Karaelmas Science and Engineering Journal
Journal home page: http://fbd.beun.edu.tr

Research Article

Upper Bound on θ_{13} from Combined Analysis of Solar Neutrino Data Together with Reactor Data

Deniz Yılmaz*

Ankara University, Faculty of Engineering, Department of Physics Engineering, 06100 Tandogan, Ankara, Turkey

Abstract

A joint analysis of solar neutrino data together with the new KamLAND data is presented with different confidence intervals and sin2(2θ13) values. It is investigated how the allowed regions are effected in those cases. Limits on sin2(2θ13) value are found at different confidence level (C. L.) intervals: sin2(2θ13) < 0.19, 0.23 at % 90 C. L. and % 95 C. L. respectively.

Keywords: Solar neutrinos, Reactor neutrinos, Neutrino mixing

1. Introduction

After first observation of the solar neutrino oscillation in Homestake neutrino experiment, serious solar, atmospheric and reactor neutrino experiments were established to confirm it during the last decades. Both KamLAND experiment detecting reactor antineutrinos (Araki et al. 2005) and global analysis of the solar neutrino experiments, high precision water Cherenkov experiments SNO (Aharmim et al. 2007) and SK (Fukuda et al. 2002) and the radiochemical experiments Homestake (Cleveland et al. 1998), SAGE (Abdurashitov et al. 1999), GALLEX (Anselmann et al. 1994) and GNO (Altmann et al. 2005), indicated the same region of the neutrino parameter space (Balantekin and Yuksel 2003). Although the allowed regions for solar and reactor neutrino experiments are in the so-called large mixing angle (LMA) region, the mass squared differences (δ) and mixing angle (θ_{12}) at their minimum chi-square are slightly differ from each other for solar and reactor data. One can think that θ_{13} can be responsible for this small effect besides the other alternative scenarios such as combined magnetic moment effect or density fluctuations in the Sun which may alter the solar neutrino flux observed or the new physics effect beyond the Standard Model (Loreti et al. 1996, Balantekin and Volpe 2005, Caldwell and Sturrock 2005, Friedland et al. 2004).

Up to now, neutrino mass-mixing parameters, θ_{12}, θ_{23}, δ, Δ have been well determined by numerous experiments except for θ_{13} and CP-violating phase δ. An observation of a non-zero value of θ_{13} is very crucial to understanding of CP violation in the lepton sector and the mass hierarchy of the neutrinos. After the KamLAND collaboration released the data in 2008 (Abe et al. 2008), first hints of the non-zero θ_{13} were shown in (Balantekin and Yilmaz 2008, Fogli et al. 2008) by combining solar and new KamLAND data. A few years later, a relatively large value of θ_{13} was suggested by T2K experiment (Abe et al. 2011). After the results of the T2K experiment, the first direct mesurements of this angle came from the Daya Bay (An et al. 2012) and RENO reactor neutrino experiments (Ahn et al. 2012). Recent experimental developments for obtaining the θ_{13} value are summarized by Balantekin (Balantekin 2012).

In this paper, a combined analysis of solar and new KamLAND data is presented in the presence of the non-zero values of θ_{13}. It is investigated how the allowed regions in the LMA region are effected as the θ_{13} value is increased. Formalism and analysis is given in the second section. In the last section, Results and Conclusion are presented.

2. Materials and Methods

In three neutrino cases, flavor eigenstates can be written in terms of the mass eigenstates through the neutrino mixing matrix $U_{\alpha i}$

$$va = \sum_{i=1}^{3} U_{\alpha i} v_i \quad (1)$$

where α and i indicate flavor index (e,μ,τ) and mass index, respectively. Pontecorvo-Maki-Sakata (PMNS) neutrino mixing matrix is (Pontecorvo 1957, Maki et al. 1962):

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (2)$$

*Corresponding author: dyilmaz@eng.ankara.edu.tr

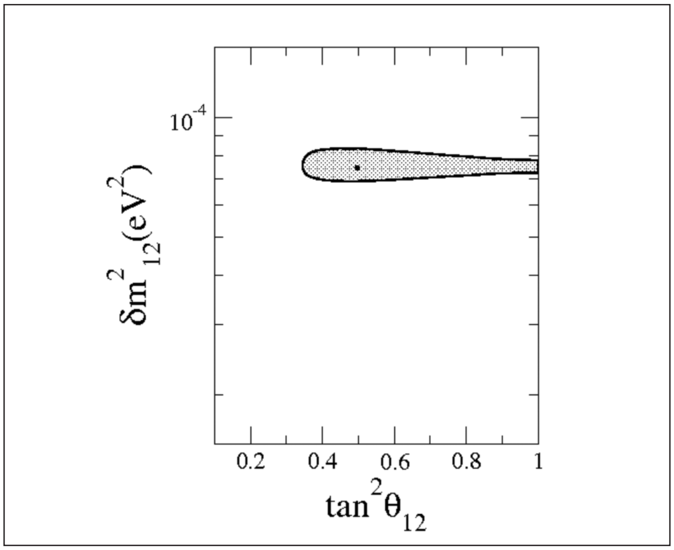

Figure 1. Allowed region for KamLAND experiment at% 95 C. L.

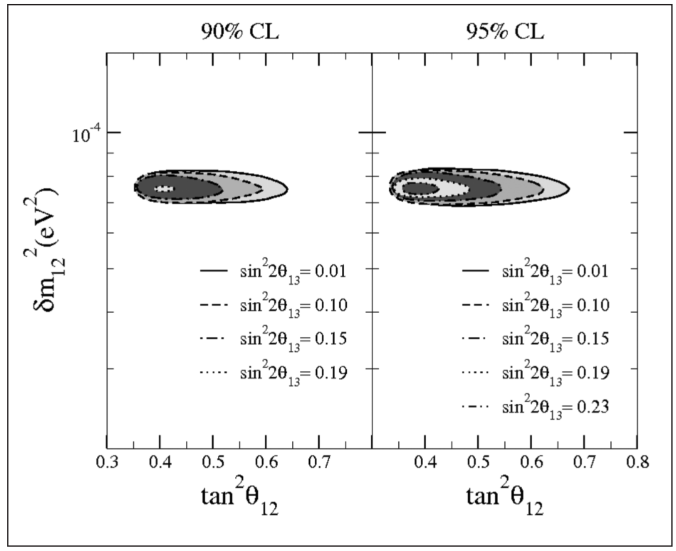

Figure 2. Three parameter analysis for the combined solar and KamLAND data at different values (% 90 C. L. (left-hand side), % 95 C. L. (right-hand side)). Countors for different values of are moving from outside to inside region for increasing θ_{13} values.

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$ and δ is the CP-violation phase. Electron survival probability for three flavors (Kuo and Pantaleone 1989, Fogli et al. 2000)

$$P_{3x3}(\nu_e \rightarrow \nu_e) = \cos^4\theta_{13}\ P_{2x2}(\nu_e \rightarrow \nu_e\ with\ N_e \cos^2\theta_{13}) + \sin^4\theta_{13} \quad (3)$$

where is the 2-flavors survival probability with electron density instead of . In our calculations, exact solutions of the neutrino evolution equations are obtained numerically. For KamLAND experiment observing reactor antineutrinos, survival probability with three flavors is

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \tfrac{1}{2}\sin^2 2\theta_{13} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2_{12}}{4E}\right) \quad (4)$$

3. Results and Conclusions

In this study, upper limits were found for the mixing angle θ_{13} by combining the solar and reactor data. Allowed region of KamLAND data at % 95 C. L. for only is shown in Figure 1. Detailed analysis for the behavior of the non-zero value of θ_{13} for solar and reactor experiments is given by Balantekin and Yilmaz (2008). In Figure 2, the allowed regions of the combined analysis of the solar neutrino and KamLAND data are given for two different confidence levels, % 90 C. L. (left-handed panel) and % 95 C. L. (right-handed panel), on different θ_{13} values. In that figure, as θ_{13} value is increased, the allowed regions in the LMA region of the neutrino parameter space are getting smaller and vanishes when is greater than 0.19 and 0.23 at %90 C. L. and %95 C. L. respectively. Since the solution of the neutrino oscillation must be in the LMA region, one can placed a limit on θ_{13} parameter from Figure 2: < 0.19, 0.23 at %90 C. L. and %95 C. L., respectively. From the recent experiments (e.g. Daya Bay and RENO), the value of the θ_{13} seems to be large compared to the previous expectations. However, in order to get more precisely θ_{13}, we need more data.

4. References

Abdurashitov, JN. et al. [SAGE Collaboration] 1999. Measurement of the Solar Neutrino Capture Rate by SAGE and Implications for Neutrino Oscillations in Vacuum. *Phys. Rev. Lett., 83: 4686-4689*

Abe, S. et al. [KamLAND Collaboration] 2008. Precision Measurement of Neutrino Oscillation Parameters with KamLAND. *Phys. Rev. Lett. 100: 221803*

Abe, K. et al. [T2K Collaboration] 2011. Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam. *Phys. Rev. Lett., 107: 041801*

Aharmim, B. et al. [SNO Collaboration] 2007. Measurement of the ν_e and Total ^{8}B Solar Neutrino Fluxes with the Sudbury Neutrino Observatory Phase I Data Set. *Phys. Rev. C, 75: 045502*

Ahn, JK. et al. [RENO Collaboration] 2012. Comment on Phys. Rev. Lett. 108, 191802 (2012): "Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment. *Phys. Rev. Lett. ,108: 191802*

Altmann, M. et al. [GNO Collaboration] 2005. Complete results for five years of GNO solar neutrino observations. *Phys. Lett. B, 616:174-190*

An, FP. et al. [DAYA-BAY Collaboration] 2012. Observation of Electron-Antineutrino Disappearance at Daya Bay. *Phys. Rev. Lett., 108: 171803*

Anselmann, P. et al. [GALLEX Collaboration] 1994. GALLEX results from the first 30 solar neutrino runs. *Phys. Lett. B, 327: 377-385*

Araki, T. et al. [KamLAND Collaboration] 2005. Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion. *Phys. Rev. Lett., 94: 081801*

Balantekin, AB. 2012., Towards a very precise knowledge of theta13. *[arXiv:hep-ph/1211.3069]*

Balantekin, AB., Volpe, C. 2005. Does the neutrino magnetic moment have an impact on solar neutrino physics? *Phys. Rev. D 72: 033008.*

Balantekin, AB., Yilmaz, D. 2008. Contrasting solar and reactor neutrinos with a non-zero value of theta13. *J. Phys. G, 35: 075007*

Balantekin, AB., Yuksel, H. 2003. Global Analysis of Solar Neutrino and KamLAND Data. *J. Phys. G, 29: 665-682.*

Caldwell, DO., Sturrock, PA. 2005. Evidence for solar neutrino flux variability and its implications. *Astropart. Phys., 23: 543-556.*

Cleveland, BT. , Daily, T. , Davis, R. Jr., Distel, JR., Lande, K., Lee, CK., Wildenhain, PS., Ullman, J. 1998. Measurement of the Solar Electron Neutrino Flux with the Homestake Chlorine Detector. *Astrophys. J. 496, 505-526.*

Fogli , GL., Lisi, E., Montanino, D., Palazzo, A. 2000. Day-night asymmetry of high and low energy solar neutrino events in Super-Kamiokande and in the Sudbury Neutrino Observatory . *Phys. Rev. D, 62: 013002*

Fogli , GL., Lisi, E., Marrone, A., Palazzo, A., Rotunno, AM. 2008. Neutrino oscillations, global analysis and theta(13). *Phys. Rev. Lett.,101: 141801.*

Friedland, A., Lunardini, C. and Pena-Garay, C. 2004. Solar neutrinos as probes of neutrino-matter interactions. *Phys., Lett., B,594: 347-354.*

Fukuda, S. et al. [Super-Kamiokande Collaboration] 2002. Determination of solar neutrino oscillation parameters using 1496 days of Super-Kamiokande I data . *Phys. Lett. B, 539: 179-187.*

Kuo, TK., Pantaleone, JT. 1989. Neutrino Oscillations in Matter. *Rev. Mod. Phys.,61: 937-979.*

Loreti, FN., Balantekin, AB. 1994. Neutrino oscillations in noisy media. *Phys. Rev. D, 50: 4762-4770.*

Maki, Z., Nakagawa, M., Sakata, S. 1962. Remarks on the unified model of elementary particles. *S., Prog. Theor. Phys.,28: 870-880.*

Pontecorvo, B. 1957. Mesonium and anti-mesonium. *Zh.Eksp. Teor.Fiz., 33: 549-551.*