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Neutrino physics from new SNO and KamLAND data and future prospects

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Abstract

We analyze the cumulative data from the SNO, KamLAND and other solar neutrino experiments in the standard scenario of three oscillating active neutrinos. We determine the solar neutrino oscillation parameters and obtain new bounds on θ_x. We also place constraints on the fraction of oscillating solar neutrinos that transform to sterile neutrinos with the ^{8}B flux normalization left free. Concomitantly, we assess the sensitivity of future data from the SNO and KamLAND experiments to θ_x and to the sterile neutrino content of the solar flux.

The SNO [1] and KamLAND [2] experiments have been crucial in selecting the large mixing angle (LMA) solution [3], thereby solving the long-standing solar neutrino problem. Additional KamLAND data [4] have narrowed the two-neutrino oscillation parameter space even further [4,5]. We perform a more general three-neutrino analysis of KamLAND and solar neutrino data including the cumulative salt-phase SNO data announced recently [6]. We refine the existing upper bound on θ_x.[1] We also explore if future data from KamLAND and SNO can play an important role in the study of neutrino physics beyond the determination of the primary solar oscillation parameters.

One of the main goals of ongoing and planned neutrino experiments is a measurement of θ_x, and if it is large enough, to determine if CP is violated in the neutrino sector [7]. Today, we know from

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[1] We use the notation of Ref. [7] in which δm_a^2 and δm_s^2 are the atmospheric and solar mass-squared differences, and θ_a, θ_s and θ_x are the mixing angles conventionally denoted by θ_{23}, θ_{12} and θ_{13}, respectively.

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the CHOOZ [8] and Palo Verde [9] experiments that $\sin^2 2\theta_x \leqslant 0.19$ at the 90% C.L. for $\delta m_a^2 = 0.002\ \mathrm{eV}^2$; our analysis below yields $\sin^2 2\theta_x \leqslant 0.17$. Data from the K2K experiment have established an independent and consistent bound, $\sin^2 2\theta_x \leqslant 0.45$ for the same δm_a^2 [10][2]; further support that θ_x is small is obtained from Super-Kamiokande (SuperK) atmospheric data [11]. Long-baseline experiments such as MINOS [12] and the CERN to Gran Sasso (CNGS) experiments, ICARUS [13] and OPERA [14], will begin the hunt for $\nu_\mu \to \nu_e$ transitions resulting from a nonzero θ_x in the near future. Within five years of running they could have compelling evidence for such transformations or they will strengthen the CHOOZ bound. In the meantime, however, there is a possibility that additional solar neutrino data may provide guidance on the size of θ_x. A constraint from solar neutrino data is independent of δm_a^2 so long as it is much larger than δm_s^2. This is especially important because the values of δm_a^2 from the SuperK Collaboration's analyses have shifted with additional data and refinements in the analyses (in quite a narrow range which, however, sensitively affects conclusions about the size of θ_x); compare the results from a zenith-angle analysis [15] and from an L/E analysis [16]. If δm_a^2 turns out to be smaller than $0.001\ \mathrm{eV}^2$, then the CHOOZ bound will be inoperable, and solar data will provide the most stringent bound on θ_x; even MINOS and the CNGS experiments will not do better. Although we have no reason to believe that this will be the case, we mention this as a hypothetical possibility under which solar/KamLAND data provide the best bound on θ_x. After all, the K2K experiment confirms the δm_a^2 values from SuperK at the 2σ C.L. [17].

More realistically, we investigate if future solar data can improve on the CHOOZ bound for the δm_a^2 values that are consistent with SuperK and K2K.

Another unresolved issue is whether solar neutrinos oscillate into sterile species [18]. We know from solar data that the possibility that solar neutrinos oscillate exclusively to sterile states is excluded at 7.6σ [7]. However, it is easily conceivable that solar ν_e oscillate into both active and sterile neutrinos. The latter scenario is not satisfactorily constrained at present, and significant improvement in this direction is unlikely in the near future [19]. We evaluate how future SNO and KamLAND data may confirm and somewhat improve existing bounds on a sterile fraction in the solar flux with minimal dependence on the standard solar model (SSM) and without resort to involved global analyses of strongly correlated datasets from many experiments.

All the ^{3}He proportional counter tubes or neutral current detectors are installed and are taking data for the third phase of the SNO experiment. The future NC measurement is expected to have an overall uncertainty (statistical and systematic uncertainties combined) of about 6.4%. At the same time an improved CC integrated flux measurement will be made with an expected overall uncertainty of about 5.5%. To a good approximation, these measurements will be uncorrelated with previous measurements and with each other. We use these expectations in our analyses.

In the analysis of the latest KamLAND data we take into account the fact that some of the reactors were nonoperational by using the expected number of nonoscillated events given in Fig. 1 of Ref. [4].

We employ the SSM [20] in our analyses, but treat the ^{8}B flux normalization as a free parameter throughout.

1. Sensitivity to θ_x

For the ν_e survival probability in the three-neutrino framework, we use the standard modification of the two-neutrino survival probability as derived in Ref. [21].

The regions of parameter space allowed by existing CHOOZ, KamLAND and solar data are shown in Fig. 1.

The effect of how future data from the SNO experiment will impact our knowledge of θ_x is comprehensively represented in Fig. 2. The figure clearly suggests that future SNO data will not have a significant impact on existing bounds, especially for δm_a^2 values relevant to atmospheric neutrino oscillations.

2. Sensitivity to sterile neutrinos

In a scenario in which oscillations to sterile neutrinos are allowed, the fraction of oscillating neutrinos

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[2] The aforementioned limits are quoted for two degrees of freedom.

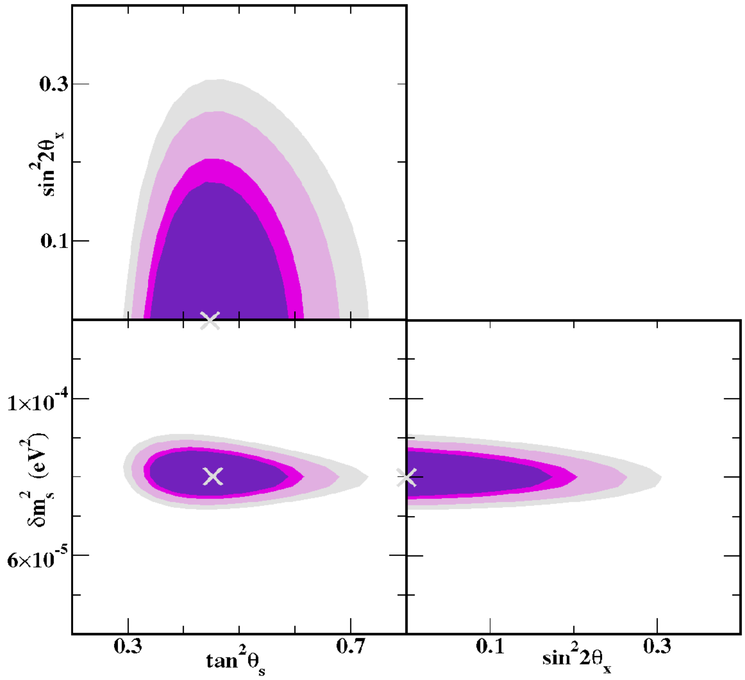

Fig. 1. The 90% C.L., 2σ, 99% C.L. and 3σ allowed regions from a combined three-neutrino fit to CHOOZ, KamLAND and solar neutrino data. The best-fit point $\delta m_s^2 = 8 \times 10^{-5}$ eV^2, $\tan^2\theta_s = 0.45$ and $\sin^2 2\theta_x = 0$ is marked with an "×". In the analysis, the ^{8}B flux was a free parameter.

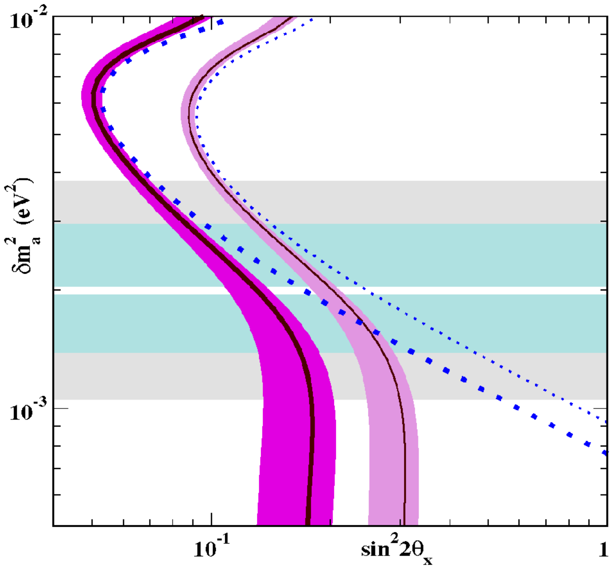

Fig. 2. Estimates of how future SNO data will affect bounds on θ_x. The shaded curved bands depict the effect of future SNO 6.4% NC and 5.5% CC measurements (whose central values lie within their current 1σ values) on bounds from all existing CHOOZ, KamLAND and solar neutrino data. The thick (thin) solid curves are the 90% C.L. (3σ) bounds from current CHOOZ, KamLAND and solar data. The dotted curves are the corresponding CHOOZ bounds. The horizontal shaded regions encompass the values of δm_a^2 favored by SuperK atmospheric data at the 90% and 99% C.L. [15]. The ^{8}B flux normalization is a free parameter in our analyses.

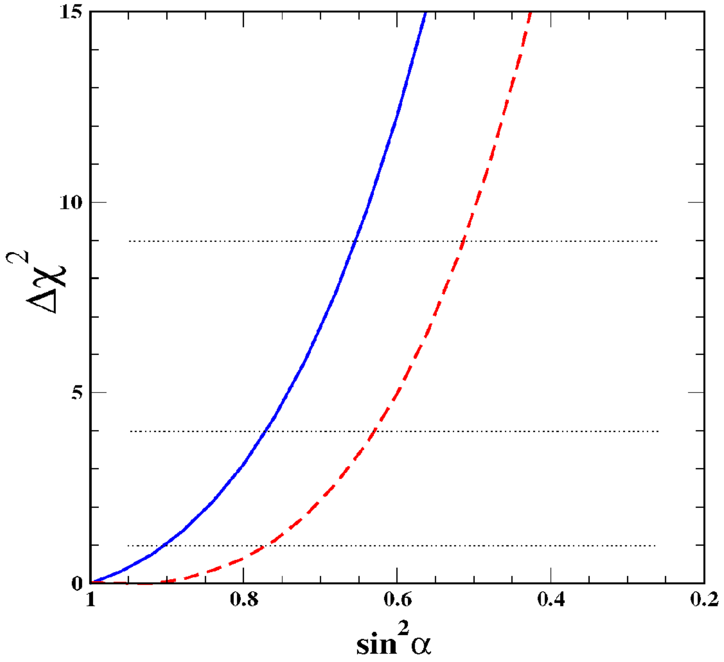

Fig. 3. $\Delta\chi^2$ vs $\sin^2\alpha$ from analyses of all solar and KamLAND data (solid), and only SNO and KamLAND data (dashed), with the ^{8}B flux free in both analyses. From bottom to top, the horizontal dotted lines indicate the $\Delta\chi^2$ values corresponding to 1σ, 2σ and 3σ.

that transform to active neutrinos is (in terms of quantities measured by SNO) [19]

$$\sin^2\alpha = \frac{\Phi_{\rm NC} - \Phi_{\rm CC}}{\Phi_{^8{\rm B}} - \Phi_{\rm CC}}. \tag{1}$$

The current constraints on $\sin^2\alpha$ are shown in Fig. 3. The most stringent bound from all available solar and KamLAND data is $\sin^2\alpha \geqslant 0.91$ (0.65) at 1σ (3σ). Our estimates are conservative since the ^{8}B flux normalization is left free in the analyses.

Our knowledge of $\sin^2\alpha$ can be refined if we can observationally infer the ^{8}B flux produced in the Sun. We now describe such a method.

The KamLAND experiment which detects $\bar{\nu}_e$ from surrounding nuclear reactors will determine the solar oscillation parameters to 10% precision independently of solar physics. These parameters can be used as inputs in analyses of SNO data to extract the average ν_e survival probability measured by SNO. The solar flux can be obtained via

$$\Phi_{^8{\rm B}} = \Phi_{\rm CC}/P_{ee}, \tag{2}$$

where P_{ee} is the average survival probability of ν_e at SNO. It has been shown in Ref. [22] that with a few years of KamLAND data, P_{ee} should be known to about 7% for parameters in the LMA region obtained from solar data. Although matter effects in the Sun depend on the active–sterile admixture, for the oscillation parameters and sterile fraction allowed by current data, they have little effect on P_{ee}.

The dotted lines in Fig. 4 are iso-$\sin^2\alpha$ lines and the solid lines are iso-$\sigma_{\sin^2\alpha}/\sin^2\alpha$ lines, or lines with the same fractional uncertainty in the $\nu_{\mu,\tau}$ content at 1σ. Although $\sin^2\alpha > 1$ values are unphysical, they are experimentally obtainable since $\Phi_{\rm NC}$ could be measured to be higher than $\Phi_{\rm SSM}$. The figure should be interpreted as follows: each point marks the central values of the $\Phi_{\rm NC}$ and $\Phi_{\rm CC}$ measurements with 6.4% and 5.5% uncertainties, respectively. The solid line passing through each point gives the corresponding $\sigma_{\sin^2\alpha}/\sin^2\alpha$. Since the expected uncertainties on $\Phi_{\rm NC}$ and $\Phi_{\rm CC}$ are incorporated in the solid lines, one should not plot the measurements with their uncertainties to read-off the envelope of $\sigma_{\sin^2\alpha}/\sin^2\alpha$.

In Fig. 4, from left to right, we show our expectations for $\sigma_{\sin^2\alpha}/\sin^2\alpha$ for $P_{ee} = 0.28$, 0.33 and 0.38, all with 7% uncertainties. Since both the solid and dotted lines have slopes higher than 2.5, both

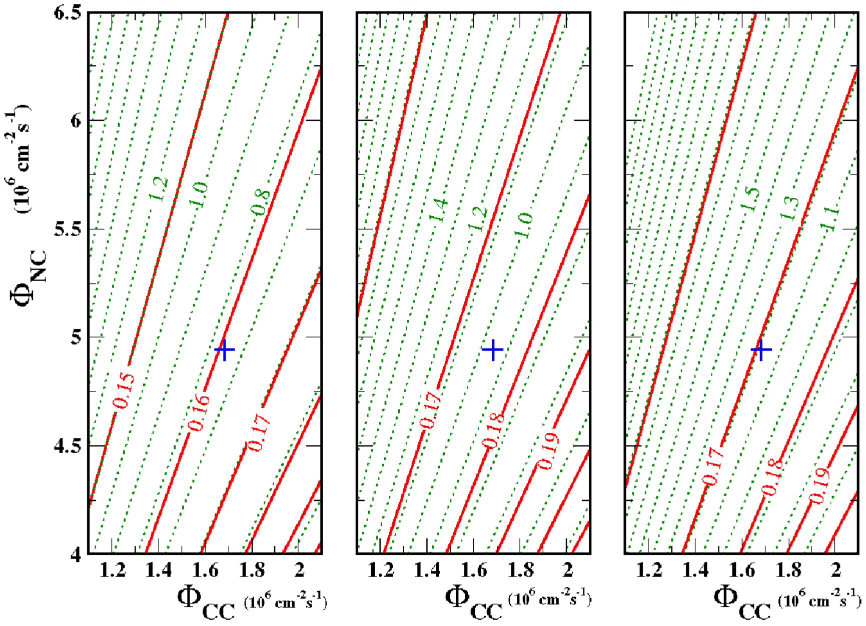

Fig. 4. Iso-$\sigma_{\sin^2\alpha}/\sin^2\alpha$ (solid) lines and iso-$\sin^2\alpha$ (dotted) lines for future 6.4% Φ_{NC} and 5.5% Φ_{CC} measurements from SNO. $\Phi_{^8B}$ is obtained from Eq. (2) and P_{ee} is determined by KamLAND with 7% uncertainty. From left to right, the three panels are for three possible measurements, $P_{ee} = 0.28$, 0.33 and 0.38, respectively. The "+" signs mark the current central values of Φ_{NC} $(= 4.94)$ and Φ_{CC} $(= 1.68)$ measured by SNO.

$\sigma_{\sin^2\alpha}/\sin^2\alpha$ and $\sin^2\alpha$ will have greater sensitivity to the value of Φ_{CC} than to the value of Φ_{NC}. We conclude that $\sigma_{\sin^2\alpha}/\sin^2\alpha$ will be known to 16–17%. These projections are comparable with existing bounds as represented by the dashed line of Fig. 3.

Since these expectations are based only on future SNO and KamLAND data, they are conservative. Further improvement can be achieved by combining with other solar data. Joint analyses of solar data are dictated by the paucity of the data. With the future availability of larger datasets it will be worthwhile to perform more definitive analyses of data from experiments which do not have correlations with each other (such as SNO and KamLAND).

3. Conclusions

In a three-neutrino framework, our analysis of all existing KamLAND, CHOOZ and solar neutrino data yields

$$\delta m_s^2 = 8.0^{+0.7}_{-0.6} \times 10^{-5}\ \mathrm{eV}^2,$$

$$\tan^2\theta_s = 0.45^{+0.17}_{-0.12},$$

where the uncertainties are at the 2σ C.L. Current bounds on θ_x are significantly improved for lower values of δm_a^2 favored by SuperK. For the SuperK best-fit $\delta m_a^2 = 0.002\ \mathrm{eV}^2$, the CHOOZ upper limit is slightly improved by KamLAND and solar data to

$$\sin^2 2\theta_x \leqslant 0.13\ (0.20)$$

at the 90% C.L. (3σ).

The fraction of solar neutrinos oscillating into active neutrinos is greater than (0.91) 0.65 at 1σ (3σ) from all existing solar and KamLAND data.

A substantially improved constraint on θ_x from future SNO data should not be anticipated unless δm_a^2 is at the lower edge of what SuperK atmospheric data prefer (in which case, the CHOOZ data are not very constraining).

With future SNO and KamLAND data alone, it will be possible to know the fraction of solar neutrinos transforming to active species to a precision of 16–17% at 1σ. This will be an important confirmation of existing bounds because the SNO and KamLAND datasets are completely uncorrelated with each other.

A nonnegligible sterile neutrino component in the solar flux incident on the earth will remain a possibility.

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