\mu\tau} \frac{A}{2E}\right| L\right). \quad (32)$$

For the OPERA experiment, the important NSI parameter is $\varepsilon_{\mu\tau}$ and the interesting transition probability is (assuming $\Delta m_{21}^2 = 0$) [34]

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\tau; L) &= \left| c_{13}^2 \sin(2\theta_{23}) \frac{\Delta m_{31}^2}{4E} + \varepsilon_{\mu\tau}^* \frac{A}{2E} \right|^2 \\ &\quad \times L^2 + O(L^3). \end{aligned} \quad (33)$$

Thus, there exists a degeneracy between the fundamental neutrino oscillation parameters and the NSI parameter $\varepsilon_{\mu\tau}$. Note that it has been shown that the OPERA

Figure 2: Allowed parameter regions for $\sin^2(2\theta_{23})$ and Δm^2_{32} using the two-flavor hybrid model (solid curves) and standard two-flavor neutrino oscillations (dashed curves). The undisplayed parameters ε and ε' have been integrated out. This figure has been adopted from Ref. [32].

experiment is not very sensitive to the NSI parameters $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$ [35]. Using a model based on the ν_μ survival probability together with data from the MINOS experiment, the MINOS collaboration has obtained the following result for the matter NSI parameter $\varepsilon_{\mu\tau}$ at 90 % C.L. [36]

$$-0.200 < \varepsilon_{\mu\tau} < 0.070,$$

which means that MINOS has found no evidence for matter NSIs in its neutrino data, at least not a non-zero value for the matter NSI parameter $\varepsilon_{\mu\tau}$.

To my knowledge, there exist only three studies with reactor neutrinos and NSIs. (i) A combined study of the performance of reactor and superbeam neutrino experiments in the presence of NSIs [37], (ii) a study of only reactor neutrino experiments and NSIs [38], and (iii) NSIs at the Daya Bay experiment [39]. In the second study, it turns out that the measured value for θ_{13} could be a combination of the fundamental value for θ_{13} and effects of NSI parameters, whereas in the third study, one can estimate the effects of the NSIs in the determination of the standard oscillation parameters θ_{13} and Δm^2_{32} at Daya Bay after 3 years of running, see Fig. 3.

For accelerators, LEP provides bounds on NSIs of the order of $\varepsilon \lesssim (10^{-2} \div 10^{-3})$ at $\sqrt{s} \sim 200$ GeV [40]. If NSIs are contact interactions at LHC energies, LHC should have a sensitivity reach of NSIs of the order of $\varepsilon \gtrsim 3 \cdot 10^{-3}$ at 14 TeV and with 100 fb^{-1} of data.

For a future neutrino factory, it holds that (i) a

Figure 3: Effects of NSIs on θ_{13} and Δm^2_{32} for Daya Bay after three years of running. This figure has been adopted from Ref. [39].

100 GeV neutrino factory could probe flavor-changing neutrino interactions of the order of $|\varepsilon| \lesssim 10^{-4}$ at 99 % C.L. [41], (ii) there is an entanglement between the mixing angle θ_{13} and NSI parameters, which would be solved in the best way by using the appearance channel $\nu_e \rightarrow \nu_\mu$ [42, 43], (iii) there are degeneracies between CP violation and NSI parameters, (iv) a neutrino factory has excellent prospects in detecting NSIs originating from “new physics” at the TeV scale [44], and (v) off-diagonal NSI parameters could be tested down to the order of 10^{-3} , whereas diagonal NSI parameter combinations such as $\varepsilon_{ee} - \varepsilon_{\tau\tau}$ and $\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}$ could only be tested down to 10^{-1} and 10^{-2} , respectively [45].

Finally, in the case of NSIs with astrophysical neutrinos, there exist investigations with solar neutrinos, supernova neutrinos, and astrophysical sources of neutrinos. For solar neutrinos and NSIs, one has obtained the following results (i) a sensitivity analysis of NSIs, using data from the Super-Kamiokande and SNO experiments [46], (ii) signature and bounds for NSIs at the Borexino experiment, and (iii) the LENA proposal – a probe for NSIs [47]. For supernova neutrinos, one has obtained the following results (i) a three-flavor analysis for the possibility of probing NSIs [48] and (ii) an interplay between collective effects and NSIs [49, 50]. In addition, for neutrinos from astrophysical sources, one has studied production and detection NSIs of high-energy neutrinos at neutrino telescopes, using neutrino flux ratios [51].

5. Phenomenological bounds on NSIs and sensitivity and discovery reach of NSIs

Phenomenological bounds on NSIs have been determined in the literature. Concerning direct bounds on matter NSIs, the following model-independent bounds on the matter NSI parameters (for the Earth) [52] have been found

$$\left(\begin{array}{ccc} |\varepsilon_{ee}| < 4.2 & |\varepsilon_{e\mu}| < 0.33 & |\varepsilon_{e\tau}| < 3.0 \\ & |\varepsilon_{\mu\mu}| < 0.068 & |\varepsilon_{\mu\tau}| < 0.33 \\ & & |\varepsilon_{\tau\tau}| < 21 \end{array} \right).$$

This means that the bounds on matter NSIs are of the order $10^{-2} \div 10$. Similarly, concerning direct bounds on production and detection NSIs, such bounds have also been obtained, which are of the order 10^{-2} .

In addition, sensitivity and discovery reaches of NSIs have been estimated. Experiments that could find signatures of NSIs are (i) reactor neutrino experiments, (ii) the LHC, and (iii) a future neutrino factory.

6. Summary and conclusions

In this plenary talk, we have discussed NSIs as sub-leading effects to the standard paradigm for neutrino flavor transitions (i.e. neutrino oscillations). Especially, we have investigated production and detection NSIs, including the zero-distance effect, as well as matter NSIs. Moreover, we have studied approximate analytical model-independent mappings between fundamental neutrino parameters and effective NSI parameters as well as approximate two-flavor formulas for neutrino flavor transitions using NSIs. Experimental results of upper bounds on NSIs from the Super-Kamiokande and MINOS collaborations have been presented. So far, no evidence for matter NSIs have been found. However, there are sensitivity reaches of NSIs for accelerators, a future neutrino factory, and the reactor neutrino experiment Daya Bay. So-called mimicking effects play an important role in reactor neutrino experiments, especially for θ_{13} . Thus, one can ask the question: Is the fundamental value for θ_{13} smaller than the measured value? Furthermore, we have presented phenomenological upper bounds on NSIs as well as sensitivity and discovery reach of NSIs (such as for the LHC and a future neutrino factory). In conclusion, it remains to be seen if one can probe NSIs with neutrino experiments or other experiments in the future.

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