Constraining nonstandard neutrino-quark interactions with solar, reactor and accelerator data

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Abstract. We present an analysis of nonstandard neutrino interactions (NSI) of electron and tau neutrinos with down-quark using solar, reactor and accelerator data. We include new solar data from SNO phase III and Borexino, as well as new KamLAND data and solar fluxes. We combine these results with the CHARM data allowing us to better constrain the axial and axial-vector electron and tau-neutrino NSI parameters.

1. Introduction
Current solar neutrino data, in conjunction with reactor data from the KamLAND experiment show that the neutrino oscillation mechanism is the correct picture to explain the solar neutrino physics. Solar neutrino experiments are also sensitive to matter effects, and the combination of both solar and KamLAND data determines the so-called Large Mixing Angle (LMA) solution as the correct explanation to the data. The different cases involving nonstandard effects can only play a subleading role.

However, while constrained by the solar and KamLAND data in an important way, neutrino nonstandard interactions (NSI) still provide an important exception to the robustness of the neutrino oscillation interpretation. Indeed, it has been found that they might even shift the solution to the so-called dark side region of the neutrino parameter space [1].

In what follows we are going to analyze the robustness of the oscillation interpretation of the solar neutrino data in the presence of nonstandard interactions (NSI) using the next effective low-energy neutral currents four-fermion operator:

\[ L_{\text{NSI}} = -\epsilon_{\alpha\beta}^{f\bar{f}} \sqrt{2} G_F \left( \bar{\nu}_\alpha \gamma_\mu L \nu_\beta \right) (\bar{f} \gamma^\mu P f) \]  

where \( P = L, R \) and \( f \) is a first generation fermion: \( e, u, d \). The coefficients \( \epsilon_{\alpha\beta}^{f\bar{f}} \) denote the strength of the NSI between the neutrinos of flavours \( \alpha \) and \( \beta \) and the \( P \)-handed component of the fermion \( f \). For definiteness, we take for \( f \) the down-type quark. However, one can also consider the presence of
NSI with electrons and up and down quarks simultaneously. Here we confine ourselves to NSI couplings involving only electron and tau neutrinos.

Nonstandard interactions may in principle affect neutrino propagation properties in matter as well as detection cross sections. NSI effects in neutrino propagation affect the analysis of data from solar neutrino experiments and to some extent also KamLAND, through the vectorial NSI couplings $\varepsilon^{\alpha\beta}_{\text{eff}} = \varepsilon^{\alpha\beta}_{\text{el}} + \varepsilon^{\alpha\beta}_{\text{dr}}$. On the other hand, detection shows sensitivity also to the axial NSI couplings $\varepsilon^{\alpha\beta}_{\text{eff}} = \varepsilon^{\alpha\beta}_{\text{el}} - \varepsilon^{\alpha\beta}_{\text{dr}}$ in the SNO experiment.

2. Effects of NSI in neutrino propagation

We first analyze the determination of the oscillation parameters in the presence of nonstandard interactions. The Hamiltonian describing solar neutrino evolution in the presence of NSI contains, in addition to the standard oscillations term, a term involving NSI, accounting for an effective potential induced by the NSI with matter:

$$H_{\text{vac}} = \begin{pmatrix} \frac{\Delta m^2}{2E} \cos 2\theta & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} + H_{\text{mat}} = \sqrt{2} G_F N_c \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + H_{\text{NSI}} = \sqrt{2} G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon' & \varepsilon \end{pmatrix} \quad (2)$$

Here $\varepsilon$ and $\varepsilon'$ are two effective parameters related with the vectorial components of NSI which affect the neutrino propagation by:

$$\varepsilon = -\sin \theta_{23} \varepsilon^{\alpha\beta}_{\text{el}} \quad \varepsilon' = \sin \theta_{23} \varepsilon^{\alpha\beta}_{\text{ax}} - \varepsilon^{\alpha\beta}_{\text{el}}$$

The quantity $N_d$ is the density of the down-type quark along the neutrino path, and $\theta_{23}$ is the atmospheric neutrino mixing angle.

In the adiabatic regime the survival probability can be approximated by Parke’s formula [1]:

$$P(\nu_e \to \nu_e) = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m] \quad (4) \Rightarrow \cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2 \sqrt{2} E G_F N_c}{[\Delta m^2]_{\text{matter}}} \quad (5)$$

$$[\Delta m^2]_{\text{matter}} = \sqrt{[\Delta m^2 \cos 2\theta - 2 \sqrt{2} E G_F (N_e - \varepsilon N_d)]^2 + [\Delta m^2 \sin 2\theta + 4 \sqrt{2} E G_F N_d]^2} \quad (6)$$

where $\theta_m$ is the effective mixing angle at the neutrino production point inside the sun. In this case we have already introduced NSI in addition to oscillations.

Using data from solar experiments as Chlorine, Super-K spectrum, SAGE, SNO day/night, SNO salt data and combining them with KamLAND reactor experiment we obtain the figure 1 [1] where NSI are included. As we can see the presence of NSI will lead to the appearance of the LMA-D solution and thus to the ambiguous determination of the solar mixing angle.

2.1. Updating data

In a new analysis we have included for the solar data the most updated results from the radiochemical experiments Homestake, SAGE, and GALLEX/GNO, the zenith-spectra data set from Super-Kamiokande I, and the two first phases of SNO.

As main updates have been included:

- The third phase of SNO.
- The latest measurements of the $^7$Be solar neutrino rate performed by Borexino.
Figure 1: Allowed regions for the generalized OSC + NSI case, determined from previous data (2006): left panel correspond to a solar only analysis, while the right panel corresponds to solar+KamLAND.

- The fluxes of the latest version of SSM: BPS08 high metallicity.
- The latest data from KamLAND reactor experiment.

Combining again solar + KamLAND we obtain the result shown in the figure 2 [2]. One can see that the region in the so-called dark side of the neutrino parameters remains even after the inclusion of the new data. Note however that its status is worse than previously. In contrast, as seen in the figure 2, the other solutions LMA-0 and LMA-II [1], which were present before, have disappeared as a result of the new KamLAND data, that now provide a very precise measurement of $\Delta m^2$.

By analyzing the goodness of the neutrino oscillation solutions in the presence of NSI we can also constrain the NSI parameters $\varepsilon$ and $\varepsilon'$:

$$-0.41 < \varepsilon < 0.06$$

$$-0.50 < \varepsilon < 0.19 \quad \& \quad 0.89 < \varepsilon' < 0.99$$

We can see that the new data allow us to constrain $\varepsilon$, the flavor changing parameter, while for the flavor conserving case there is still room for relatively large values $\varepsilon'$ that correspond to the solution in the dark side of the neutrino oscillation parameters.

For the flavor-changing parameter $\varepsilon$ we can use the Eq. (3) and the Eq.(7) in order to obtain a limit over the vectorial coupling $\varepsilon_{\tau e}^{\alpha 

$$-0.08 < \varepsilon_{\tau e}^{\alpha} < 0.58 \quad (90\% \text{ C.L.})$$

where we have used the best fit value for the atmospheric mixing angle [1].
Figure 2: The left bottom panel indicates 90%, 95% and 99% C.L. allowed regions from the solar and solar + KamLAND combined analysis, which is presented as a zoom in the top right panel, where the shaded regions show the result of the current analysis while the lines indicate the earlier region [1]. The other two panels indicate the corresponding $\chi^2$.

3. Effects of NSI in neutrino detection

The presence of NSI can also affect the detection processes at some experiments. In particular, the cross section for the neutral current detection reaction at SNO is proportional to $g_A^2$, which is the coupling of the neutrino current to the axial isovector hadronic current, giving an extra contribution to the NC signal at SNO experiment. This nonstandard contribution can be parameterized as:

$$\phi_{NC} = f_B (1 + 2 \varepsilon_A) \quad (10) \quad \Rightarrow \quad \varepsilon_A = - \sum_{\alpha=e,\mu,\tau} \langle P_{\alpha\alpha} \rangle_{NC} \varepsilon_A^{dA} \quad (11)$$

where $f_B$ is the boron neutrino flux and the nonstandard axial couplings with up-type quark are set to zero.

The results obtained in a generalized 5-parameters analysis including the axial component of NSI are summarized in the figure 3 [2]. We can observe that the previous analysis (Sec. 2) without axial component and the present analysis are consistent, thought, as expected, the inclusion of the axial parameter in the analysis extends the allowed region.
Figure 3: The shaded regions of the left panel show the updated analysis including the axial parameter combining solar+KamLAND while the lines show the updated regions obtained only with vectorial NSI couplings. In the right panel we show $\chi^2 - \varepsilon_A$ where we can see how the data prefer $\varepsilon_A = 0$.

From the $\chi^2$ analysis we obtain the following allowed range at 90% C.L.

$$-0.14 < \varepsilon_A < 0.06 \quad (12)$$

4. Constraints on non-universal NSI: CHARM+solar+KamLAND

Laboratory experiments measuring neutrino-nucleon scattering show sensitivity to neutrino NSI on d-type quarks. In particular, here we will combine the results of the accelerator experiment CHARM together with the ones in Sec. 2 in order to obtain stronger constraints on the NSI parameters focusing our analysis on the flavor-conserving NSI couplings.

The regions for the vector (left) and axial-vector (right) NSI couplings allowed by the global analysis are given in the figure 4 [2], where they are also compared with the constraints coming only from the CHARM analysis (vertical bands in Fig. 4 [2]) and that from solar+KamLAND analysis (diagonal band in the Fig. 4 [2]).

In the vectorial case we can appreciate the existence of two allowed islands corresponding to the usual LMA solution (lower one) and to the dark solution (upper one). On the other hand, using the average probabilities reported by SNO [2] we have reanalyzed the results obtained for the effective axial coupling $\varepsilon_A$ in Eq. (12) obtaining a constraint in the axial couplings $\varepsilon_{ee}^{da}$ and $\varepsilon_{\tau\tau}^{da}$. The results are summarized in the table I.

5. Conclusions

The neutrino oscillation interpretation of solar neutrino data is still fragile in the presence of NSI.

We have updated the solar NSI analysis using new data from SNO-III, Borexino, KamLAND and solar fluxes but the dark solution (LMA-D) still survives, while the previous LMA-0 and LMA-II have disappeared as a result of new data.

Further information relevant to lift the degeneracy may come from atmospheric and laboratory data. Indeed the LMA-D solution may become inconsistent with atmospheric and laboratory data [1] but new improved data will be needed.
In summary, we have studied the limits on the NSI couplings combining solar, KamLAND (reactor experiment) and CHARM (accelerator experiment) and we have obtained improved bounds on the vector and axial parameters involving electron and tau neutrino on down-type quarks.

**Figure 4:** Constraints on the vector (left panel) and axial-vector (right panel) NSI coupling from our global analysis at 90%, 95% and 99% C.L.

| Present results | Previous results |
|-----------------|------------------|
| **Vectorial couplings** | | |
| Global | $-0.5 < \epsilon_{ee}^{dV} < 1.2$ | $-1.8 < \epsilon_{ee}^{dV} < 4.4$ | |
| CHARM | $-0.5 < \epsilon_{ee}^{dV} < 1.2$ | | |
| Global | $-0.2 < \epsilon_{ee}^{dV} < 0.5$ | $-1.1 < \epsilon_{\tau\tau}^{dV} < 0.4 \& 1.6 < \epsilon_{ee}^{dV} < 2.2$ | $-0.9 < \epsilon_{ee}^{dV} < 0.8$ | $-2.7 < \epsilon_{\tau\tau}^{dV} < 2.7$ |
| **Axial couplings** | | | |
| Global | $-0.4 < \epsilon_{ee}^{dA} < 1.4$ | $-1.5 < \epsilon_{ee}^{dA} < 0.7$ | |
| CHARM | $-0.4 < \epsilon_{ee}^{dA} < 1.4$ | | |
| Global | $-0.2 < \epsilon_{ee}^{dA} < 0.3$ | $-0.2 < \epsilon_{\tau\tau}^{dA} < 0.4$ | $-0.8 < \epsilon_{ee}^{dA} < 0.9$ | $-1.8 < \epsilon_{\tau\tau}^{dA} < 1.8$ |

**Table I:** New constraints on the vectorial and axial NSI couplings at 90% C.L. obtained from the CHARM data alone and combining it with solar+KamLAND data.

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**References**
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