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Combined Analysis of Solar Neutrino Data within The RSFP Framework Together with New KamLAND Data

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Abstract

A combined analysis of solar neutrino data together with the new KamLAND data is presented in the RSFP framework. It is investigated how the allowed regions are effected from the new KamLAND data at different μB values. Limits on μB value is found at the different confidence level intervals.

Key Words: Neutrino, magnetic moment, RSFP.

1. Introduction

Neutrino oscillations were proposed as a possible mechanism to explain the deficit between solar neutrino fluxes detected by solar neutrino experiments and the standard solar model predictions [1, 2]. Mikheyev-Simirnov-Wolfenstein (MSW) [3–5] effect is, together with vacuum oscillations, one of the most popular solutions. When a neutrino passes through matter, a resonant enhancement of neutrino oscillation appears in the MSW solution. Combined analysis of the four neutrino experiments (chlorine [6], three galium measurements [7–9], Super-Kamiokande (SK) [10, 11] and SNO [12–14]) showed that the so-called large mixing angle (LMA) region of the neutrino parameter space was the most likely solution [15–19]. Neutrino oscillation is one of the implications of the new physics beyond the Standard Model. Neutrinos have a mass and neutrino magnetic moment in a minimal extension of the Standard Model:

$$\mu_v = \frac{3eG_f m_v}{8\pi^2\sqrt{2}} = \frac{3eG_f m_e m_v}{4\pi^2\sqrt{2}}\mu_B. \tag{1}$$

μ_B is the Bohr magneton. If the neutrinos have large magnetic moments, they are affected by the solar magnetic field as they pass through the Sun. Solar magnetic field can flip their spins and change a left handed neutrino to a right handed neutrino, and thus not detectable. Okun, Voloshin and Vysotsky (OVV) [20] investigated the solar neutrino deficit assuming that neutrinos have a magnetic moment. Shortly after, the combined effect of matter and magnetic field called Resonance Spin Flavor Precession (RSFP) was examined by Akhmedov [21, 22], Barbieri and Fiorentini [23] and Lim and Marciano [24]. RSFP effect was investigated in detail by Balantekin et al. [25] via chlorine and gallium experiments; and has been studied in different aspects by others [26–31]. The combined analysis of solar neutrinos and KamLAND data [32] was examined in reference [33] and a limit on the μB was placed. Detailed discussion on neutrino magnetic moment is given in [34].

In this article, a joint analysis of the solar neutrino data within the RSFP framework together with the new KamLAND data is examined [35]. In the second secion, RSFP formalism and analysis are given. Results and conclusion are presented in section 3.

2. Formalism and Analysis

In two generations case of Dirac neutrinos, the evolution equation of a neutrino propagating through matter and in the presence of a transverse magnetic field B is

$$i\frac{d}{dt}\begin{bmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{e_R} \\ \nu_{\mu_R} \end{bmatrix} = \begin{bmatrix} \frac{\delta m^2}{2E_\nu}\sin^2\theta_{12} + V_e & \frac{\delta m^2}{4E_\nu}\sin 2\theta_{12} & \mu_{ee}B & \mu_{e\mu}B \\ \frac{\delta m^2}{4E_\nu}\sin 2\theta_{12} & \frac{\delta m^2}{2E_\nu}\cos^2\theta_{12} + V_\mu & \mu_{\mu e}B & \mu_{\mu\mu}B \\ \mu^*_{ee}B & \mu^*_{\mu e}B & \frac{\delta m^2}{2E_\nu}\sin^2\theta_{12} & \frac{\delta m^2}{4E_\nu}\sin 2\theta_{12} \\ \mu^*_{e\mu}B & \mu^*_{\mu\mu}B & \frac{\delta m^2}{4E_\nu}\sin 2\theta_{12} & \frac{\delta m^2}{2E_\upsilon}\cos^2\theta_{12} \end{bmatrix} \begin{bmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{e_R} \\ \nu_{\mu_R} \end{bmatrix}. \tag{2}$$

Here, θ_{12} is the vacuum mixing angle, δm^2 is the difference of the squares of the masses and E_ν is the neutrino energy. V_e and V_μ are matter potentials for an unpolarized medium given as

$$V_e = \frac{G_f}{\sqrt{2}}(2N_e - N_n) \qquad V_\mu = -\frac{G_f}{\sqrt{2}}N_n \tag{3}$$

where N_e and N_n are electron and neutron number densities, respectively, and G_f is the Fermi constant.

In this analysis, results are found numerically via the diagonalization of the Hamiltonian in equation (2), which is discussed in detail in [25], and magnetic field profile is taken to be Gaussian shape of the form in the convective zone, as shown in Figure 1.

It is common in the literature to calculate the best fits and confidence levels of allowed regions in the neutrino parameter space (δm^2 and $\tan^2\theta_{12}$) using χ^2 analysis [36–41]. We use the Covariance approach to find the allowed regions. In this method, least-squares function for the solar data is

$$\chi^2_\odot = \sum_{i_1,i_2}^{N_{\rm exp}} (R^{(\rm exp)}_{i_1} - R^{(\rm thr)}_{i_1})(V^{-1})_{i_1 i_2}(R^{(\rm exp)}_{i_2} - R^{(\rm thr)}_{i_2}) \tag{4}$$

where V^{-1} is the inverse of the covariance matrix of experimental and theoretical uncertainties, $R^{(\rm exp)}_i$ is event rate calculated in the $i^{\rm th}$ experiment and $R^{(\rm thr)}_i$ is the theoretical event rate calculated for $i^{\rm th}$ experiment. For all solar neutrino experiments, chlorine (Homestake), gallium (SAGE, GALLEX, GNO), Super-Kamiokande and SNO, expressions of theoretical event rates are given in detail in [42]. Finally, one needs KamLAND data for the global analysis:

$$\chi^2_{\text{Global}} = \chi^2_{\odot} + \chi^2_{\text{KamLAND}} \tag{5}$$

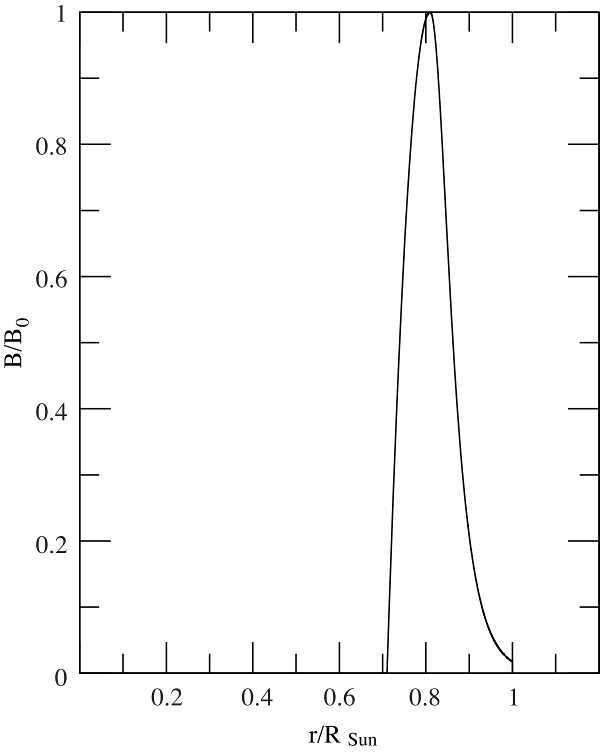

Figure 1. Magnetic field profile of Gaussian shape.

3. Results and Conclusions

In Figure 2, allowed region for KamLAND data within the MSW framework alone is shown at 95% CL. Combined analysis of solar neutrino and KamLAND data is given in Figure 3 at different μB values at 95% CL. In that figure, the allowed regions in the LMA region are getting smaller as μB value is increased and vanishes when μB is greater than $2.3 \times 10^{-7} \mu_B G$ at 95% CL. Projection of the global $\Delta\chi^2$ function on the μB is presented in Figure 4. As shown in Figure 4, the best minimum is at $\mu B = 0.8 \times 10^{-7} \mu_B G$. A limit on the μB can be found from that figure for different confidence intervals. Such as: $\mu B < 1.47 \times 10^{-7}, 2.0 \times 10^{-7}, 2.54 \times 10^{-7} \mu_B G$ for the 1σ, 2σ, 3σ limits, respectively. Direct limits of neutrino magnetic moment from new experiments will be expected lower than $\mu < 10^{-12} \mu_B$ or 1 order of magnitude lower [43–46]. According to the results found here, magnetic field B in the Sun must be higher than $10^6 G$ to get such a lower limit. However, the limit on the magnetic field is about $10^7 G$ [47]. Therefore, since μB found in this paper is too high to place such a lower limit on μ one can say that for the magnetic field profile given here RSFP scenerio does not have a crucial role on the solar neutrino data which agrees with the results of [31].

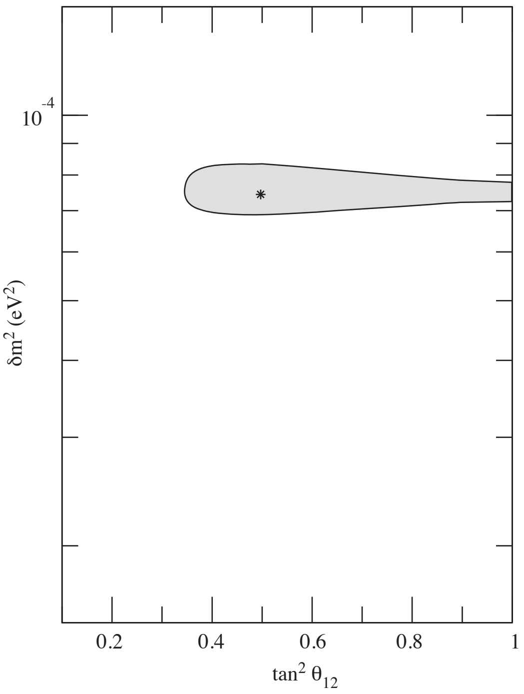

Figure 2. 95% confidence level interval allowed by KamLAND experiment within the MSW framework alone.

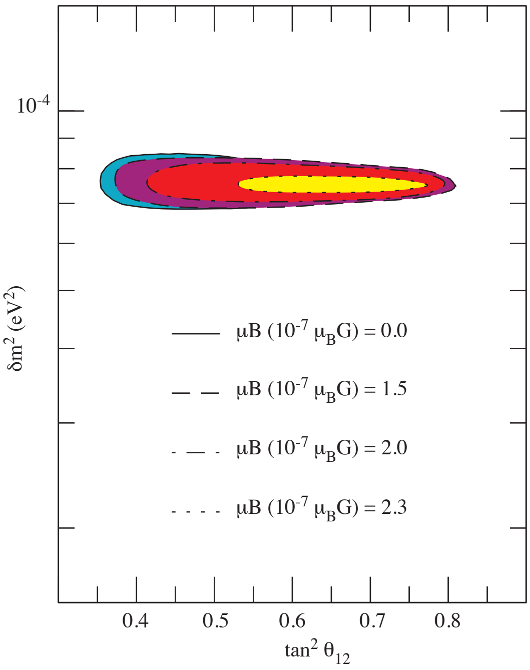

Figure 3. Three parameter 95% CL intervals for the combined analysis of the solar and KamLAND data at some different μB values. $\mu B(10^{-7}\mu_B G) = 0.0,\ 1.5,\ 2.0,\ 2.3$ from outside to inside.

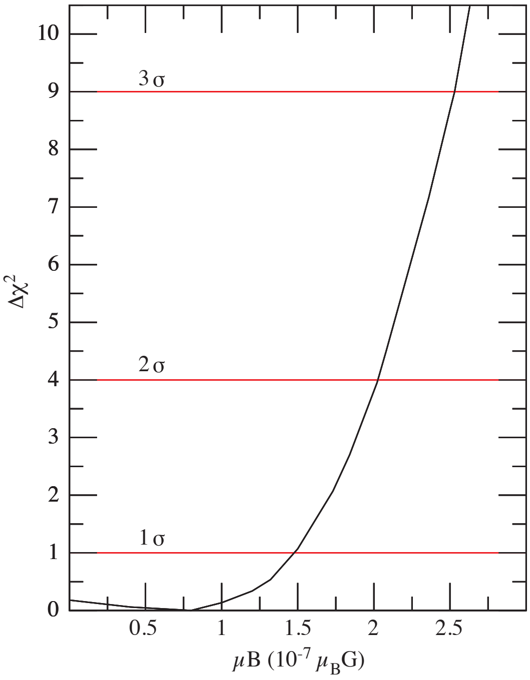

Figure 4. Projection of the global $\Delta\chi^2$ on μB.

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