Evidence for Mikheyev-Smirnov-Wolfenstein effects in solar neutrino flavor transitions

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Abstract

We point out that the recent data from the Sudbury Neutrino Observatory, together with other relevant measurements from solar and reactor neutrino experiments, convincingly show that the flavor transitions of solar neutrinos are affected by Mikheyev-Smirnov-Wolfenstein (MSW) effects. More precisely, one can safely reject the null hypothesis of no MSW interaction energy in matter, despite the fact that the interaction amplitude (formally treated as a free parameter) is still weakly constrained by the current phenomenology. Such a constraint can be improved, however, by future data from the KamLAND experiment. In the standard MSW case, we also perform an updated analysis of two-family active oscillations of solar and reactor neutrinos.

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I. INTRODUCTION

The Sudbury Neutrino Observatory (SNO) experiment has recently released new data \cite{SNO} with enhanced sensitivity to neutral-current (NC) interactions of solar neutrinos in deuterium. Charged current (CC) and elastic scattering (ES) events have also been statistically separated from NC events in a model-independent way, i.e., without using priors on the $^8$B neutrino energy spectrum shape \cite{SNO}. These data corroborate the explanation of the solar neutrino deficit \cite{SNO,Green} in terms of (dominant) two-family $\nu_e \rightarrow \nu_a$ flavor transitions ($\nu_a = \nu_{\mu,\tau}$), which have convincingly emerged from the combined data of previous solar neutrino experiments (Chlorine \cite{Chlorine}, Gallium \cite{Gallium,Super-Kamiokande}, Super-Kamiokande (SK) \cite{Super-Kamiokande}, and SNO \cite{SNO,Gallium,Super-Kamiokande}) and of long-baseline reactor oscillation searches at KamLAND \cite{KamLAND}. Moreover, the new SNO data appear to forbid relatively high values of the neutrino mixing angle $\theta_{12}$ (close to maximal mixing) and of the squared mass difference $\delta m^2$ (close to the CHOOZ \cite{CHOOZ} upper bound), which were marginally allowed prior to \cite{SNO} (see, e.g., \cite{Fogli,Miranda}). In the current global fit \cite{SNO}, the mass-mixing parameters appear to be tightly confined in the so-called large mixing angle (LMA) region, and especially in a subregion previously denoted as LMA-I \cite{Fogli}.

In the LMA parameter range, flavor transitions between $\nu_e$ and $\nu_a$ should be significantly affected by the neutrino interaction energy difference $V = V_e - V_a$ arising in solar (and possibly Earth) background matter \cite{Mikheyev,Beleniya},

$$
V(x) = \sqrt{2} G_F N_e(x)
$$

(1)

where $N_e$ is the electron number density at the point $x$. The associated flavor change, known as Mikheyev-Smirnov-Wolfenstein (MSW) effect \cite{Mikheyev}, should occur adiabatically \cite{Mikheyev} in the solar matter, for LMA parameters. In the context of Hamiltonian ($H$) evolution of 2$\nu$ active flavors, the MSW effect enters through a dynamical term $H_{\text{dyn}}$ in matter, in addition to the kinetic term $H_{\text{kin}}$ in vacuum:

$$
i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = (H_{\text{dyn}} + H_{\text{kin}}) \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix},
$$

(2)

where

$$
H_{\text{dyn}} = \frac{V(x)}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}
$$

(3)

and

$$
H_{\text{kin}} = \frac{\delta m^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix},
$$

(4)

$E$ being the neutrino energy.

In a previous work \cite{Beleniya} we pointed out that, while the evidence for $H_{\text{kin}} \neq 0$ was overwhelming, the phenomenological indications in favor of $H_{\text{dyn}} \neq 0$ (and thus of MSW effects) were not as compelling. In particular, we introduced in \cite{Beleniya} a free parameter $a_{\text{MSW}}$ modulating the overall amplitude of the dynamical term $H_{\text{dyn}}$ through the substitution

$$
V \rightarrow a_{\text{MSW}} \cdot V,
$$

(5)

both in the Sun and in the Earth. We showed that $a_{\text{MSW}}$ was poorly constrained, despite an intriguing preference for the standard MSW expectation $a_{\text{MSW}} \sim 1$ \cite{Beleniya}. The null hypothesis $a_{\text{MSW}} = 0$ was not clearly disproved by any single experiment, and could be rejected at a
relevant confidence level ($\Delta \chi^2 \simeq 13$, formally equivalent to $\sqrt{\Delta \chi^2} \simeq 3.5\sigma$) only in the global fit. We concluded that the available phenomenological data clearly favored MSW effects in solar neutrinos, but did not prove unequivocally their occurrence. We deemed it necessary to wait for new KamLAND or SNO data, in order to clarify the situation and to probe MSW effects with higher statistical significance [19].

In this work, we point out that the recent SNO data [1] contribute significantly to disprove the null hypothesis of no MSW oscillations. In the global combination of solar and reactor data, we find that, with respect to the (preferred) standard case $a_{\text{MSW}} \sim 1$, the null hypothesis $a_{\text{MSW}} = 0$ can be safely rejected at the level of $\sim 5.6\sigma$, despite the fact the allowed range of $a_{\text{MSW}}$ is still rather large. In other words, the evidence in favor of MSW effects is now very strong, although precision tests of the MSW physics cannot be performed until new, high statistics KamLAND data become available (as we show later).

In the following sections, we analyze the current solar and reactor neutrino phenomenology with an increasing degree of dependence on assumptions about the MSW effect. In Sec. II we do not make any hypothesis about MSW effects, and show that SNO data alone, as well as a model-independent SNO+SK combination, constrain the energy-averaged $\nu_e$ survival probability $\langle P_{ee} \rangle$ to be significantly smaller than $1/2$. This fact, by itself, excludes the vacuum case $a_{\text{MSW}} = 0$ (which would predict $\langle P_{ee} \rangle \geq 1/2$ in the LMA region selected by KamLAND), and proves that dynamical effects must occur in solar neutrino propagation with unspecified amplitude $a_{\text{MSW}} > 0$. In Sec. III we fit all the available solar and reactor data with $(\delta m^2, \theta_{12}, a_{\text{MSW}})$ taken as free parameters. We find that MSW effects with standard amplitude $(a_{\text{MSW}} = 1)$ are favored, while the null hypothesis $(a_{\text{MSW}} = 0)$ can be safely rejected at the $\sim 5.6\sigma$ level. However, we show that the allowed range of $a_{\text{MSW}}$ is still very large, and can be significantly narrowed only by future KamLAND data. Assuming standard MSW effects $(a_{\text{MSW}} = 1)$, we perform in Sec. IV an updated analysis of the $2\nu$ kinematical parameters $(\delta m^2, \sin^2 \theta_{12})$. We briefly discuss the impact of $3\nu$ mixing in Sec. V, and conclude our work in Sec. VI.

II. MODEL-INDEPENDENT CONSTRAINTS

It has been shown in [20] (see also [21]) that the SK and SNO experiments probe the same energy-averaged $\nu_e$ survival probability $\langle P_{ee} \rangle$ to a good accuracy, provided that the detector thresholds are appropriately chosen. For the kinetic energy threshold ($T_{\text{SNO}} = 5.5$ MeV) and energy resolution characterizing the latest SNO data [1], we find that the equivalent SK threshold is $E_{\text{SK}} \simeq 7.8$ MeV in total energy. For equalized thresholds, the SK ES flux and the SNO NC and CC fluxes are linked by the exact relations [20]

$$
\Phi_{\text{SK ES}}^{\nu_e} = \Phi_B \langle P_{ee} \rangle + r(1 - \langle P_{ee} \rangle),
$$

(6)

$$
\Phi_{\text{SNO CC}}^{\nu_e} = \Phi_B \langle P_{ee} \rangle,
$$

(7)

$$
\Phi_{\text{SNO NC}}^{\nu_e} = \Phi_B,
$$

(8)

where $r = 0.154$ is the ratio of (properly averaged) $\nu_{\mu,\tau}$ and $\nu_e$ CC cross sections, and $\Phi_B$ is the true $^8\text{B}$ flux from the Sun. From the above equations, one can (over)constrain both $\Phi_B$

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1 In any case, we assume active flavor oscillations only, and do not consider hypothetical sterile neutrinos.

2 In practice, adopting this threshold amounts to discard the first three bins of the SK energy spectrum in the range $E \in [5, 8]$ MeV.
and $\langle P_{ee} \rangle$ in a truly model-independent way, namely, without any prior assumption about the energy profile of $P_{ee}$ or about $\Phi_B$ predictions in standard solar models (SSM).

Figure 1 shows the current constraints on $\Phi_B$ and on $\langle P_{ee} \rangle$ as derived from the final SNO CC and NC fluxes \cite{1} (correlations included \cite{22}). The constraints are shown both by individual bands and by their combination at the 3σ level ($\Delta \chi^2 = 9$). The projections of the SNO+SK combination (solid ellipse in Fig. 1) provide the ranges

$$\Phi_B = (5.5 \pm 1.2) \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \ (3\sigma) ,$$

in good agreement with SSM predictions \cite{23},

$$\langle P_{ee} \rangle = 0.31^{+0.12}_{-0.08} \ (3\sigma) .$$

The above 3σ limits on $\langle P_{ee} \rangle$ are in very good agreement with the “3σ range” obtained by naively tripling the errors of the SNO CC/NC flux ratio, which is a direct measurement of $\langle P_{ee} \rangle$: $\Phi_{\text{SNO CC}}/\Phi_{\text{SNO NC}} = 0.306 \pm 0.105(3\sigma)$ \cite{1}. However, as emphasized in \cite{22}, the errors of the CC/NC ratio are not normally distributed, and should not be used in fits. Conversely, our bounds in Eq. (10) are statistically safe and well-defined, and will be used in the following discussion.

The above SK+SNO constraints appear to be currently dominated by the SNO data, as shown by the dotted ellipse in Fig. 1. In particular, the upper bound on the $\nu_e$ survival probability,

$$\langle P_{ee} \rangle < 0.43 \ (3\sigma) ,$$

can be basically derived from the SNO (CC+NC) data \cite{1} alone. The upper limit in Eq. (11) is significantly stronger than the one derived in \cite{21} prior to the latest SNO data \cite{1}. In particular, we have now robust, model-independent evidence that $P_{ee}$ is definitely smaller than 1/2 at > 3σ level. This inequality has important consequences for both the dynamical and the kinematical term in Eq. (2). First, in the $\delta m^2$ range accessible to KamLAND and below the CHOOZ bound ($\delta m^2 \sim O(10^{-4}_{\pm 1}) \text{ eV}^2$), the absence of the dynamical MSW term $H_{\text{dyn}}$ (i.e., the case $a_{\text{MSW}} = 0$ would imply $\langle P_{ee} \rangle \geq 1/2$ (see, e.g., \cite{19}), contrary to Eq. (11). Second, assuming standard MSW dynamics ($a_{\text{MSW}} = 1$), the inequality in Eq. (11) allows to place upper limits on the kinematical parameters $\delta m^2$ and $\sin^2 \theta_{12}$ (see, e.g., the discussions in \cite{19, 24, 25}).

Figure 2 illustrates the previous statements through isolines of $\langle P_{ee} \rangle$ in the ($\delta m^2, \sin^2 \theta_{12}$) parameter range relevant to KamLAND, for both $a_{\text{MSW}} = 0$ (left panel) and $a_{\text{MSW}} = 1$ (right panel). The superposed grey region is allowed by the 3σ model-independent bounds in Eq. (10). No such region exists in the case $a_{\text{MSW}} = 0$, which is therefore rejected at the 3σ level (at least). In the standard MSW case (left panel), the allowed region appears to confine $\delta m^2$ below $\sim 2 \times 10^{-4} \text{ eV}^2$ and $\sin^2 \theta_{12}$ below $\sim 0.4$. In particular, the latest SNO data significantly contribute to reject maximal mixing ($\sin^2 \theta_{12} = 1/2$) and to reduce the likelihood of the so-called \cite{14} LMA-II parameter region, as emphasized in \cite{1}.

Summarizing, the latest SNO CC and NC data \cite{1}, either by themselves or in combination with the SK ES data \cite{8}, provide the strong, model-independent upper bound $\langle P_{ee} \rangle < 0.43$ at 3σ. In the context of 2ν mixing, and within the mass-mixing region probed by KamLAND, this bound allows to reject the null hypothesis ($a_{\text{MSW}} = 0$), and provides upper limits on the mass-mixing parameters in the standard MSW case ($a_{\text{MSW}} = 1$). In the next Section, we examine the more general case of variable $a_{\text{MSW}}$, in order to test whether current and future data can significantly constrain, by themselves, the size of matter effects.
III. CONSTRAINTS ON THE MSW DYNAMICAL TERM

In this section we present the results of a global analysis of solar and reactor (KamLAND+CHOOZ) data with \((\delta m^2, \sin^2 \theta_{12}, a_{\text{MSW}})\) unconstrained. The latest SNO data are incorporated according to the recommendations in [22]. The reader is referred to [19] for other details of the analysis.

Figure 3 shows the results of the global \(\chi^2\) fit, in terms of the function \(\Delta \chi^2(a_{\text{MSW}})\) after \((\delta m^2, \sin^2 \theta_{12})\) marginalization. Such marginalization is appropriate to test the size of \(H_{\text{dyn}}\) independently of \(H_{\text{kin}}\). It can be seen that the best fit is intriguingly close to the standard case \((a_{\text{MSW}} = 1)\), although there are other acceptable local minima over about three decades in \(a_{\text{MSW}}\). As discussed in [19] for the case of variable \(a_{\text{MSW}}\), the \(\delta m^2\) range allowed by solar neutrino data sweeps through the tower of LMA-\(n\) solutions allowed by KamLAND, leading to a series of “bumps” in the \(\Delta \chi^2\) function (solid line). Such features are unavoidable, as far as KamLAND allows multiple solutions in the mass-mixing parameter space. However, the situation should improve with higher KamLAND statistics. Assuming that KamLAND will confirm the current best-fit solution in the \((\delta m^2, \sin^2 \theta_{12}, a_{\text{MSW}})\) space, and simulating the corresponding KamLAND data, we obtain the prospective dotted and dashed curves in Fig. 1, which refer, respectively, to a fivefold and tenfold increase of the present statistics (54 events [12]). It appears that, with the help of a few hundreds KamLAND events, the global fit of solar and reactor data can pinpoint the predicted size of MSW effects within a factor of \(~2\), allowing future “precision tests” of this effects (e.g., to probe additional nonstandard interactions).

Although the current bounds on \(a_{\text{MSW}}\) appear to be rather weak, the rejection of the null hypothesis \(a_{\text{MSW}} = 0\) is quite strong, and corresponds to a significance level of \(\Delta \chi^2 \sim 32\), i.e., \(\sim 5.6 \sigma\). Summarizing the results of this and the previous section, we can state that current solar and reactor data reject the hypothesis of no MSW effect at \(> 5\sigma\) level, with a \(> 3\sigma\) contribution from the recent SNO data [1]. Therefore, in our opinion, the phenomenological indications in favor of MSW effects can now be promoted to the level of evidence.

IV. CONSTRAINTS ON KINEMATICAL MASS-MIXING TERM

In this section, assuming standard MSW dynamics, we update our previous bounds [14] on the mass-mixing parameters \((\delta m^2, \sin^2 \theta_{12})\) which govern the kinematical term \(H_{\text{kin}}\). The reader is referred to [14, 21] for technical details. Here we just add that the statistical correlations of recent SNO data [1] are incorporated through a straightforward generalization of the pull approach [21], as explicitly described in [26]. We have checked that our analysis “SNO data only” reproduces the results of [1] with very good accuracy. Finally, we have updated the total rate and winter-summer asymmetry from Gallium experiments [27]. In total, we have 84 solar neutrino observables, plus 13 KamLAND bins.

Figure 4 shows the results of our fit to all solar neutrino data.\(^3\) The best fit (\(\chi^2_{\text{min}} = 72.9\)) is reached at \(\delta m^2 = 5.7 \times 10^{-5}\) and \(\sin^2 \theta_{12} = 0.29\). The upper and lower bounds on the mass-mixing parameters are in good agreement with the results in [1], and confirm that the

\(^3\) We used to add CHOOZ data [13] in order to strengthen the upper bound on \(\delta m^2\) [14, 21]. However, current solar neutrino data make this addition no longer necessary in the context of 2\(\nu\) mixing with standard MSW effects.
solar neutrino parameter space is steadily narrowing.

Figure 5 incorporates the analysis of KamLAND data \[12\] as in \[14\]. The best fit (\(\chi^2_{\text{min}} = 79.7\)) is reached at \(\delta m^2 = 7.2 \times 10^{-5}\) and \(\sin^2 \theta_{12} = 0.29\) (LMA-I solution), while the second best fit (LMA-II solution) is only marginally allowed at the \(\Delta \chi^2 = 9.4\) level (\(\sim 99\%\) C.L. for \(N_{\text{DF}} = 2\)). Also in this case, we find good agreement with the results in \[1\], modulo the obvious transformation from our linear abscissa \(\sin^2 \theta_{12}\) to their logarithmic abscissa \(\tan^2 \theta_{12}\).

In conclusion, the kinematical 2\(\nu\) mass-mixing parameters appear to be strongly constrained in a basically unique region (LMA-I), with only a marginal possibility left for the LMA-II region. The decrease of the previous LMA-II likelihood \[14\] is an important contribution of the latest SNO data \[1\].

V. COMMENTS ON THREE-FAMILY MIXING

So far, we have assumed flavor oscillations in the active 2\(\nu\) channel \(\nu_e \rightarrow \nu_a\) (\(\nu_a\) being a linear combination of \(\nu_\mu\) and \(\nu_\tau\)) driven by the \((\delta m^2, \theta_{12})\) parameters. The \((\nu_\mu, \nu_\tau)\) combination orthogonal to \(\nu_a\) is probed by atmospheric \(\nu_\mu \rightarrow \nu_\tau\) oscillations, with different parameters \((\Delta m^2, \theta_{23})\) \[28\]. As far as the third mixing angle \(\theta_{13}\) is zero (and \(\delta m^2/\Delta m^2 \ll 1\)), the two oscillation channels are practically decoupled, and all our previous considerations hold without changes. However, for small but nonzero \(\theta_{13}\), the 3\(\nu\) survival probability deviates from the 2\(\nu\) case for both solar and KamLAND \(\nu_e\) oscillations:

\[
P_{ee}^{3\nu} \simeq (1 - 2 \sin^2 \theta_{13}) P_{ee}^{2\nu}.
\]

In particular, for \(a_{\text{MSW}} = 0\), the minimum value of \(\langle P_{ee}\rangle\) in the right panel of Fig. 2 can slightly decrease from \(1/2\) to \(1/2 - \sin^2 \theta_{13}\). Until very recently, the upper bound on \(\theta_{13}\) (dominated by CHOOZ and atmospheric data) could be quoted as \(\sin^2 \theta_{13} < 0.05\) (3\(\sigma\)) \[14, 29\], leading to \(P_{ee}^{3\nu}(a_{\text{MSW}} = 0) > 0.45\). A new SK atmospheric data analysis \[30\], however, appears to imply the weaker bound \(\sin^2 \theta_{13} < 0.067\) (3\(\sigma\)) \[31\], leading to \(P_{ee}^{3\nu}(a_{\text{MSW}} = 0) > 0.43\). In both cases, there is no overlap with the experimental upper bound in Eq. (11). Therefore, the null hypothesis \(a_{\text{MSW}} = 0\) can be rejected at the 3\(\sigma\) level also in the 3\(\nu\) mixing case, using only SNO(+SK) data.

In the more general case of variable \(a_{\text{MSW}}\), we have not performed the 3\(\nu\) generalization of the analysis in Sec. III. Our educated guess is that an allowance for small values of \(\theta_{13}\) should only slightly weaken—but should not spoil—the main results discussed therein.

VI. CONCLUSIONS

In recent years, solar and reactor neutrino data have been shown to be consistent with (and to favor) Mikheyev-Smirnov-Wolfenstein effects in the flavor evolution of solar neutrinos. However, in our opinion, the null hypothesis of “no MSW effect” could not be safely rejected \[19\]. The current situation appears, however, more favorable. In this work we have pointed out that recent SNO data \[1\] strongly favor the occurrence of MSW effects in the solar matter and, together with world solar and reactor data, provide a many-sigma rejection of the null hypothesis. We have also performed an analysis where the MSW interaction energy is freely rescaled, and found weak constraints on the scaling parameter. These constraints can be potentially improved by higher-statistics KamLAND data, which
will then allow more precise tests of the MSW dynamics. In the standard MSW case, we have also performed an updated analysis of two-family active oscillations of solar and reactor neutrinos.

We conclude by observing that, although MSW effects are an unavoidable consequence of the standard theory of electroweak interactions, their basic confirmation in the current neutrino phenomenology represents an important and reassuring experimental accomplishment, which strengthen our confidence in the emerging picture of neutrino masses and mixings.

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FIG. 1: Results of the model-independent analysis of SNO (CC and NC) and SK (ES) neutrino fluxes. The projections of the solid ellipse provide 3σ bounds on the $^8$B neutrino flux $\Phi_B$ and on the energy-averaged $\nu_e$ survival probability $\langle P_{ee} \rangle$. 
FIG. 2: Isolines of $\langle P_{ee} \rangle$ with standard MSW effects ($a_{\text{MSW}=1}$) and with no matter effect ($a_{\text{MSW}} = 0$). The gray region is allowed by the SK+SNO combination. No such region exist in the absence of MSW effects.
FIG. 3: Bounds on $a_{\text{MSW}}$ (considered as a continuous free parameter), including all current solar, CHOOZ, and KamLAND data (solid curve). Prospective KamLAND data with higher statistics are used to draw the dotted and dashed curves. See the text for details.
FIG. 4: Results of the $2\nu$ oscillation analysis of solar neutrino data, for standard MSW effects.
FIG. 5: Results of the $2\nu$ oscillation analysis of solar and KamLAND data, for standard MSW effects.