KamLAND and solar neutrino data eliminate the LOW solution

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Abstract

The KamLAND reactor antineutrino experiment has detected a 3.4\(\sigma\) flux suppression relative to the expectation if no neutrino oscillations occur. We combine KamLAND data with solar neutrino data and show that the LMA solution is the only viable oscillation solution to the solar neutrino problem at the 4.4\(\sigma\) C. L.
The neutral-current measurement at SNO convincingly demonstrated that electron neutrinos from the sun undergo a flavor transformation. Yet, the cause of this conversion was debatable. With the results from the KamLAND experiment [1], one can confidently state that the solar neutrino problem is solved. All explanations of the solar anomaly other than that neutrinos oscillate because they are massive are now either discarded or are sub-leading effects. From solar neutrino data alone, it has been deduced that the Large Mixing Angle (LMA) and LOW solutions are the most likely oscillation solutions [2]. Reactor antineutrino data from KamLAND prove that neutrinos oscillate with parameters confined to the Large Mixing Angle (LMA) region at the $3.4\sigma$ C. L. We assess how much more stronger this evidence becomes when KamLAND’s data is combined with solar neutrino data.

Since solar neutrino experiments and the KamLAND experiment have different neutrino sources, their systematics are uncorrelated and their results independent. A statistical analysis involving a combination of these two types of experiments entails two distinct analyses, one of the solar data and one of KamLAND data. Subsequently the $\chi^2$ contributions of the two are simply summed. For details and results of the solar analysis used in this work, we refer the reader to Ref. [2]. Here, we briefly describe our analysis of the KamLAND data only.

Electron antineutrinos from 20 nuclear reactors in Japan and S. Korea are incident at the KamLAND detector. About 95% of the unoscillated flux originates with baselines between 80 – 344 km. We therefore evaluate the survival probability of the neutrinos in the vacuum limit of two-flavor oscillations; the transition probability of muon to electron neutrinos is known to be small at the atmospheric neutrino oscillation scale [3]. We use the spectra from the fission products of $^{235}$U, $^{239}$Pu, $^{238}$U and $^{241}$Pu provided in Ref. [4]. We adopt the time-averaged relative fission yields from the fuel components as provided by the KamLAND collaboration [1]. This serves as a good representation of the averaging of time-evolution effects of the isotope evolution since all the reactors will not start and end their cycles at the same times. We assume that the fluctuations in the power output of each reactor arising from dead time for maintenance and seasonal variations of power requirements average so that the live times and efficiencies of all the reactors are the same. For the inverse neutron $\beta$-decay process via which antineutrinos are detected, we adopt the cross-section with nucleon recoil corrections. To determine the expected signal at KamLAND from each reactor, the fluxes are convoluted with the survival probability corresponding to the baseline of the reactor,
the antineutrino cross-section and the detector response function (with energy resolution, 7.5%/\sqrt{E\text{(MeV)}}), and prompt energy threshold at 2.6 MeV \( [1] \). Finally, the cumulative expected signal is obtained by summing over all the reactors.

To evaluate the statistical significance of an oscillation solution, we define \( \chi^2 = \chi^2_\odot + \chi^2_{\text{KamLAND}} \), where \( \chi^2_\odot \) is defined by Eq. (9) of Ref. [2], and

\[
\chi^2_{\text{KamLAND}} = \sum_{i=1}^{8} 2(\alpha N_i^{\text{th}} - N_i^{\text{exp}} + N_i^{\text{exp}} \ln \frac{N_i^{\text{exp}}}{\alpha N_i^{\text{th}}}) + \sum_{i=9}^{13} 2\alpha N_i^{\text{th}} + \left(\frac{1-\alpha}{\sigma}\right)^2. \tag{1}
\]

Here, \( N_i^{\text{th}} \) and \( N_i^{\text{exp}} \) are the theoretical and experimental numbers of events in the \( i \)-th bin (each of width 0.425 MeV) and \( \sigma = 6.42\% \) is the uncertainty in the event rate calculation \([1]\). The normalization factor \( \alpha \) is allowed to float so as to yield the smallest \( \chi^2_{\text{KamLAND}} \) for a given set of oscillation parameters.

We first show the results of an analysis of KamLAND data alone to demonstrate that our assumption that the live times and efficiencies of all the reactors are the same does not affect the allowed regions. The \( 1\sigma \) and \( 2\sigma \) allowed regions are shown. The similarities between Fig. 1 and Fig. 6 of Ref. [1] are convincing after accounting for the fact that we have chosen \( \tan^2 \theta \) as the abscissa. The best-fit solution is \( \Delta m^2 = 7.1 \times 10^{-5} \text{eV}^2 \) and \( \tan^2 \theta = 0.64 \) with \( \alpha = 1.008 \) and \( \chi^2 = 5.57 \). In the LOW region we find \( \chi^2 = 19.89 \) which is therefore acceptable only at the \( 3.4\sigma \) C. L. (KamLAND quotes 99.95% C. L. \([1]\) which is equivalent to about 3.5\( \sigma \)). Note that with solar neutrino data alone, the LOW solution is allowed at the 99% C. L. or about \( 2.6\sigma \) \([2]\). Thus, KamLAND data already constrains the LOW solution more than solar data.

In Fig. 2 we show the \( 2\sigma \) and \( 3\sigma \) allowed regions from a combined analysis of KamLAND and solar neutrino data. The best-fit solution moves to \( \Delta m^2 = 7.1 \times 10^{-5} \text{eV}^2 \) and \( \tan^2 \theta = 0.42 \) with \( \alpha = 0.994 \) and \( \chi^2 = 57.08 \). The best-fit point in the LOW region has \( \chi^2 = 79.78 \) thereby implying that the LOW solution is allowed only at 4.4\( \sigma \).

We conclude that the LMA solution is unique at the 4.4\( \sigma \) C. L. A precise determination of the oscillation parameters is now only a matter of time \([3]\).

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Figure 1: The $1\sigma$ and $2\sigma$ allowed regions from a fit to KamLAND data only. The best-fit point is at $\Delta m^2 = 7.1 \times 10^{-5} \text{eV}^2$ and $\tan^2 \theta = 0.64$. The figure is symmetric under reflection about $\tan^2 \theta = 1$. 
Figure 2: The $2\sigma$ and $3\sigma$ allowed regions from a combined fit to KamLAND and solar neutrino data. The best-fit point is at $\Delta m^2 = 7.1 \times 10^{-5} \text{ eV}^2$ and $\tan^2 \theta = 0.42$. 