Random magnetic fields inducing solar neutrino spin-flavor precession in a three generation context

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Abstract. We study the effect of random magnetic fields in the spin-flavor precession of solar neutrinos in a three generation context, when a non-vanishing transition magnetic moment is assumed between the second and third families. We have analyzed the high energy solar neutrino data and the KamLAND experiment to constrain the solar mixing angle, $\theta_\odot$, and solar mass difference, $\Delta m^2_2$, and we have found a large shift of allowed values. Also sizable effects in Borexino experiment are expected which can discriminate this scenario and standard Large Mixing Angle (LMA) solution to the solar neutrino problem.

1. Introduction

Recent results of KamLAND experiment [1] confirmed the LMA realization of the Mikheyev-Smirnov-Wolfenstein [2] phenomena as the explanation of the solar neutrino anomaly [3, 4, 5, 6, 7, 8]. We analyze here the scenario where neutrinos interact with random solar magnetic fields [9] through a non-vanishing magnetic moment between muon and anti-tau-neutrinos as a sub-leading effect in the context of LMA solution to the solar neutrino anomaly. We show that the mixed scenario of LMA with $\mu\tau$ magnetic momentum leads to change of the allowed region for $\theta_\odot$ and $\Delta m^2_2$, towards large values for $\theta_\odot$ (reaching maximal mixing) and the appearing of a very-low LMA-region for small values of $\Delta m^2_2 \sim [1 - 2] \times 10^{-5}$ eV$^2$. This scenario can be tested in future experiments like Borexino [10]. The final solar neutrino flux can be a mixing of $\nu_e$, $\nu_\mu$, $\nu_\tau$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$, which can have some interesting phenomenological consequences.

2. Formalism

We assume that the magnetic field will be composed by a regular and a random component. In general, there will be a competition between the rate in which the neutrino oscillate, given by the neutrino oscillation length, $L_{\text{osc}} \equiv \frac{4E}{\Delta m^2_2}$, and the rate of change of the random magnetic field, the coherence length $D_0$.

We decide to take the approximation called delta-correlated fluctuations [11]. The resulting neutrino evolution, averaged over a finite interval $\tau$, equals:

$$\left\langle \frac{d\rho_\mu}{dt} \right\rangle = \sum_{\nu\alpha} \langle h_{\nu\alpha} f_{\nu\alpha\mu} \rangle \rho_\alpha = \sum_{\nu\alpha} \langle h_{\nu\alpha} \rangle f_{\nu\alpha\mu} \langle \rho_\alpha \rangle + \sum_\nu L_{\mu\nu} \langle \rho_\nu \rangle , \quad \mu, \nu, \alpha = 0, \ldots, 8 , \quad (1)$$
and \( I \) is the neutrino matter potentials denoted by \( \delta \) and KamLAND data. The details of the analysis are given in Ref. [12].

The neutrino magnetic momentum between the second and third families is denoted by \( \lambda \). In all panels we used \( \tan^2 \theta = 0.4 \) in all panels. The vertical solid line denotes the position of Beryllium line and the vertical dotted line denotes the limit of validity of our approximation \((L_{\text{osc}} = D_0)\) for \( \Delta m_{23}^2 = 8 \times 10^{-5} \) eV\(^2\) and random magnetic field \( B_{\text{rand}} = 3 \) MG. The shallow area denoted the relevant neutrino energy for \( ^7\text{B} \) neutrino experiments.

where a complete set of Gell-Mann matrices is used: \( \lambda_i, (\nu = 0, ..., 8) \) (where \( \lambda_0 = \sqrt{2/3} I_3 \) and \( I_3 \) is the \( 3 \times 3 \) identity matrix) and the \( h_{ij} = \text{Trace}(H\lambda_i)/2 \) and \( \rho_{ij} = \text{Trace}(\rho\lambda_i)/2 \). Here \( H \) is the Hamiltonian given in the \((\nu_e, \nu'_\mu, \nu'_\tau)\) basis,

\[
H = \begin{pmatrix}
-\delta c_{2\beta} + V_e + V_n & \delta s_{2\beta} & 0 \\
\delta s_{2\beta} & \delta c_{2\beta} + V_e + V_n & \mu_{\nu\tau} B \exp(i\alpha) \\
0 & \mu_{\nu\mu} B \exp(-i\alpha) & \Delta - V_n
\end{pmatrix},
\]

where \( \delta = (\Delta m_{23}^2)/(4E), \Delta = (\Delta m_{32}^2 + \Delta m_{13}^2)/(4E), \Delta m_{ij}^2 \) is the mass squared difference between neutrino families \( i \) and \( j \), and \( c_{2\beta} \equiv \cos(2\theta_\odot), s_{2\beta} \equiv \sin(2\theta_\odot) \) and \( \theta_\odot \) is the solar angle. The neutrino matter potentials are denoted by \( V_e = G_F \sqrt{2} N_e(t) \) and \( V_n = G_F \sqrt{2} (-N_n(t)/2) \) where \( N_e(t) \) and \( N_n(t) \) are the number densities of the electrons and neutrons, respectively. The neutrino magnetic momentum between the second and third families is denoted by \( \mu_{\nu\tau}, B \) is the magnetic field and \( \alpha \) is a phase of magnetic field. The eigenstates \( \nu'_\mu \equiv c_{\theta_{23}} \nu_\mu + s_{\theta_{23}} \nu_\tau \), and \( \nu'_\tau \equiv -s_{\theta_{23}} \nu_\mu + c_{\theta_{23}} \nu_\tau \). The details are given in Ref. [9]. All dependence from the random magnetic field are enclosed in the parameter the parameter \( k \),

\[
k \equiv \frac{\mu^2_{\mu\tau} (B_{\text{rand}}^2)}{D_0} = 1.7 \times 10^{-17} \left[ \frac{\mu_{\mu\tau}}{10^{-11} \mu_B} \right]^2 \left[ \frac{B_{\text{rand}}}{1 \text{MG}} \right]^2 \left[ \frac{D_0}{1 \text{km}} \right] \text{eV}
\]

We obtain the probabilities \( P(\nu_e \rightarrow \nu_e), \alpha = e, \mu, \tau \) by solving numerically the Eq. (1). The effect of the random magnetic field in evolution equation can be seen in Fig. 1. The solid line represents the electronic neutrino survival probability, \( P(\nu_e \rightarrow \nu_e) \), while the dashed line is \( P(\nu_e \rightarrow \nu_e) + P(\nu_e \rightarrow \nu_\mu) \). The remaining until the no-oscillation value is the contribution of the \( P(\nu_e \rightarrow \nu_\mu) \) probability. The dot-dashed line is the survival probability for the standard LMA scenario. In all panels we used \( \tan^2 \theta = 0.4 \).

In Fig. 2 we present the allowed region for a combined analysis of high-energy solar neutrino and KamLAND data. The details of the analysis are given in Ref. [12].
3. Conclusions

We have investigated new effects in solar neutrino phenomenology due to interactions of these particles with a random solar magnetic when a non-vanishing neutrino magnetic moment linking the second and the third families is assumed.

We can see from Fig. 1 that the neutrino probabilities of $^7\text{Be}$ solar neutrinos are $P(\nu_e \rightarrow \nu_e) = 0.58\ (0.43)$ for the pure LMA scenario (for $k = 10^{-15.5}\ eV$). This scenario can be tested in Borexino experiment [10] that will detect the mono-energetic $^7\text{Be}$ solar neutrinos. The results of our analysis of SNO+Super-Kamiokande compatibility region indicate that in the presence of random magnetic fields the allowed region for $\Delta m_{21}^2$ becomes larger while higher values of $\theta_\odot$ are found as can be seen in Fig.2. We have found a totally new region of compatibility between solar neutrinos and KamLAND, which we call very-low LMA, appears at 99% C.L. for small values of $\Delta m_{21}^2 \sim [1 - 2] \times 10^{-5}\ eV^2$ and maximal mixing.

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Figure 2. Combined result for SNO [8]+Super-Kamiokande [7] and KamLAND [1] data, at 99% C.L., the black line stands for no magnetic field, the long-dashed line for $k = 10^{-15.5}\ eV$, the short-dashed line for $k = 10^{-15}\ eV$, the dotted line for $k = 10^{-14.5}\ eV$ and the dot-dashed line for $k = 10^{-14}\ eV$. Maximal mixing is allowed for $k > 10^{-14.5}\ eV$. 
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