Solar neutrino oscillations
and indications of matter effects in the Sun

G.L. Fogli, E. Lisi, A. Palazzo, and A.M. Rotunno

Dipartimento di Fisica and Sezione INFN di Bari
Via Amendola 173, 70126 Bari, Italy

Abstract

Assuming the current best-fit solutions to the solar neutrino problem at large mixing angle, we briefly illustrate how prospective data from the Sudbury Neutrino Observatory (SNO) and from the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) can increase our confidence in the occurrence of standard matter effects on active neutrino flavor oscillations in the Sun, which are starting to emerge from current data.

PACS numbers: 26.65.+t, 13.15.+g, 14.60.Pq, 95.55.Vj
I. INTRODUCTION

The Chlorine [1], Gallium [2, 3, 4], Super-Kamiokande (SK) [5, 6] and Sudbury Neutrino Observatory (SNO) [7, 8, 9] solar neutrino experiments have convincingly established that the deficit of the observed solar $\nu_e$ flux with respect to expectations [10, 11] implies new neutrino physics. In particular, the charged and neutral current (CC and NC) data from SNO have proven the occurrence of $\nu_e$ transitions into a different active state $\nu_a$ with a statistical significance greater than 5$\sigma$ [8].

Barring sterile neutrinos and nonstandard $\nu$ interactions, such transitions can be naturally explained by the hypothesis of flavor oscillations [12] in the $\nu_e \rightarrow \nu_a$ channel ($\nu_a$ being a linear combination of $\nu_\mu$ and $\nu_\tau$) driven by nonzero $\nu$ squared mass difference and mixing angle parameters ($\delta m^2, \theta_{12}$) [13]. The ($\nu_\mu$, $\nu_\tau$) combination orthogonal to $\nu_a$ is probed by atmospheric $\nu$ oscillations [14], with different parameters ($\Delta m^2, \theta_{23}$) [15]. The third mixing angle $\theta_{13}$, needed to complete the $3 \times 3$ mixing matrix, is constrained to be small by additional reactor results [15, 16, 17], and can be set to zero to a good approximation for our purposes.

The recent results from the Kamioka Liquid scintillator AntiNeutrino Detector (KamLAND) [18] have provided a beautiful and crucial confirmation of the solar $\nu_e$ oscillation picture through a search for long-baseline oscillations of reactor $\nu_e$'s. The observed $\nu_e$ disappearance in KamLAND has confirmed the previously favored solution in the ($\delta m^2, \theta_{12}$) parameter space [18], often referred to as the large mixing angle (LMA) region [9] in the literature (see, e.g., [19] and references therein). Moreover, the KamLAND data have basically split this region into two allowed subregions, which we will refer to as LMA-I and LMA-II, following Ref. [20]. Although the LMA-I solution is favored by global fits, the LMA-II solution at higher $\delta m^2$ is also statistically acceptable, and we will discuss both cases in this work.\footnote{When the distinction between the LMA-I and LMA-II solutions is irrelevant, we will refer to a generic “LMA solution.”}

Within the LMA region, solar neutrino oscillations are governed not only by the kinematical mass-mixing parameters ($\delta m^2, \theta_{12}$), but should also be significantly affected by the interaction energy difference ($V = V_e - V_a$) between $\nu_e$'s and $\nu_a$'s propagating in the solar (and possibly Earth) background matter [21, 22], through the so-called Mikheev-Smirnov-Wolfenstein (MSW) mechanism [21] in adiabatic regime [23]. Although Earth matter effects (i.e., day-night variations of solar event rates) remain elusive, solar matter effects seem to emerge, at least indirectly, from the combination of the available data (and especially from SNO), through a preference for an average oscillation probability smaller than $1/2$ at energies of a few MeV (see [24] and references therein).

The purpose of this article is to briefly illustrate how such emerging indications of solar matter effects can be corroborated in the LMA parameter region. In particular, we show that the amplitude of matter effects (introduced as a free parameter $a_{\text{MSW}}$ in Sec. II) can be significantly constrained by using prospective data from SNO (Sec. III) and KamLAND (Sec. IV). Both SNO and KamLAND can discriminate the case $a_{\text{MSW}} = 1$ (standard matter effects) against the case $a_{\text{MSW}} = 0$ (matter effects zeroed), and can thus provide indirect indications for the MSW mechanism in the Sun.\footnote{A really “direct” evidence for MSW effects in the Sun would require a full program of low-energy solar $\nu$ spectroscopy, probing the energy profile of the oscillation probability down to the sub-MeV range [25].}

Although the occurrence of solar matter effects in the LMA region is an unavoidable
consequence of the standard model of electroweak interactions, the importance of proving experimentally that “they are there” and have the correct size cannot be overlooked. Current and future research programs in neutrino physics, including the accurate reconstruction of the kinematical mass and mixing parameters for the three known generations of neutrinos, and the associated searches for leptonic CP violation, largely rely on our knowledge of the dynamical $\nu$ properties in matter. Therefore, we think that increasing our confidence in the occurrence of standard MSW effects in the solar interior is a relevant (and reassuring) intermediate step towards the realization of these difficult and long-term research programs.$^3$

II. SWITCHING MATTER EFFECTS ON AND OFF

In the active two-flavor oscillation picture, the solar $\nu$ evolution equation in the space coordinate $x$ reads

$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = \mathcal{H} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix},$$

where the Hamiltonian $\mathcal{H}$ can be split into kinematical $^{[12, 13]}$ and dynamical $^{[21]}$ components, describing the free and interaction $\nu$ energy, respectively,

$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{dyn}},$$

with

$$\mathcal{H}_{\text{kin}} = \frac{k}{2} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix},$$

and

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

In the above equations, $E$ is the neutrino energy, $k = \delta m^2 / 2E$ is the neutrino oscillation wavenumber, and $V(x)$ is the difference between the $\nu_e$ and $\nu_a$ interaction energies with ordinary matter $^{[21]}$ at the position $x$, characterized by the electron number density $N_e$,

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

The relevance of the dynamical term $\mathcal{H}_{\text{dyn}}$ on the $\nu_e$ survival probability $P_{ee}$ strongly depends on the oscillation parameter values. As it is well known, for $\delta m^2 \lesssim 10^{-9} \text{ eV}^2$ dynamical effects are small or negligible (so-called quasivacuum and vacuum oscillation regimes), while for $\delta m^2 \gtrsim 10^{-7} \text{ eV}^2$ they are definitely relevant (so-called MSW regime) $^{[15]}$. The available solar neutrino data favor solutions in the MSW regime (and in particular the LMA region of parameters $^{[3]}$), but do not exclude (quasi)vacuum solutions with sufficiently high confidence $^{[13, 26, 27]}$. In other terms, cases where one can phenomenologically set $\mathcal{H}_{\text{dyn}} \approx 0$ are not ruled out by current solar neutrino data alone, implying that no compelling evidence for matter effects has been found so far in this data set.

The first KamLAND data $^{[18]}$, however, have excluded (quasi)vacuum solutions to the solar neutrino problem, and have unambiguously selected the LMA region of the parameter

---

$^3$ For similar reasons, an important goal of current and future oscillation searches “in vacuum” is to observe a periodic flavor change pattern, unavoidably associated to the mass-mixing parameters.
Therefore, we can restrict ourselves to relatively high values of $\delta m^2$ (say, above $10^{-5}$ eV$^2$), where matter effects are expected to play a relevant role. It makes then sense to ask whether the data, by themselves, can globally provide some evidence that matter effects are really there ($\mathcal{H}_{\text{dyn}} \neq 0$) and have their expected size [Eq. (5)]. One can rephrase this question by introducing a free parameter $a_{\text{MSW}}$ modulating the overall amplitude of the interaction energy difference $V$ in the dynamical term $\mathcal{H}_{\text{dyn}}$,

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

so that standard matter effects can be formally switched on and off by setting $a_{\text{MSW}} = 1$ and $a_{\text{MSW}} = 0$, respectively. One can then try to check whether the data prefer the first or the second option for $a_{\text{MSW}}$. Furthermore, by treating $a_{\text{MSW}}$ as a continuous parameter, one can try to constrain its allowed range through global data analyses: A preference for $a_{\text{MSW}} \sim O(1)$ would then provide an indirect indication for the occurrence of matter effects with standard size, as opposed to the case of pure “vacuum” oscillations ($\mathcal{H}_{\text{dyn}} \simeq 0$).

We have verified that the current solar neutrino data, by themselves, place only very loose and uninteresting limits on $a_{\text{MSW}}$, as far as the mass-mixing oscillation parameters are left unconstrained. In fact, since the oscillation physics depends mostly on the ratio $V/k$, a variation of the kind $V \rightarrow a_{\text{MSW}} V$ is largely absorbed by a similar rescaling of $k$ (i.e., of $\delta m^2$). In order to break this degeneracy, we need to include explicitly an experiment which is highly sensitive to $\delta m^2$ and basically insensitive to matter effects, such as KamLAND.

We will thus focus, in the following, on the $\delta m^2$ values selected by reactor neutrino data in the LMA range (roughly $10^{-4} \pm 1$ eV$^2$), and eventually on the specific LMA-I and LMA-II solutions favored by current global fits including KamLAND.

### III. Matter Effects and the SNO CC/NC Double Ratio

Let us restrict the analysis to the LMA region, whose best-fit to solar neutrino data alone, as taken from [19], is reached at $\delta m^2 = 5.5 \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.3$. Within this region, current solar neutrino data from SK and SNO provide already some indirect indications in favor of matter effects in the Sun, through their preference for $P_{ee} \sim 1/3 < 1/2$, where $P_{ee}$ is the average $\nu_e$ survival probability in the SK-SNO energy range [29, 30, 31].

Indeed, in the LMA region and for $a_{\text{MSW}} = 1$ (standard matter effects), adiabatic MSW transitions [21, 23] occur in the Sun, leading to a survival probability of the form (up to residual Earth matter effects):

$$P_{ee} \simeq \cos^2 \theta_1' \cos^2 \theta_{12} + \sin^2 \theta_1' \sin^2 \theta_{12} \quad (a_{\text{MSW}} = 1) ,$$  

where $\theta_1'$ is the rotation angle which diagonalizes $\mathcal{H}$ at the $\nu_e$ production point in the solar core. On the other hand, for hypothetically zeroed matter effects ($a_{\text{MSW}} = 0$), one would

---

4 A similar approach has been used in the context of atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations, in order to find indirect indications for the expected $L/E$ oscillation pattern [28]. In that case, a continuous free parameter $n$ has been formally introduced as an energy exponent ($L \cdot E^n$), and a strong preference of the data for $n \simeq -1$ has been found [28], supporting the standard $\nu_\mu \rightarrow \nu_\tau$ oscillation picture.

5 For the sake of consistency, we will include Earth matter effects with variable $a_{\text{MSW}}$ also in the analysis of current or prospective KamLAND data (Sec. III). Such effects become formally nonnegligible only for large values of $a_{\text{MSW}}$.,
get an energy-independent form for $P_{ee}$ in the LMA region,

$$P_{ee} \simeq 1 - \frac{1}{2} \sin^2 2\theta_{12} \quad (a_{\text{MSW}} = 0),$$

(8)

as originally suggested by Gribov and Pontecorvo [32] prior to the MSW papers [21] (see also [33, 34]).

In the SNO energy range ($E \gtrsim 5$ MeV), the above two expressions lead to comparable results in the second octant of the mixing angle ($\theta_{12} > \pi/4$), but differ considerably in the first octant, where $P_{ee}(a_{\text{MSW}} = 1) < 1/2$, while $P_{ee}(a_{\text{MSW}} = 0) > 1/2$. Since the LMA likelihood extends only marginally in the second octant [19], there are very good chances that SNO can discriminate the cases $a_{\text{MSW}} = 0$ and $a_{\text{MSW}} = 1$ through the double ratio of experimental-to-theoretical CC and NC events, which is SSM-independent, and is equivalent to the average of $P_{ee}$ over the SNO energy response function [24, 29, 35, 36].

Figure 1 shows isolines of the CC/NC double ratio in the usual mass-mixing plane,6 for both $a_{\text{MSW}} = 1$ and $a_{\text{MSW}} = 0$, using the current SNO CC threshold [8]. It is evident from this figure that, by excluding CC/NC values greater than 1/2 with high confidence, the SNO experiment can conclusively discriminate the cases of standard and zeered matter effects, and will provide two very useful (correlated) indications, namely: (1) that $\theta_{12} < \pi/4$; and (2) that matter effects indeed take place in the Sun. To reach this conclusion one needs only to know, in addition, that the oscillation parameters are roughly in the LMA region—a piece of information which has been indeed provided by the first KamLAND data.

Although such simple considerations arise from well-known properties of the oscillation probability [33, 34], we think that the crucial role of future SNO CC/NC data [37] in establishing the occurrence of matter effects in the Sun has perhaps not been stressed enough. Let us review, in fact, the current situation. Within the LMA region, neither SK nor the Gallium experiments can really discriminate the two octants of $\theta_{12}$ at present (see, e.g., Fig. 2 in [29]), and cannot individually prove that solar matter effects are taking place. The Chlorine experiment [1], which observes an event rate suppression of $\sim 1/3$ as compared to standard solar model (SSM) predictions [11], prefers the first octant and thus the presence of matter effects, as it is well known; however, this indication is unavoidably SSM-dependent and thus not totally compelling, especially if additional (hypothetical) experimental systematics are invoked [33, 34]. A SSM-independent preference for $P_{ee} < 1/2$ has been provided first by the combination of SNO CC and SK data [5] and then by SNO data alone through the CC/NC double ratio [8], but not yet with a significance high enough to rule out $P_{ee} = 1/2$ [29]. Let us consider, in particular, the latest SNO constraints in the plane ($\Phi_e, \Phi_{\mu\tau}$) charted by the solar $\nu_e$ and $\nu_{\mu,\tau}$ fluxes, as shown in Fig. 3 of the original SNO paper [8]. In such a figure, although the SNO best-fit point clearly prefers $P_{ee} \sim 1/3$ (corresponding to $\Phi_{\mu\tau} \simeq 2\Phi_e$), the 95% C.L. ellipse is still compatible with $P_{ee} \sim 1/2$ (namely, $\Phi_{\mu\tau} \simeq \Phi_e$). However, future SNO NC and CC data can considerably improve the constraints on $P_{ee}$, by reducing both the statistical and the systematic error on the CC/NC ratio [37]. In particular, the current anticorrelation between the CC and NC event rate uncertainties, which prevents a significant cancellation of errors in the CC/NC ratio, will be largely suppressed by the future event-by-event reconstruction of the NC data sample [37].

---

6 In Fig. 1, the choice of a linear scale for $\sin^2 \theta_{12}$ enhances the large mixing region, at the cost of “squeezing” the (currently excluded) region of small mixing angles. Among the three $\delta m^2$ decades shown, the middle one is relevant for the LMA solution.
In conclusion, although the combination of all current solar neutrino data suggests a pattern of $P_{ee}$ compatible with the LMA energy profile \cite{30,31} and indicates an overall preference for the first octant of $\theta_{12}$ \cite{9}, the emerging indications in favor of solar matter effects from this data set are not strongly compelling yet. Among the solar neutrino experiments, in the near future only SNO appears to be able to improve significantly this situation through new CC and NC data \cite{37}, which can discriminate $a_{\text{MSW}} = 1$ from $a_{\text{MSW}} = 0$ by excluding $P_{ee}$ values greater than $1/2$ in the LMA region, as we have tried to emphasize in this Section.\footnote{In the presence of 3$\nu$ mixing ($\theta_{13} \neq 0$), this requirement would become slightly more stringent: SNO should prove that $P_{ee} < s_{13}^2 + c_{13}^2/2 \leq 0.453$, where the global 3$\sigma$ upper limit on $s_{13}^2 = \sin^2 \theta_{13}$ ($s_{13}^2 \leq 0.05$ \cite{19}) is assumed.}

At the same time, upper bounds on CC/NC smaller than $1/2$ will be helpful to strengthen the upper limits on $\delta m^2$, as evident from the left panel in Fig. 1 (see also \cite{36}). Should instead future SNO data drive the preferred value of $P_{ee}$ from $\sim 1/3$ to relatively higher values, it would clearly become much more difficult to assess the occurrence of MSW effects in the Sun.

### IV. MATTER EFFECTS IN GLOBAL ANALYSES INCLUDING KAMLAND

In the previous Section, we have briefly illustrated how a single datum (the SNO CC/NC double ratio) can discriminate the case of standard matter effects ($a_{\text{MSW}} = 1$) from the case of zeroed matter effects ($a_{\text{MSW}} = 0$) in the LMA parameter region. By using further experimental information from KamLAND, one could try to test whether the “solar + KamLAND” combination of data can constrain matter effects in the Sun to have the right size \cite{a_{\text{MSW}} \sim O(1)}

In this kind of analyses, KamLAND basically fixes the oscillation parameters ($\delta m^2, \sin^2 \theta_{12}$), and thus the kinetic part of the Hamiltonian, $H_{\text{kin}}$ [Eq. (3)]. The role of solar neutrino data is then to check that the overall amplitude $a_{\text{MSW}}$ of the interaction energy difference $V$ in the dynamical term $H_{\text{dyn}}$ [Eqs. (4–6)] is consistent with the standard electroweak model ($a_{\text{MSW}} = 1$).

We have thus performed global analyses including both current solar neutrino data and current (or prospective) KamLAND data, with ($\delta m^2, \sin^2 \theta_{12}, a_{\text{MSW}}$) unconstrained.\footnote{We refer the reader to \cite{29} and \cite{19,20} for technical details of our solar and KamLAND data analysis, respectively.}

In particular, the analysis of current KamLAND data is based on the binned energy spectrum of reactor neutrino events observed above 2.6 MeV (54 events) \cite{18}. Prospective KamLAND spectral data have instead been generated, with the same energy threshold and binning, by assuming either the LMA-I best-fit point ($\delta m^2 = 7.3 \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.315$) or the LMA-II best-fit point ($\delta m^2 = 15.4 \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.300$) \cite{20}, and increased statistics ($5 \times 54$ and $10 \times 54$ events). The CHOOZ reactor data \cite{16} are also included.

Figure 2 and 3 show the results of such global fits, in terms of the function $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ for variable $a_{\text{MSW}}$ and unconstrained (i.e., minimized away) mass-mixing parameters. The $n\sigma$ bounds on $a_{\text{MSW}}$ are then given by $\Delta \chi^2 = n^2$. Let us focus first on the solid curve, which refers to the fit with \textit{current} KamLAND data, and is identical in both Figs. 2 and 3. It appears that such curve can already place $> 3\sigma$ upper and lower bounds on $a_{\text{MSW}}$. In particular, the hypothetical case of zeroed matter effects is already disfavored at $\sim 3.5\sigma$, thus providing an indirect indication in favor of matter effects in the Sun. The best-fit value...
of $a_{\text{MSW}}$ is close to the standard prediction ($a_{\text{MSW}} = 1$). However, there are also other quasi-degenerate minima, and the overall $\pm 3\sigma$ range for $a_{\text{MSW}}$, spanning about three orders of magnitude, is rather large. The width of this range can be understood by recalling the following facts: (1) the LMA range of $\delta m^2$ constrained by solar neutrino data, which covers about one decade [19, 29], can be shifted up or down by shifting $a_{\text{MSW}}$ with respect to 1, since the LMA oscillation physics depends on $V/k \propto a_{\text{MSW}}/\delta m^2$; (2) the range of $\delta m^2$ constrained by current terrestrial data (including KamLAND+CHOOZ) data, which covers about two decades [20], is much less affected by $a_{\text{MSW}}$ variations. As a consequence, by appropriately shifting $a_{\text{MSW}}$, it is possible to overlap the reconstructed ranges of $\delta m^2$ from solar and from reactor data over about $1+2$ decades. When the overlap sweeps through the degenerate $\delta m^2$ intervals allowed by KamLAND alone [20], the fit is locally improved, leading to a “wavy” structure in the $\Delta \chi^2$. In conclusion, although current solar+reactor data strongly disfavor $a_{\text{MSW}} = 0$ (zeroed matter effects) and provide a best fit close to $a_{\text{MSW}} = 1$ (standard matter effects), the presence of other local minima in the $\Delta \chi^2$ function, as well as the broad $3\sigma$ allowed range for $a_{\text{MSW}}$, do not allow to claim a clear evidence of standard matter effects from current data.

The previous qualitative arguments about the overlap of the reconstructed ranges of $\delta m^2$ from solar and reactor data fits (with variable $a_{\text{MSW}}$) also provide a clue to what one should expect with future KamLAND data. With increasing statistics, the KamLAND reconstructed range of $\delta m^2$ will shrink from two decades to a fractionally small value, so that the overlap with the $\delta m^2$ range constrained by current solar neutrino data will also be reduced from the current “$1+2$” decades to prospective “$1+0$” decades. Therefore, for both the LMA-I and the LMA-II case, we expect that $a_{\text{MSW}}$ can be constrained within about one order of magnitude by future KamLAND data. These expectations are quantitatively verified by the broken curves in Figs. 2 and 3, as we now discuss.

The broken curves in Fig. 2 refer to prospective KamLAND data, generated by assuming as true solution the LMA-I best-fit point. The energy threshold, the binning, and the systematic uncertainties are assumed to be the same as for the current KamLAND data. The dotted (dashed) curve refers to a number of reactor neutrino events five (ten) times larger than the current statistics, $N = 54$. It can be seen that the global fit will progressively constrain $a_{\text{MSW}}$ within one decade at $\pm 3\sigma$ and, most importantly, will lead to a marked preference for $a_{\text{MSW}} \sim 1$, which is not yet evident in the present data (solid curve). A further increase of the simulated KamLAND data sample will not lead to significantly more stringent bounds on $a_{\text{MSW}}$, the fit being then dominated by the solar neutrino data uncertainties. In conclusion, if the LMA-I solution is the true one, there are good prospect to test unambiguously the occurrence and size of standard matter effects in the Sun with higher KamLAND statistics. The uncertainty on $a_{\text{MSW}}$ will eventually be saturated by the solar $\nu$ uncertainties.

Figure 3 is analogous to Fig. 2, but the broken curves refer now to KamLAND data simulated for the LMA-II solution. Two important differences emerge by a comparison of the prospective fits to $a_{\text{MSW}}$ in Figs. 2 and 3, namely, a shift of the best-fit value, and a relaxation

---

9 Provided that $\delta m^2 \lesssim 2 \times 10^{-4}$ eV$^2$ (see, e.g., [19]). This condition is fulfilled by the LMA-I best-fit point and, to a large extent, also by the LMA-II point.

10 As previously remarked, new solar $\nu$ data, especially from SNO, might reduce such uncertainties. However, it seems to us premature to study in detail also the effect of prospective solar neutrino data from current and future experiments.
of the upper bounds for the LMA-II case. The shift is a reflection of the “mismatch” between the LMA-II value $\delta m^2 = 15.4 \times 10^{-5}$ eV$^2$ and the value $\delta m^2 = 5.5 \times 10^{-5}$ eV$^2$ preferred by current solar neutrino data, which is traded for an increase of $a_{\text{MSW}}$, when this parameter is left free. The relaxation of the $a_{\text{MSW}}$ upper bound in Fig. 3 is instead due to the vicinity of the LMA-II $\delta m^2$ value to the critical onset of average oscillations in KamLAND ($\sim 2 \times 10^{-4}$ eV$^2$). However, despite these drawbacks, the prospective allowed range of $a_{\text{MSW}}$ for the LMA-II case in Fig. 3 will be still compatible with standard matter effects at the $\sim 2\sigma$ level.

From Fig. 3 we also learn a more general lesson. Any mismatch between the oscillation parameters (especially $\delta m^2$) as separately reconstructed by KamLAND data and by solar data will lead to deviations from the standard oscillation picture, if allowance is given the fitting model. In our case, the deviation will show up as a slightly nonstandard matter effect ($a_{\text{MSW}} \neq 1$) in the LMA-II case. If such a situation occurs in the future, it might be difficult to assess whether this kind of “deviation” is due to statistical fluctuations, or rather to new neutrino interactions (e.g., nonuniversal neutral current couplings in the $\nu_e - \nu_a$ sector). Therefore, selecting between the LMA-I and LMA-II solution is of crucial importance to test any subleading effects on solar neutrinos, beyond standard adiabatic oscillations in matter. While a confirmation of the LMA-I case will probably lead to tight upper bounds on any subleading effect, in the LMA-II case one should expect such effects to be slightly favored by global fits.

V. SUMMARY AND CONCLUSIONS

In the simplest picture, solar neutrino oscillations depend on the kinematical parameters ($\delta m^2, \sin^2 \theta_{12}$) and on standard dynamical MSW effects in matter. The knowledge of the kinematical mass-mixing parameters has been enormously improved after the first KamLAND data, which have restricted their range within the so-called LMA region and, in particular, in two subregions named LMA-I and LMA-II. Standard dynamical effects in current solar neutrino data are starting to emerge through an increasingly marked preference for $P_{ee} < 1/2$, but still remain not clearly identified and partly elusive.

In order to quantify statistically the occurrence of MSW effects, we have introduced a free parameter $a_{\text{MSW}}$ modulating the amplitude of the $\nu$ interaction energy difference in the neutrino evolution equation, the cases $a_{\text{MSW}} = 1$ and $a_{\text{MSW}} = 0$ corresponding to the standard and (hypothetically) zeroed MSW effect, respectively. The SNO double ratio of CC/NC events can clearly discriminate, in a SSM-independent way, the case $a_{\text{MSW}} = 1$ against $a_{\text{MSW}} = 0$, provided that the current indication in favor of $P_{ee} < 1/2$ is confirmed with higher statistical significance.

By treating $a_{\text{MSW}}$ as a continuous parameter, we have then performed a global analysis including current solar, CHOOZ, and KamLAND data. The results are encouraging, since upper and lower bounds on $a_{\text{MSW}}$ appear to emerge at the $> 3\sigma$ level. In particular, the case of “zeroed” matter effects is significantly disfavored. Moreover, the best-fit is tantalizingly close to the standard expectations for matter effects ($a_{\text{MSW}} = 1$). However, the presence of other quasi-degenerate minima, and the very wide allowed range for $a_{\text{MSW}}$ (spanning about three decades at the $3\sigma$ level) prevent any firm conclusion about the occurrence of standard matter effects at present.

The situation will greatly improve, even with unaltered solar neutrino data, through higher KamLAND statistics (say, by a factor of five or ten, as considered in Figs. 2 and 3). In both the LMA-I and LMA-II cases, it appears possible to reduce the current uncertainty
on $a_{\text{MSW}}$ by about two orders of magnitude. The prospects are particularly promising for the LMA-I solution. In the LMA-II case, in fact, the reconstructed parameter $a_{\text{MSW}}$ might be biased towards higher values than the standard expectation, as a result of a slight mismatch between the solar and KamLAND reconstructed value of $\delta m^2$. Therefore, the selection of a single solution in the LMA oscillation parameter space appears to be crucial, before any definite conclusion can be made on the emerging indications of standard matter effects in the Sun.

Acknowledgments

This work is supported in part by the Istituto Nazionale di Fisica Nucleare (INFN) and by the Italian Ministry of Education (MIUR) through the “Astroparticle Physics” project. We thank A. Marrone and D. Montanino for useful discussions and suggestions.

[1] Homestake Collaboration, B.T. Cleveland, T. Daily, R. Davis Jr., J.R. Distel, K. Lande, C.K. Lee, P.S. Wildenhain, and J. Ullman, Astrophys. J. 496, 505 (1998).
[2] SAGE Collaboration, J.N. Abdurashitov et al., J. Exp. Theor. Phys. 95, 181 (2002) [Zh. Eksp. Teor. Fiz. 95, 211 (2002)].
[3] GALLEX Collaboration, W. Hampel et al., Phys. Lett. B 447, 127 (1999).
[4] T. Kirsten for the GNO Collaboration, in Neutrino 2002, 20th International Conference on Neutrino Physics and Astrophysics (Munich, Germany, 2002). Transparencies available at: neutrino2002.ph.tum.de.
[5] SK Collaboration, S. Fukuda et al., Phys. Rev. Lett. 86, 5651 (2001); ibidem, 5656 (2001).
[6] SK Collaboration, S. Fukuda et al., Phys. Lett. B 539, 179 (2002).
[7] SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 87, 071301 (2001).
[8] SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89, 011301 (2002).
[9] SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89, 011302 (2002).
[10] J.N. Bahcall, Neutrino Astrophysics (Cambridge U. Press, Cambridge, England, 1989).
[11] J.N. Bahcall, M.H. Pinsonneault, and S. Basu, Astrophys. J. 555, 990 (2001).
[12] B. Pontecorvo, Zh. Eksp. Teor. Fiz. 53, 1717 (1968) [Sov. Phys. JETP 26, 984 (1968)].
[13] Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. 28, 870 (1962).
[14] T. Kajita and Y. Totsuka, Rev. Mod. Phys. 73, 85 (2001).
[15] See, e.g., the reviews: S.M. Bilenky, C. Giunti, and W. Grimus, Prog. Part. Nucl. Phys. 43, 1 (1999); P. Langacker, in NOW 2000, Proceedings of the Neutrino Oscillation Workshop 2000 (Conca Specchiulla, Italy, 2000), ed. by G.L. Fogli, Nucl. Phys. Proc. Suppl. 100, 383 (2001); M. C. Gonzalez-Garcia and Y. Nir, hep-ph/0202058, to appear in Rev. Mod. Phys.
[16] CHOOZ Collaboration, M. Apollonio et al., Phys. Lett. B 466, 415 (1999); M. Apollonio et al., [hep-ex/0304017] to appear in Eur. Phys. J. C.
[17] Palo Verde Collaboration, F. Boehm et al., Phys. Rev. D 64, 112001 (2001).
[18] KamLAND Collaboration, K. Eguchi et al., Phys. Rev. Lett. 90, 021802 (2003). Additional information available at the sites: hep.stanford.edu/neutrino/KamLAND/KamLAND.html and kamland.lbl.gov.
[19] G.L. Fogli, G. Lettera, E. Lisi, A. Marrone, A. Palazzo, and A. Rotunno, Phys. Rev. D 66, 093008 (2002).
[20] G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, and A. Rotunno, hep-ph/0212127, submitted to Phys. Rev. D.
[21] L. Wolfenstein, Phys. Rev. D 17, 2369 (1978); S.P. Mikheev and A.Yu. Smirnov, Yad. Fiz. 42, 1441 (1985) [Sov. J. Nucl. Phys. 42, 913 (1985)].
[22] V.D. Barger, K. Whisnant, S. Pakvasa, and R.J.N. Phillips, Phys. Rev. D 22, 2718 (1980).
[23] L. Wolfenstein, in Neutrino ’78, 8th International Conference on Neutrino Physics and Astrophysics (Purdue U., West Lafayette, Indiana, 1978), ed. by E.C. Fowler (Purdue U. Press, 1978), p. C3.
[24] A.Yu. Smirnov, in Neutrino 2002 [4], hep-ph/0209131.
[25] Proceedings of LowNu 2002, 3rd International Workshop on Low Energy Solar Neutrinos (Heidelberg, Germany, 2002), to appear; transparencies available at www.mpi-hd.mpg.de/nubis/www_lownu2002. See also S. Schönert, in Neutrino 2002 [4].
[26] J. N. Bahcall, M. C. Gonzalez-Garcia, and C. Peña-Garay, J. High Energy Phys. 7, 54 (2002).
[27] A. Strumia, C. Cattadori, N. Ferrari, and F. Vissani, Phys. Lett. B 541, 327 (2002).
[28] G.L. Fogli, E. Lisi, A. Marrone, and G. Scioscia, Phys. Rev. D 60, 053006 (1999).
[29] G.L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, Phys. Rev. D 66, 053010 (2002).
[30] V. Berezinsky and M. Lissia, Phys. Lett. B 521, 287 (2001).
[31] V. Barger, D. Marfatia, K. Whisnant, and B.P. Wood, Phys. Lett. B 537, 179 (2002).
[32] V. N. Gribov and B. Pontecorvo, Phys. Lett. B 28, 493 (1969); S. M. Bilenky and B. Pontecorvo, Phys. Rept. 41, 225 (1978).
[33] S. Choubey, S. Goswami, N. Gupta, and D.P. Roy, Phys. Rev. D 64, 053002 (2001); S. Choubey, S. Goswami, and D.P. Roy, Phys. Rev. D 65, 073001 (2002).
[34] V. Berezinsky, M.C. Gonzalez-Garcia, and C. Peña-Garay, Phys. Lett. B 517, 149 (2001).
[35] F.L. Villante, G. Fiorentini, and E. Lisi, Phys. Rev. D 59, 013006 (1999).
[36] M. Maris and S.T. Petcov, Phys. Lett. B 534, 17 (2002).
[37] A. Hallin for the SNO Collaboration, in Neutrino 2002 [4].
FIG. 1: The SNO CC/NC double ratio for standard and zeroed matter effects ($a_{\text{MSW}} = 1$ and 0, respectively). The parameter $a_{\text{MSW}}$ is conventionally introduced to modulate the standard amplitude of the $\nu$ interaction energy difference $V = \sqrt{2} G_F N_e$ in matter ($V \rightarrow a_{\text{MSW}} V$). CC/NC values lower than 0.5, being reachable for $a_{\text{MSW}} = 1$ (but not for $a_{\text{MSW}} = 0$) are clearly indicative of the occurrence of matter effects in the LMA region. The exclusion of CC/NC values greater than 0.5 with high statistical significance is thus an important future goal for SNO.
FIG. 2: Bounds on $a_{\text{MSW}}$ (considered as a continuous free parameter) for unconstrained ($\delta m^2$, $\sin^2 \theta_{12}$), including current solar and CHOOZ neutrino data, as well as current or prospective KamLAND data. The solid curve refers to the fit including current KamLAND spectrum data above 2.6 MeV threshold (54 events), and shows that the hypothetical case of zeroed matter effects is already significantly disfavored. The other curves refer simulated KamLAND data, generated by assuming the LMA-I solution of Ref. [20], and statistics increased by a factor of five (dotted curve) and of ten (dashed curve). The marked preference for $a_{\text{MSW}} \simeq 1$ illustrates the possibility of assessing the standard size of solar matter effects within a factor of $\sim 2$ in future global analyses, provided that LMA-I solution is correct. See the text for details.
FIG. 3: As in Fig. 2, except that the dotted and dashed curves here refer to simulated KamLAND data for the LMA-II solution of Ref. [20]. This solution would imply a mismatch between the reconstructed best-fit values of $\delta m^2$ obtained separately from current solar data and prospective KamLAND data. The mismatch is reflected here through a reconstructed amplitude of matter effects $a_{\text{MSW}}$ typically greater than (although still compatible with) standard expectations. See the text for details.