

Confusing nonzero θ_{13} with nonstandard interactions in the solar neutrino sector

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Solar and KamLAND data are in slight tension when interpreted in the standard two-flavor oscillations framework and this may be alleviated allowing for a nonzero value of the mixing angle θ_{13} . Here we show that, likewise, nonstandard flavor-changing interactions (FCI), possibly intervening in the propagation of solar neutrinos, are equally able to alleviate this tension and therefore constitute a potential source of confusion in the determination of θ_{13} . By performing a full three-flavor analysis of solar and KamLAND data in presence of FCI we provide a quantitative description of the degeneracy existing between θ_{13} and the vectorial coupling $\epsilon_{e\tau}^{\text{dV}}$ characterizing the nonstandard transitions between ν_e and ν_τ in the forward scattering process with d-type quarks. We find that couplings with magnitude $\epsilon_{e\tau}^{\text{dV}} \sim 10\%$, compatible with the existing bounds, can mimic the nonzero values of θ_{13} indicated by the latest analyses.

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I. INTRODUCTION

After many decades of efforts neutrino oscillations have been definitively identified as the leading mechanism governing the flavor transitions observed in a variety of experimental setups exploiting both natural and artificial sources of neutrinos. In analogy with the quark sector, where the mixing is described by the unitary Cabibbo-Kobayashi-Maskawa matrix, the leptonic mixing is also described by a nontrivial matrix connecting the flavor (ν_α , $\alpha = e, \mu, \tau$) and the mass eigenstate neutrinos (ν_i , $i = 1, 2, 3$). However, it has long been noted [1] that the matrix describing the propagation of light neutrinos is substantially more complex than the quark mixing matrix in that (i) deviations from unitarity may appear and (ii) there are additional CP phases, which have no quark analogue. Here we neglect both. Regarding the first we simply assume that their magnitude is small, as expected in high-scale seesaw schemes¹. It is also well-known that Majorana CP phases affect only lepton-number violating processes [14, 15, 16], and therefore can be neglected when discussing conventional neutrino oscillations.

Hence, for simplicity, here we adopt the unitary approximation for the lepton mixing matrix U describing neutrino oscillations, for which we take the standard factorized parametrization given in [1]

$$U = U(\theta_{23})U(\theta_{13})U(\theta_{12}). \quad (1)$$

as a product of three complex rotations characterized by three mixing angles (θ_{12} , θ_{13} , θ_{23}) and three corresponding CP violating phases, and adopt the ordering prescription of the PDG [17]. There are two Majorana

phases which do not contribute to neutrino oscillations; the Dirac phase is set to zero since current experiments show no sensitivity.

The small mixing angle θ_{13} is still unknown and its measurement constitutes one of the major goals in particle physics, as it will open the door to possible measurements of CP violation in the leptonic sector [18, 19].

Sensitivity studies of *future* experimental setups [20, 21] have evidenced how the identification of θ_{13} can be problematic due to a potential confusion problem which may arise if nonstandard interactions (NSI) are present. These new interactions typically arise in low-scale models of neutrino mass, such as radiative ones [22, 23, 24], in the form of low-energy four-fermion operators $\mathcal{O}_{\alpha\beta} \sim \bar{\nu}_\alpha \nu_\beta \bar{f} f$, inducing either flavor-diagonal ($\alpha = \beta$) or flavor-changing ($\alpha \neq \beta$) neutrino transitions in the forward scattering with the background f fermion [11, 25, 26, 27]. More specifically, flavor-changing interactions (FCI) inducing transitions among ν_e and ν_τ ($\alpha = e$, $\beta = \tau$) have been recognized as an important source of confusion, as they can mimic the effect of nonzero θ_{13} at neutrino factories [20, 21].

The possibility that an analogous difficulty may be *already* present in the interpretation of the *available* neutrino data has not been considered so far. Indeed, in the past years the null result reported by the short-baseline CHOOZ reactor experiment [28] ($\sin^2 \theta_{13} \lesssim \text{few}\%$) was corroborated by the independent findings of the global neutrino data analyses. As a consequence, various works aimed at establishing the (subleading) role of NSI in the neutrino oscillation phenomenology have focused on the well-motivated two-flavor limit, in which $\theta_{13} = 0$ is assumed. Furthermore, none of such analyses have evidenced any significant preference for NSI.

Recently, however, a nonzero value of θ_{13} has been hinted in various analyses [29, 30, 31, 32, 33, 34, 35, 36] of the latest neutrino oscillation data. In particular, all the existing analyses [31, 33, 35] find such a feature in the “solar sector” (solar and KamLAND data), while its

¹ Low-scale seesaw models [2, 3, 4, 5, 6] would provide an exception to this, leading to large flavor and CP violating effects in the charged lepton sector [4, 7, 8, 9, 10], as well as effects in neutrino propagation [11, 12, 13].

presence in the “atmospheric sector” (atmospheric and $\nu_\mu \rightarrow \nu_\mu$ disappearance long-baseline data) is more uncertain, being found in some analyses [31, 34, 36, 37] but not in others [33, 38]. Interestingly, the preliminary searches performed by the Main Injector Neutrino Oscillation Search (MINOS) in the $\nu_\mu \rightarrow \nu_e$ appearance channel [39] seem to support such hints, showing a weak preference for a nonzero value of θ_{13} , just below the upper limit established by CHOOZ.

In view of these hints we deem timely to investigate whether a confusion problem may already exist in the interpretation of the present data. Such an issue seems even more pressing, considering that the clearest hint of nonzero θ_{13} comes from the solar sector, which naturally offers a sensitive setting, where the first signs of NSI may possibly emerge. Indeed, one should note that the “solar” hint of nonzero θ_{13} arises from a tension among the standard interpretation of two-flavor transitions in matter (solar ν 's) — where NSI may intervene — and in vacuum (KamLAND) — where NSI are unimportant. Although the standard 3ν interpretation ($\theta_{13} > 0$) seems the most natural one, the possibility that this tension can be the result of some unknown effect intervening in solar flavor transitions cannot be discarded *a priori*. Here we investigate the possibility that such an effect may result from the theoretically well-motivated FCI, analyzing in detail their impact on the extraction of the estimates of θ_{13} from the presently available data.

The paper is organized as follows. In Sec. II, we review the notation necessary to describe three-flavor transitions in matter in the presence of NSI. In Sec. III, we present the results of our numerical analysis in the framework of 2ν ($\theta_{13} = 0$) and 3ν ($\theta_{13} > 0$) matter transitions in the presence of FCI. We draw our conclusions and discuss future perspectives in Sec. IV.

II. NOTATION

The 3ν evolution in the flavor basis (ν_e, ν_μ, ν_τ) is described by the equation

$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}, \quad (2)$$

where H is the total Hamiltonian,

$$H = H_{\text{kin}} + H_{\text{dyn}}^{\text{std}} + H_{\text{dyn}}^{\text{NSI}}, \quad (3)$$

split as the sum of the kinetic term, the standard MSW (Mikheev-Smirnov-Wolfenstein) matter term [25, 40], and of a new, NSI-induced, matter term [11]. Indicating with U the 3×3 mixing matrix, the kinetic term reads

$$H_{\text{kin}} = U \begin{pmatrix} -\delta k/2 & 0 & 0 \\ 0 & +\delta k/2 & 0 \\ 0 & 0 & k/2 \end{pmatrix} U^\dagger, \quad (4)$$

where E is the neutrino energy and $\delta k = \delta m^2/2E$, $k = m^2/2E$ (δm^2 and m^2 being the “solar” and “atmospheric” neutrino squared mass differences, respectively). The second term $H_{\text{dyn}}^{\text{std}}$ describes the standard (MSW) dynamics in matter [25, 40], and is given by

$$H_{\text{int}}^{\text{std}} = \text{diag}(V, 0, 0), \quad (5)$$

where $V(x) = \sqrt{2}G_F N_e(x)$ is the effective potential induced by the interaction with the electrons with number density $N_e(x)$. The term characterizing the nonstandard dynamics, assuming for definiteness interactions only with d-type quarks, can be cast in the form

$$(H_{\text{dyn}}^{\text{NSI}})_{\alpha\beta} = \sqrt{2}G_F N_d(x)\epsilon_{\alpha\beta}, \quad (6)$$

where $\epsilon_{\alpha\beta} \equiv \epsilon_{\alpha\beta}^{dV}$ are the dimensionless vectorial couplings between neutrinos with flavors (α, β) with d-type quarks having number density $N_d(x)$. In the phenomenological approximation of one-mass-scale dominance,

$$\delta m^2 \ll m^2, \quad (7)$$

we can take the limit $m^2 \rightarrow \infty$, and, similarly to the standard MSW case [41], reduce the 3ν dynamics to an effective 2ν one [42]. In fact, the 3×3 mixing matrix $U(\theta_{12}, \theta_{13}, \theta_{23})$ can be factorized (assuming no CP violating phase) into three real rotations

$$U \equiv R = R(\theta_{23})R(\theta_{13})R(\theta_{12}). \quad (8)$$

Performing a rotation of the initial neutrino (flavor) basis by $R^T(\theta_{13})R^T(\theta_{23})$, and extracting the submatrix with indices (1, 2) one finds that the survival probability of solar electron neutrinos is given by

$$P_{ee} = c_{13}^4 P_{ee}^{\text{eff}} + s_{13}^4, \quad (9)$$

where $s_{ij} \equiv \sin \theta_{ij}$, $c_{ij} \equiv \cos \theta_{ij}$, and P_{ee}^{eff} is the ν_e survival probability in an effective 2×2 model described by the Hamiltonian

$$H^{\text{eff}} = V(x) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2}G_F N_d(x) \begin{pmatrix} 0 & \epsilon \\ \epsilon & \epsilon' \end{pmatrix}, \quad (10)$$

where ϵ and ϵ' are two effective parameters which, considering only FCI [$\alpha \neq \beta$ in Eq. (6)], are related to the original $\epsilon_{\alpha\beta}$ couplings, as [42]

$$\epsilon = c_{13}(\epsilon_{e\mu}c_{23} - \epsilon_{e\tau}s_{23}) - s_{13}[\epsilon_{\mu\tau}(c_{23}^2 - s_{23}^2)], \quad (11)$$

$$\begin{aligned} \epsilon' = & -2\epsilon_{\mu\tau}c_{23}s_{23} + 2s_{13}c_{13}(\epsilon_{e\tau}c_{23} + \epsilon_{e\mu}s_{23}) \\ & - 2s_{13}^2\epsilon_{\mu\tau}s_{23}c_{23}. \end{aligned} \quad (12)$$

Considering we are interested in only the FCI between ν_e and ν_τ , we then remain with the expressions

$$\epsilon = -\epsilon_{e\tau}c_{13}s_{23}, \quad (13)$$

$$\epsilon' = +2\epsilon_{e\tau}s_{13}c_{13}c_{23}. \quad (14)$$

Therefore the propagation of solar neutrinos can be described effectively by a two-dimensional evolution Hamiltonian, which depends on the five parameters ($\delta m^2, \theta_{12}, \theta_{13}, \theta_{23}, \epsilon_{e\tau}$).

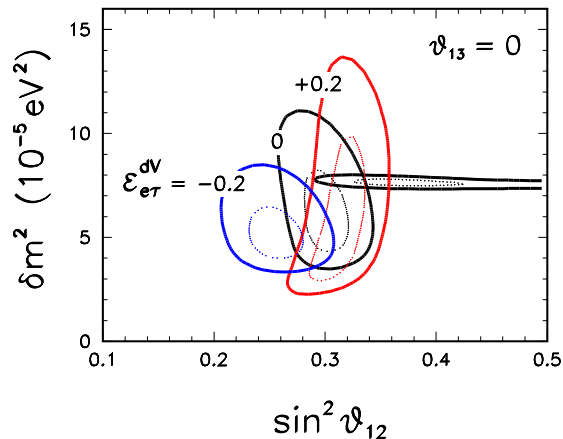


FIG. 1: The solar LMA region is represented at two C.L.’s [$\Delta\chi^2 = 1$ (thin dashed line) and $\Delta\chi^2 = 4$ (thick solid line)] for the standard case ($\epsilon_{e\tau}^{dV} = 0$) and for two representative nonstandard cases with FCI having equal amplitude and opposite sign ($\epsilon_{e\tau}^{dV} = \pm 0.2$). The horizontally elongated regions are those allowed by KamLAND (at the same C.L.’s) which do not depend on FCI.

III. NUMERICAL RESULTS

In our analysis we have included the data from the radiochemical experiments Homestake [43], SAGE [44] and GALLEX/GNO [45, 46, 47], Super-KamioKande [48], from all the three phases of the Sudbury Neutrino Observatory (SNO) [49, 50, 51, 52], and Borexino [53]. We have also included the latest KamLAND data [54]. For the sake of precision, we have incorporated both standard and nonstandard matter effects in KamLAND. However, due to the low density of the Earth’s crust, both have only a negligible effect for the range of parameters we are considering. Therefore, the constraints obtained on KamLAND do not depend on NSI. We also included NSI effects in the propagation of solar neutrinos in the Earth which, as noted in [55], can modify the regeneration effect.

We begin our study considering the more familiar two-flavor case ($\theta_{13} = 0$) in which the results of our analysis depend on the three parameters: $(\delta m^2, \theta_{12}, \epsilon_{e\tau})$. Indeed, we can safely assume $\sin^2 \theta_{23} = 1/2$, motivated by the results of the latest atmospheric neutrino data analyses, which indicate maximal [33] or nearly maximal [32, 56] mixing. In Fig. 1 we show the region allowed by KamLAND (horizontally elongated region) in the plane spanned by the standard oscillation parameters $[\delta m^2, \sin^2 \theta_{12}]$, superimposed to the solar large mixing angle (LMA) region of oscillation parameters obtained in the absence of FCI ($\epsilon_{e\tau} = 0$), and for two representative cases in which FCI are “switched on,” with couplings having the same amplitude but opposite sign ($\epsilon_{e\tau} = \pm 0.2$). The most important clue we have from this plot is the shift of the solar LMA region in the horizontal direction

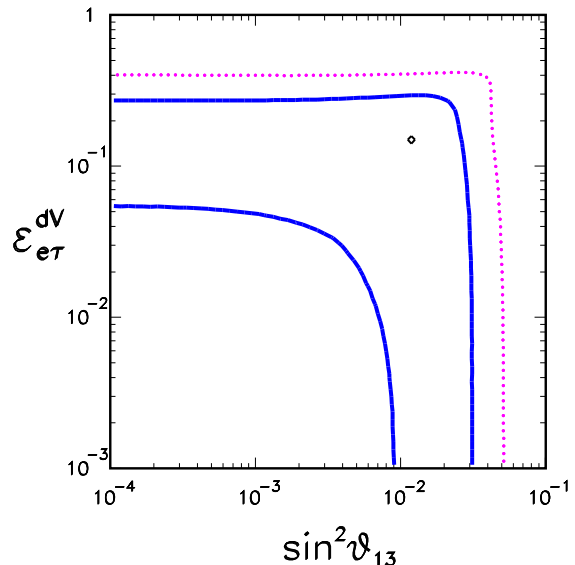


FIG. 2: Region allowed by the combination of solar and KamLAND data at two C.L.’s [$\Delta\chi^2 = 1$ (solid line) and $\Delta\chi^2 = 4$ (dashed line)] after marginalization of δm^2 and θ_{12} .

in correspondence of the (phenomenologically relevant) values of δm^2 determined by KamLAND. Indeed, the solar LMA region “moves” towards higher (lower) values of θ_{12} , for positive (negative) values of $\epsilon_{e\tau}$. From Fig. 1, it is clear that positive values of $\epsilon_{e\tau}$ tend to reduce the tension between solar and KamLAND and are preferred in the solar+KamLAND combination, which gives $\epsilon_{e\tau} \simeq 0.15$ as best fit and disfavors the standard case ($\epsilon_{e\tau} = 0$) at $\sim 1.3\sigma$ level ($\Delta\chi^2 \sim 1.7$).

These results strongly suggest that positive values of $\epsilon_{e\tau}$, with size compatible with current limits [57], can mimic the effect of nonzero θ_{13} . Notice, however, that in the standard 3ν analysis *both* the solar LMA region and the region allowed by KamLAND in the plane $[\delta m^2, \sin^2 \theta_{12}]$ get modified by values of $\theta_{13} > 0$, for which they tend to merge [29, 30, 31, 33, 35]. In contrast, in the case under consideration, only the solar LMA region is affected.

In order to trace more quantitative conclusions it is necessary to perform a full $3\nu + \text{FCI}$ analysis, where both θ_{13} and $\epsilon_{e\tau}$ are allowed to assume nonzero values. In Fig. 2 we display the main result of such an analysis, by showing the constraints (at $\Delta\chi^2 = 1, 4$) obtained from the combination of solar and KamLAND, in the plane of the two relevant parameters $[\sin^2 \theta_{13}, \epsilon_{e\tau}]$, after marginalization over the remaining parameters δm^2 and $\sin^2 \theta_{12}$. We display only the region corresponding to positive values of $\epsilon_{e\tau}$, which are relevant for the degeneracy problem under study. One sees that, at low confidence levels the preferred region is a band (delimited by the solid curves) which does not contain the origin (“disfavored” at $\Delta\chi^2 \simeq 2.0$). The slight tension among solar and KamLAND gets effectively diluted among the two parameters θ_{13} and $\epsilon_{e\tau}$. For higher confidence levels (dotted curve), the allowed region does contain the

origin and only upper limits can be put on both parameters. These results allow us to conclude that a complete degeneracy between the two parameters is present in the current neutrino data.

The question arises as to whether and how future data may remove such a degeneracy. With this purpose, in Fig. 3 we show the behavior of the solar ν_e survival probability (averaged over the ${}^8B\nu$ production region) profile $P_{ee}(E)$, for three representative cases. In all of the three cases presented the probability is calculated for the fixed values of the leading parameters ($\delta m^2 = 7.67 \times 10^{-5} \text{eV}^2$, $\sin^2 \theta_{12} = 0.3$). The three curves correspond to the following cases: (I) The solid line represents the case of pure 2ν standard transitions ($\theta_{13} = 0$, $\epsilon_{e\tau} = 0$), corresponding to the origin in Fig. 2; (II) The dashed line indicates a representative case of standard 3ν transitions ($\sin^2 \theta_{13} = 0.02$, $\epsilon_{e\tau} = 0$); (III) The dotted line shows a representative case of $2\nu + \text{FCI}$ transitions ($\theta_{13} = 0$, $\epsilon_{e\tau} = 0.1$).

As one can infer from Fig. 2, cases (II) and (III) have been chosen so as to correspond to (currently) indistinguishable points in parameter space. With respect to case (I), regarded as a benchmark, we note the following differences between the two degenerate cases, (II) and (III). In the standard 3ν case (dashed line) P_{ee} is suppressed with respect to the standard 2ν case (solid line) by the energy independent factor $\sim 1 - 2 \sin^2 \theta_{13}$ [see Eq. (9)]. In contrast, the $2\nu + \text{FCI}$ case (dotted line), is characterized by an energy-dependent suppression² respect to the standard 2ν case. In particular, the suppression is completely negligible at low energies ($E < 3 \text{ MeV}$), and it is more pronounced at intermediate energies. The net effect is a flattening of $P_{ee}(E)$ with an enhancement of the up-turn typical of the adiabatic MSW transitions.

The current data are unable to distinguish between case (II) and (III) since: (i) the differences at low energies are too small to be detected by the gallium experiments or Borexino; (ii) the current high energy experiments are not sensitive enough to probe the up-turn region, which still remains practically “invisible.” The differences at low energy between the two degenerate cases, (II) and (III), are very tiny and may prove very hard to detect even at future low-energy experiments. Instead, the possibility to disentangle the different behavior at intermediate energies could perhaps become realistic in high-energy experiments with a lowered threshold. In this respect, the new data expected from Borexino, Super-K-III [58], and from the low energy threshold analysis underway in the SNO collaboration [59], may play an important role.

We close this section with a final remark. For definiteness, we have focused on the case of interactions with d-type quarks and transitions among ν_e and ν_τ . However, the essence of our conclusions is unaltered if interactions

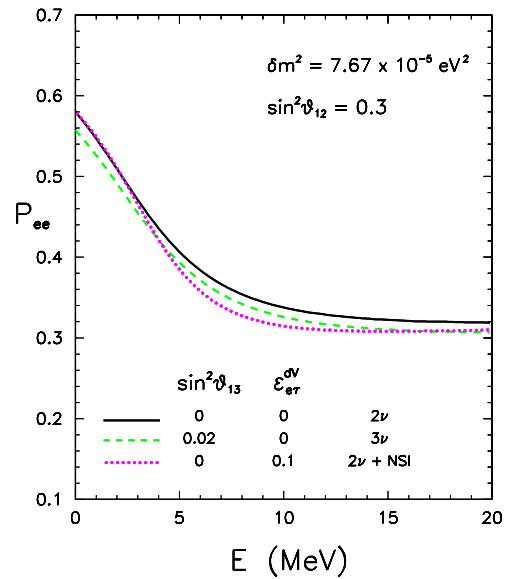


FIG. 3: Solar ν_e survival probability (averaged over the ${}^8B\nu$ production region) for three representative cases.

with u-type quarks or electrons and/or transitions among ν_e and ν_μ ($\alpha = e, \beta = \mu$) are considered. Moreover, the simultaneous inclusion of more than one type of NSI can only exacerbate the confusion problem we have posed, leading to further difficulties in data interpretation.

IV. CONCLUSIONS

We have stressed that nonstandard flavor-changing interactions may constitute a source of confusion in the interpretation of *present* solar and KamLAND neutrino data, hindering the correct determination of the mixing angle θ_{13} . In the near future, various solar experiments may help to reduce such a difficulty by providing a more precise determination of the energy profile of the solar ν_e survival probability. In the mean time, it would be very important to complement our study — focused on the solar sector — with a similar investigation on the atmospheric sector, which could hopefully be of aid in breaking the degeneracy among θ_{13} and $\epsilon_{e\tau}$. Also, a quantitative assessment of the impact of nonstandard neutrino interactions in the interpretation of the preliminary MINOS data in the $\nu_\mu \rightarrow \nu_e$ appearance channel [39] would be highly desirable. Our results underline the importance of a “clean” measurement of θ_{13} expected from the new generation reactor experiments [60], whose inferences are free from NSI effects. We also stress how, in the event of a null result by these experiments (i.e., in the case of nonconfirmation of the present hints of nonzero θ_{13}), a persisting tension among solar and KamLAND would pose a novel problem, whose resolution may involve the nonstandard interactions discussed here or other possible

² A similar behavior has been noticed in [55].

unaccounted effects.

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