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Estimate of θ_{14} independent of the reactor antineutrino flux determinations

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In a previous paper [Phys. Rev. D **83**, 113013 (2011)] we have shown that the solar sector data (solar and KamLAND) are sensitive to the parameter θ_{14}, encoding the admixture of the electron neutrino with a fourth (essentially) sterile mass eigenstate. In that work we evidenced that such data prefer a nonzero value of θ_{14} and that such a preference is completely degenerate with that of nonzero θ_{13}. In this Report we show how the evidence of $\theta_{13} > 0$, recently emerged from global neutrino data analyses, lifts such a degeneracy and disfavors the case of sterile neutrino mixing. By excluding from our analysis the total rate information coming from the reactor experiments we untie our results from any assumption on their flux normalization. In this way, we establish the robust upper bound $\sin^2\theta_{14} < 0.04$ at the 90% C.L.

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In a recent paper [1] we introduced the theoretical framework needed to describe solar neutrino oscillations within the so-called $3 + s$ schemes endowed with s new sterile neutrinos (see also [2]). In the same work, we considered the constraints attainable within such schemes from the "solar sector" (solar and KamLAND data) showing that this data set, while preferring a non-null admixture of the electron neutrino with mass eigenstates far from the solar (ν_1, ν_2) doublet, is currently unable to distinguish if such a mixing is realized with the third standard mass eigenstate ν_3 or with new ones ($\nu_{3+1}, \ldots, \nu_{3+s}$). In the simplest 3 + 1 framework, this ambiguity translates into a degeneracy of the estimates of the standard mixing angle θ_{13} and the new angle θ_{14} (see [1] for the details of the parametrization of the lepton mixing matrix).

After publication of [1] new data were released that are relevant to the analysis therein performed. In particular, the long-baseline (LBL) accelerator experiments Tokai-to-Kamioka (T2K) [3] and the Main Injector Neutrino Oscillation Search (MINOS) [4] both evidenced a phenomenon of $\nu_\mu \to \nu_e$ conversion. Moreover, the reactor experiment Double-CHOOZ (D-CHOOZ) [5], currently operating only with the far detector, found an indication of $\nu_e \to \nu_e$ disappearance. These findings, if interpreted within the standard 3-flavor framework, point toward a nonzero value of θ_{13}, in line with the first indications arising from global neutrino data analysis [6] (see also [7,8]). In fact, with the inclusion of the new crucial piece of information, an updated global neutrino data analysis [9] (see also [10,11]) provides[1] evidence of $\theta_{13} > 0$ at more than 3σ.

[1]The analyses in [9,10] do not incorporate the D-CHOOZ result, whose inclusion would further reinforce the evidence of nonzero θ_{13} therein established. A preference for $\theta_{13} > 0$ around the 3σ level has been shown also in the analysis performed in [11], which includes D-CHOOZ (together with MINOS and T2K), but not the solar and atmospheric data.

This new circumstance prompts us to improve the analysis performed in [1], in order to determine how it is affected by the new critical experimental information. Substantial changes with respect to the results presented in [1] are expected. In fact, due to the strong anticorrelation existing among the two mixing angles θ_{13} and θ_{14}, the clear preference now emerged for a nonzero value of one of the two parameters (θ_{13}) should drastically reduce the likelihood of the other one (θ_{14}) to be different from zero. Quantifying such a qualitative expectation appears particularly urgent in view of the numerous ongoing projects of new experimental setups aimed at testing potential oscillations into sterile neutrinos (see, for example, [12–20]).

The new landscape brings us to adopt a more conservative approach with respect to that espoused in [1], as here our prime aim is to establish a robust estimate of θ_{14} independent of any assumption on the determinations of the reactor antineutrino fluxes. Indeed, their recent recalculations [21,22], indicating an upward shift of about 3% with respect to previous estimates, have not only refueled the interest around sterile neutrinos, but have also engendered an intense debate around possible systematic uncertainties, being common opinion that these may not be entirely under control. Keeping this issue in mind, we treat the reactor data in a special way, minimizing the impact of the systematic uncertainties affecting the antineutrino fluxes. More specifically, in both the short-baseline reactor experiments (CHOOZ and D-CHOOZ) and the long-baseline ones (KamLAND), we will ignore the (flux dependent) *total rate* information, considering only the one provided by the energy *spectral shape*.

This stratagem, although slightly limiting the constraining power of the analysis, will render its results particularly robust. In fact, as discussed in [1], the KamLAND analysis is quite sensitive to the reactor flux normalization. In particular, the indication in favor of nonzero θ_{13} (or θ_{14}) arising from the solar sector fluctuates between 1.3σ and 1.8σ, adopting, respectively, the old or the new (higher) fluxes [1]. As a rule of thumb, we verified that an upward (downward) 1% shift of the reactor fluxes corresponds to a 0.15σ increase (decrease) in the statistical significance of the preference for a nonzero electron neutrino mixing with ν_3 (or ν_4). By removing the KamLAND total rate information from the analysis, we eliminate any dependency on the reactor flux normalization. In practice, with this procedure, the mixing angles θ_{13} and θ_{14} (and to a large extent also the "solar" mixing angle θ_{12}) are basically constrained by the solar data augmented[2] by the knowledge of the solar squared-mass difference $\Delta m^2_{\rm sol}$, whose high-precision determination is preserved by retaining the KamLAND spectral shape information.

Analogous considerations apply to the CHOOZ and D-CHOOZ experiments. Also in this case more (less) disappearance, and thus a preference of larger (smaller) values of θ_{13} or θ_{14}, is driven by higher (lower) reactor fluxes. Differently from KamLAND, however, the spectral information does not give any information on the relevant (atmospheric) mass splitting $\Delta m^2_{\rm atm}$, this being independently determined by the LBL $\nu_\mu \to \nu_\mu$ disappearance searches performed at accelerators. It should be stressed that, in principle, the CHOOZ and D-CHOOZ spectral information could distinguish between the ν_3-driven (distorted) and ν_4-driven (undistorted[3]) oscillated spectra, but its impact is negligible in practice since the expected distortions are very small (see "Analysis C" in [24]). Indeed, the observation of such spectral distortions will be a challenge even for the next generation of reactor experiments equipped with near detectors [25]. The achievement of this goal appears now even more important in light of the opportunity of testing and distinguishing standard and nonstandard physics.

Concerning the data sensitive to $\Delta m^2_{\rm sol}$ our analysis includes all the relevant solar and KamLAND data as described in detail in [1], but here the KamLAND absolute normalization is treated as a free parameter. As in [1] we made the assumption that the additional mixing angles involving sterile neutrinos are null ($\theta_{24} = \theta_{34} = 0$).[4]

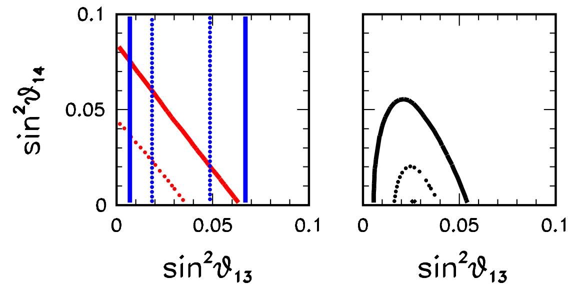

FIG. 1 (color online). Left panel: regions allowed after marginalization of the solar ($\Delta m^2_{\rm sol}$, θ_{12}) and atmospheric ($\Delta m^2_{\rm atm}$, θ_{23}) mass-mixing parameters by the solar sector data (diagonal bands) and LBL accelerator data (vertical bands). Right panel: regions allowed by their combination. The contours refer to $\Delta\chi^2 = 1$ (dotted line) and $\Delta\chi^2 = 4$ (solid line).

The regions allowed by the combined solar and KamLAND data represented by the diagonal bands in the left panel of Fig. 1 show no preference for nonzero mixing. This behavior, which is slightly different with respect to that observed in [1] (where we found a weak preference for nonzero mixing), can be traced to the following three factors: (I) The solar data taken alone give $\theta_{13} = \theta_{14} = 0$ as their best fit point[5]. (II) The KamLAND spectral shape taken alone does not show any preference for nonzero θ_{13} or θ_{14}[6]. (III) The well-known interplay of KamLAND and solar data in pushing the θ_{13} (θ_{14}) estimate upward (see [1,6–8,31]), so as to reduce the mismatch existing at $\theta_{13} = \theta_{14} = 0$ among their (slightly different) determinations of the solar mixing angle θ_{12}, is now less effective since the KamLAND spectral shape has reduced sensitivity to this last parameter.

Concerning the data sensitive to $\Delta m^2_{\rm atm}$, we incorporate the LBL accelerator results as in [9], accounting for the $\nu_\mu \to \nu_\mu$ disappearance searches performed at K2K [32] and MINOS [33], and the latest $\nu_\mu \to \nu_e$ appearance results from MINOS [3] and T2K [4]. This data set is

[2]The solar data alone, without the "external" information on $\Delta m^2_{\rm sol}$ provided by the KamLAND spectral shape, would have a reduced sensitivity to all mixing angles. On the other hand, the KamLAND spectral shape provides little information on these last ones.

[3]It must be stressed that at the far detector (the only one currently operational at the D-CHOOZ site) the oscillations driven by the new mass-mixing parameters ($\Delta m^2_{\rm new}$, θ_{14}) get completely averaged if $\Delta m^2_{\rm new} \gtrsim 0.1\ {\rm eV}^2$ (see [23,24]). Therefore, in the region of the parameter space of current interest (confined to values of $\Delta m^2_{\rm new} \sim 1\ {\rm eV}^2$), we can safely assume that the ($\Delta m^2_{\rm new}$, θ_{14})-induced oscillations are completely averaged with a consequent undistorted energy spectrum. Of course, the situation would be different at a detector located near to the reactor core (not operational at present), where non-negligible ($\Delta m^2_{\rm new}$, θ_{14})-induced spectral distortions are expected (see the discussion in [23]). Finally, we remark that in the solar sector the new oscillations get averaged provided that $\Delta m^2_{\rm new} \gg \Delta m^2_{\rm sol}$, as we have shown in [1].

[4]The assumption $\theta_{24} = \theta_{34} = 0$, implying in our parametrization (see [1]) $U_{\mu 4} = 0$, is justified by the negative results of the short-distance disappearance searches performed in the $\nu_\mu \to \nu_\mu$ channel [26,27], by the atmospheric data analyses [28], and by the neutral current interaction searches performed by MINOS [29]. These last ones provide the stringent upper bound $\theta_{24} < 7°$ at the 90% C.L. [29]. For such small values the 4ν-oscillation effects induced in LBL experiments, being (doubly) suppressed by the product $|U_{e4}||U_{\mu 4}|$, would have a negligible impact in our analysis. In passing, we notice that it is for the same reason that the excess of the electronlike events observed in T2K and MINOS is not imputable to oscillations into sterile states.

[5]This feature has also been reported in other analyses [7,8] for what concerns θ_{13}.

[6]Within a three-flavor framework the same behavior has also been observed in [30].

insensitive to θ_{14} and delimits the vertical band in the left panel of Fig. 1. To understand this point one should observe that ν_4-driven $\nu_\mu \to \nu_e$ appearance effects are proportional to the mixing matrix element $U_{\mu 4}$, which is set to zero in our analysis.

The superposition (left panel of Fig. 1) of the two data sets sensitive, respectively, to $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$ clearly evidences their complementarity in constraining the two mixing angles. Their synergy manifests quantitatively in their combination displayed in the right panel of Fig. 1. This provides the strong upper bound

$$\sin^2\theta_{14} < 0.04 \quad (90\%\ \text{C.L.}), \tag{1}$$

which constitutes the main result of this Report. For the sake of completeness, we mention that if we had included the total rate information from the reactor experiments we would have obtained a slightly weaker upper bound. For example, adopting the new (higher) fluxes' estimates the limit would become $\sin^2\theta_{14} < 0.05$ at 90% C.L. In any case, the anticorrelation existing among the two mixing angles, characteristic of the solar sector, combined with the independent preference for nonzero θ_{13}, leads to a strong upper bound on θ_{14}, also destroying any weak preference for a nonzero value of this parameter. As an additional check of the robustness of the bound in Eq. (1) we verified that it is practically insensitive to the particular choice of the solar model used for the calculations. This is important in light of the yet unresolved "metallicity issue" and its connection with solar neutrino flux estimates (see [34] for an updated discussion of the topic).

We observe that the bound in Eq. (1) is not incompatible with the estimates arising from the reactor [35] and gallium calibration [36,37] anomalies. Rather, lying near their combined best fit [35], it tends to select the lower part of the interval identified by such data. Probing such relatively low values of θ_{14} with good precision should be the goal of any well-conceived experiment devoted to sterile oscillation searches.

Finally, we note that our limit is competitive with that recently established in [38] using KARMEN and LSND ν_e-carbon cross sections, presenting the additional advantage of being independent of the new mass-squared splitting. This is a unique feature of the solar and reactor setups herein considered, where the new oscillations get completely averaged.

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