Testing light sterile neutrino species with the Sun

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Abstract. Several pieces of data seem to point towards new light sterile neutrino species. Here we show that the solar sector is able to provide stringent constraints on the most general schemes endowed with such new particles.

1. Introduction

The emergence of new anomalies observed in very-short baseline (VSBL) setups [1, 2] and in cosmological data analyses [3] has refueled both theoretical and experimental interest towards light sterile neutrino species. These new states are commonly introduced in the so-called $3+s$ schemes, where the $s$ new mass eigenstates are separated from the three standard ones by large splittings, and have small admixtures with the three standard “active” flavors.

In principle, the solar sector (solar data and KamLAND) offers a sensitive probe of the admixture of the new sterile species with the electron neutrino. However, all the existing analyses have been performed in the framework first developed in [4] of pure ($\nu_1, \nu_2$)-driven oscillations, which neglects the possible mixing of the electron neutrino with the third standard mass eigenstate ($U_{e3} = 0$) and with a new fourth one ($U_{e4} = 0$). In [5] we have recently extended the treatment of the MSW transitions to the most general case. This theoretical step allowed us to exploit the full potential of the solar sector dataset, deriving from its analysis quantitative constraints on the amplitude of the matrix element $U_{e4}$. Here we only report on the basic results of such a numerical analysis, referring the reader to the original work [5] for the relevant theoretical aspects.

2. Parameterization of the lepton mixing matrix

In the presence of a fourth sterile neutrino $\nu_s$, the flavor ($\nu_\alpha, \alpha = e, \mu, \tau, s$) and the mass eigenstates ($\nu_i, i = 1, 2, 3, 4$), are connected through a $4 \times 4$ unitary mixing matrix $U$, which depends on six complex parameters [6]. Such a matrix can thus be expressed as the product of six complex elementary rotations, which define six real mixing angles and six CP-violating phases. Of the six phases three are of the Majorana type and are unobservable in oscillation processes, while the three remaining ones are of the Dirac type. For simplicity, we set to zero all the Dirac phases referring the reader to [5] for comments on the potential sensitivity of the solar data to them.

For the treatment of the solar MSW transitions under study, it is convenient to parameterize the mixing matrix as

$$U = R_{23} R_{24} R_{34} R_{14} R_{13} R_{12}$$  (1)
where $R_{ij}$ represents a real $4 \times 4$ rotation in the $(i, j)$ plane. In such a parameterization, the elements involving the electron neutrino take the explicit expressions

\begin{align}
U_{e1} &= c_{14} c_{13} c_{12}, \\
U_{e2} &= c_{14} c_{13} s_{12}, \\
U_{e3} &= c_{14} s_{13}, \\
U_{e4} &= s_{14},
\end{align}

where $c_{ij} \equiv \cos \theta_{ij}$, $s_{ij} \equiv \sin \theta_{ij}$. In the numerical analysis we are going to present, we shall limit ourselves to the simple case $\theta_{24} = \theta_{34} = 0$. In this case, the following simple expressions hold for the mixing matrix elements involving the sterile flavor

\begin{align}
U_{s1} &= -s_{14} c_{13} c_{12}, \\
U_{s2} &= -s_{14} c_{13} s_{12}, \\
U_{s3} &= -s_{14} s_{13}, \\
U_{s4} &= c_{14}.
\end{align}

Therefore, for small values of $\theta_{13}$, the new mixing angle $\theta_{14}$ induces a non-zero admixture $U_{e4}$ of the electron neutrino with the fourth state and a non-null sterile content of the $(\nu_1, \nu_2)$ “doublet”, while leaving the flavor composition of $\nu_3$ almost unaltered with respect to the standard case ($U_{e3} \sim 0$).

### 3. Numerical results

In our analysis we have included all the available solar and KamLAND data. For definiteness, we have adopted the new improved reactor flux determinations [7]. In all numerical computations we have set $\theta_{24} = \theta_{34} = 0$. Therefore, the parameter space spanned by our analysis involves the solar mass-splitting $\Delta m^2_{12}$ and the three mixing angles ($\theta_{12}, \theta_{13}, \theta_{14}$).

We start our numerical study considering the familiar three-flavor case ($\theta_{13} \neq 0, \theta_{14} = 0$), in which the results of the analysis depend on the three parameters ($\Delta m^2_{12}, \theta_{12}, \theta_{13}$). In the left panel of Fig. 1 we show the region allowed by solar (S) and KamLAND (K) in the plane spanned by the two mixing angles, having marginalized away the solar mass splitting in the region determined by KamLAND. As first noticed in [8], for $\theta_{13} > 0$ the values of the mixing angle $\theta_{12}$ identified by the solar and KamLAND experiments are in better agreement due to the opposite-leaning correlations exhibited by their respective contours, giving rise to an enhanced preference for non-zero $\theta_{13}$ in their combination (right panel). We find that the 2-flavor case ($\theta_{13} = 0$) is disfavored at the 1.8$\sigma$ level (which is reduced to 1.3$\sigma$ using the old reactor fluxes).

As a second step we switch on only the mixing angle $\theta_{14}$, setting $\theta_{13} = 0$. In this case, the results of the analysis depend on the three parameters ($\Delta m^2_{12}, \theta_{12}, \theta_{14}$), whose allowed regions are displayed in Fig. 2. KamLAND cannot distinguish $\theta_{13}$ from $\theta_{14}$ and, as a result, the region identified by such an experiment is identical to that found in the 3-flavor case. In contrast, the region determined by the solar data is slightly different from the corresponding one identified in the 3-flavor case. Furthermore, the following small differences appear between the two cases in the global combination: I) A weaker upper bound on $\theta_{14}$ ($s_{14}^2 < 0.089$ at the 2$\sigma$ level) with respect to that obtained for $\theta_{13}$ ($s_{13}^2 < 0.070$ at the 2$\sigma$ level); II) A slightly bigger best fit value for $\theta_{14}$ ($s_{14}^2 = 0.041$) with respect to that obtained for $\theta_{13}$ ($s_{13}^2 = 0.033$).

As a third step, we have switched on both mixing angles ($\theta_{13} \neq 0, \theta_{14} \neq 0$). In Fig. 3 we show the region allowed by the combination of solar and KamLAND data in the plane spanned by such two parameters, having marginalized away both the mass splitting $\Delta m^2_{12}$ and the mixing angle $\theta_{12}$. From this plot we see that there is a complete degeneracy among the two parameters.
In practice, this dataset is basically sensitive to the combination $U_{e3}^2 + U_{e4}^2$, the small deviations from this behavior being induced by the SNO neutral current measurement (see [5]). Therefore, the solar sector data, while indicating a weak preference for non-zero admixture of the electron neutrino with the “far” mass eigenstates $\nu_3$ and $\nu_4$, cannot distinguish between them.

4. Conclusions
Working in a CPT-conserving 3+1 scheme, we have considered the constraints attainable from the solar sector data on the admixture of the electron neutrino with a fourth sterile neutrino.
Figure 3. Region allowed in the [$\sin^2 \theta_{13}, \sin^2 \theta_{14}$] plane.

species. Our quantitative analysis shows that such data are able to constrain the amplitude of the lepton mixing matrix element $U_{e4}$, with a sensitivity comparable to that achieved on the standard matrix element $U_{e3}$. In addition, our analysis evidences that, in a 4-flavor framework, the current preference for $|U_{e3}| \neq 0$ is indistinguishable from that for $|U_{e4}| \neq 0$, having both a similar statistical significance, which is $\sim 1.3\sigma$ adopting the old reactor fluxes determinations, and $\sim 1.8\sigma$ using their new estimates.

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References

[1] Mention G et al. 2011 Phys. Rev. D 83, 073006
[2] Abdurashitov J N et al. 2006 Phys. Rev. C 73, 045805
[3] Hamann J, Hannestad S, Raffelt G G, Tamborra I and Wong Y Y Y 2010 Phys. Rev. Lett. 105, 181301
[4] Dooling D, Giunti C, Kang K, Kim C W 2000 Phys. Rev. D 61, 073011
[5] Palazzo A 2011 Phys. Rev. D 83, 113013
[6] Schechter J and Valle J W F 1980 Phys. Rev. D 22, 2227
[7] Mueller T A et al. 2011 Phys. Rev. C 83, 054615
[8] Fogli G L, Lisi E, Marrone A, Palazzo A and Rotunno A M 2008 Phys. Rev. Lett. 101, 141801