Research Article

Combined Effect of NSI and SFP on Solar Electron Neutrino Oscillation

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The combined effect of spin-flavor precession (SFP) and the nonstandard neutrino interaction (NSI) on the survival probability of solar electron neutrinos (assumed to be Dirac particles) is examined for various values of ϵ_{11} , ϵ_{12} , and μ_B . It is found that the neutrino survival probability curves affected by SFP and NSI effects individually for some values of the parameters (ϵ_{11} , ϵ_{12} , and μ_B) get close to the standard MSW curve when both effects are combined. Therefore, the combined effect of SFP and NSI needs to be taken into account when the solar electron neutrino data obtained by low energy solar neutrino experiments is investigated.

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 neutrinos [1, 2] and the combined analysis of the solar neutrino experiments (high precision water Cherenkov experiments SNO [3, 4] and SK [5, 6] and the radiochemical experiments Homestake [7], SAGE [8], GALLEX [9], and GNO [10]) strongly pointed out the so-called large mixing angle (LMA) region of the neutrino parameter space [11–16]. One of the implications of the physics beyond the Standard Model (SM) is the neutrino oscillation. Since neutrinos have a mass in a minimal extension of the SM, they have also magnetic moment [17]:

$$\mu_\nu = \frac{3eG_f m_\nu}{8\pi^2 \sqrt{2}} = \frac{3eG_f m_e m_\nu}{4\pi^2 \sqrt{2}} \mu_B, \quad (1)$$

where G_f is Fermi constant; m_e and m_ν are the masses of electron and neutrino, respectively; and μ_B is Bohr magneton. While Majorana type neutrinos can only have off-diagonal (transition) magnetic moments, Dirac type neutrinos can have diagonal and off-diagonal magnetic moments [18, 19]. If the neutrinos have magnetic moments, they can be affected

by the large magnetic fields when they are passing through the magnetic region. Their spin can flip and the left-handed neutrino becomes a right-handed neutrino [20–24]. Thus the combined effect of the matter and the magnetic field called as spin-flavor precession (SFP) can change left-handed electron neutrino to another right-handed neutrino. This yields two other transitions ($\nu_{e_L} \rightarrow \nu_{\mu_R}$ or ν_{τ_R}) in addition to the left-handed ones (i.e., in this scenario, the conversion probability is mainly affected) [24]. In the Dirac case, since the right-handed neutrinos are considered as sterile, they are not detectable by the detectors. On the other hand, if the neutrinos are of Majorana type, this conversion yields a solar antineutrino flux which is detectable by the detectors. These conversions for both Dirac and Majorana cases can also be responsible for the solar electron neutrino deficit. So far several studies related with the SFP have been studied in different aspects [25–31]. Astrophysical and cosmological arguments [32], Supernova 1987A [33, 34], solar neutrino experiments looking neutrino-electron scattering [35], and the reactor neutrino experiments [36, 37] provide some bounds on the neutrino magnetic moment. The new limit recently was obtained by GEMMA experiment: $\mu_\nu < 2.9 \times 10^{-11} \mu_B$ at 90% CL [38]. However, another strong bound on neutrino transition magnetic moment was obtained in the presence of nonstandard neutrino-nucleus interactions by Papoulias

FIGURE 1: Magnetic field profile.

and Kosmas [39]. Detailed discussion on neutrino magnetic moment is also given elsewhere [40–45]. In addition to the knowledge about neutrino magnetic moment, the thorough information of solar magnetic fields is needed for the SFP analysis in the Sun. Despite the limited knowledge about it, some plausible profiles can be found in the literature [46, 47]. Standard solar model [47, 48] limits the solar magnetic field: ~ 20 G near the solar surface [49], 20 kG–300 kG at the convective zone [47], and $<10^7$ G at the solar center [47]. In this study the magnetic field profile is chosen as given in [46]. It has a peak at the bottom of the convective zone as shown in Figure 1.

Solar neutrinos can also be used for analyzing the physics beyond the Standard Model of the particle physics such as nonstandard forward scattering [50], mass varying neutrinos [51, 52], and long-range leptonic forces [53]. The probe of nonstandard neutrino interaction models is expected to observe in the transition region between 1 MeV and 4 MeV where the low energy solar neutrino experiments such as SNO+ will examine. Even though the data is poor in this region, the studies comparing the effects of nonstandard models on the neutrino oscillation to the standard MSW-LMA oscillation show that these effects modify the survival probability of neutrinos [50–56].

In this paper, the combined effect of nonstandard neutrino interactions (NSI) and SFP is examined in the case of two neutrino generations by assuming that the neutrinos are of Dirac type. The best fit LMA values are used for δm_{12}^2 and θ_{12} [57]. It is shown that the neutrino survival probability curves affected by SFP and NSI effects individually for some values of the parameters (ϵ_{11} , ϵ_{12} , and μB) get close to the standard MSW curve when both effects are combined. Therefore, one can say that the combined effect of them needs

to be taken into account when the solar electron neutrino data obtained by low energy solar neutrino experiments is investigated. Another analysis on the SFP effect in the presence of the NSI is examined for Majorana type solar neutrinos in [58].

2. Spin-Flavor Precession (SFP) including Nonstandard Neutrino Interaction (NSI)

The evolution equation including NSI matter effects in the SFP scenario for Dirac neutrinos can be written as

$$i \frac{d}{dt} \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{e_R} \\ \nu_{\mu_R} \end{pmatrix} = \begin{pmatrix} H_L + H_{\text{NSI}} & BM^\dagger \\ BM & H_R \end{pmatrix} \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{e_R} \\ \nu_{\mu_R} \end{pmatrix}, \quad (2)$$

where H_L , H_R , H_{NSI} , and M are the 2×2 submatrices and B is the transverse magnetic field [24, 50]. For the Dirac neutrinos one writes down

$$H_L = \begin{pmatrix} V_c + V_n + \frac{\delta m_{12}^2}{2E} \sin^2 \theta_{12} & \frac{\delta m_{12}^2}{4E} \sin 2\theta_{12} \\ \frac{\delta m_{12}^2}{4E} \sin 2\theta_{12} & V_n + \frac{\delta m_{12}^2}{2E} \cos^2 \theta_{12} \end{pmatrix}, \quad (3)$$

and $H_R = H_L$ ($V_c = 0 = V_n$). The matter potentials here are given as

$$\begin{aligned} V_c &= \sqrt{2} G_F N_e, \\ V_n &= -\frac{G_F}{\sqrt{2}} N_n, \end{aligned} \quad (4)$$

where N_e and N_n are electron and neutron density, respectively [59–61]. The magnetic moment matrix for the Dirac neutrinos in (2) is written as [24]

$$M = \begin{pmatrix} \mu_{ee} & \mu_{e\mu} \\ \mu_{\mu e} & \mu_{\mu\mu} \end{pmatrix}. \quad (5)$$

The NSI contributions in (2) can be parametrized by four-fermion operator as given in [50]:

$$\begin{aligned} \mathcal{L} &= -2\sqrt{2} G_F (\nu_\alpha \gamma_\rho \nu_\beta) \left(\epsilon_{\alpha\beta}^{f\bar{f}L} \bar{f}_L \gamma^\rho \bar{f}_L + \epsilon_{\alpha\beta}^{f\bar{f}R} \bar{f}_R \gamma^\rho \bar{f}_R \right), \end{aligned} \quad (6)$$

where $\epsilon_{\alpha\beta}^{f\bar{f}P}$ denotes the strength of the nonstandard interaction between α and β types of neutrinos and the P (left- or right-handed) components of the fermions f and $\bar{f}$. Since the neutrino propagation can only be effected by the vector components where $f = \bar{f}$ of the nonstandard interaction ($\epsilon_{\alpha\beta}^f = \epsilon_{\alpha\beta}^{ffL} + \epsilon_{\alpha\beta}^{ffR}$), one can define $\epsilon_{\alpha\beta}$ as the sum of the contributions from electrons, up quarks and down quarks in

FIGURE 2: Survival probabilities for MSW-LMA prediction alone (solid lines), SFP effect at different μB values (dotted lines), NSI effect alone (dashed lines), and the combined effect of the NSI and SFP (dotted-dashed lines). Each column uses the same ϵ_{11} and ϵ_{12} values, and each row uses the same μB values.

matter: $\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \epsilon_{\alpha\beta}^f N_f / N_e$. Then, the three-flavor NSI Hamiltonian can be written as

$$H_{\text{NSI}}^{3 \times 3} = V_c \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}. \quad (7)$$

After performing a rotation to $H_{\text{NSI}}^{3 \times 3}$ by using the two factors of the neutrino mixing matrix, $T_{13} T_{23}$,

$$T_{13}^\dagger T_{23}^\dagger H_{\text{NSI}}^{3 \times 3} T_{13} T_{23}, \quad (8)$$

and decoupling the third flavor as in the standard three-flavor neutrino oscillation calculations, one can find the 2×2 neutrino nonstandard interaction (NSI) part in (2) as

$$H_{\text{NSI}} = V_c \begin{pmatrix} 0 & \epsilon_{12}^* \\ \epsilon_{12} & \epsilon_{11} \end{pmatrix}, \quad (9)$$

where ϵ_{11} and ϵ_{12} are the contributions from the new physics related to the original vectorial couplings, $\epsilon_{\alpha\beta}$, given as

$$\begin{aligned} \epsilon_{11} = & \epsilon_{\mu\mu} c_{23}^2 - (\epsilon_{\mu\tau} + \epsilon_{\mu\tau}^*) s_{23} c_{23} + \epsilon_{\tau\tau} s_{23}^2 - \epsilon_{ee} c_{13}^2 \\ & + s_{13} [(e^{-i\delta} \epsilon_{e\mu} + e^{i\delta} \epsilon_{e\mu}^*) c_{13} s_{23} \\ & + (e^{-i\delta} \epsilon_{e\tau} + e^{i\delta} \epsilon_{e\tau}^*) c_{13} c_{23}] - s_{13}^2 [(\epsilon_{\mu\tau} + \epsilon_{\mu\tau}^*) s_{23} c_{23} \\ & + \epsilon_{\mu\mu} s_{23}^2 + \epsilon_{\tau\tau} c_{23}^2], \\ \epsilon_{12} = & c_{13} (\epsilon_{e\mu} c_{23} - \epsilon_{e\tau} s_{23}) + s_{13} e^{i\delta} [\epsilon_{\mu\tau} s_{23}^2 - \epsilon_{\mu\tau}^* c_{23}^2 \\ & - (\epsilon_{\mu\mu} - \epsilon_{\tau\tau}) s_{23} c_{23}]. \end{aligned} \quad (10)$$

Here $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$ and δ is the CP-violating phase that we will ignore in our discussion [54].

The direct bounds on the NSI parameters come from atmospheric neutrino experiments (Super-Kamiokande,

FIGURE 3: Allowed regions in the $(\epsilon_{11}, \mu B)$ and $(\epsilon_{12}, \mu B)$ planes at 90% CL for 10 MeV neutrino energy.

Ice-Cube-79) [62, 63], accelerator neutrino experiments (MINOS) [64], and some phenomenological studies [65–68]: $|\epsilon_{ee}| \lesssim 0.5$ [62], $|\epsilon_{e\tau}| \lesssim 0.5$ [62], $|\epsilon_{\mu\tau}| \lesssim 6 \times 10^{-3}$ [63], $|\epsilon_{\tau\tau} - \epsilon_{\mu\mu}| \lesssim 3 \times 10^{-2}$ [63], $-0.067 \leq \epsilon_{\mu\tau} \leq 0.023$ [64]. The effects of NSI were also studied by using data of reactor neutrino experiment, Daya Bay, [69] and solar neutrino experiments [70]. Detailed analysis on the nonstandard neutrino interactions and their limits is given in [71, 72].

3. Results and Conclusions

In this analysis the combined effect of the nonstandard neutrino interaction and SFP on the survival probability of solar electron neutrinos (assumed to be Dirac particles) is examined for various values of ϵ_{11} , ϵ_{12} , and μB . Results presented here are obtained numerically by diagonalizing the Hamiltonian in (2). In the calculations, the magnetic field profile given in Figure 1 is chosen as a Gaussian shape extending over the entire Sun [46] and the MSW-LMA best fit values are used: $\delta m_{12}^2 = 7.54 \times 10^{-5} \text{ eV}^2$ and $\sin^2 \theta_{12} = 0.308$ [57].

Electron neutrino survival probabilities plotted as a function of neutrino energy are shown in Figure 2 for all situations: MSW-LMA prediction alone (solid lines), SFP alone (dotted lines), MSW-LMA + NSI (dashed lines), and SFP + NSI (dotted-dashed lines). In this figure, different from the SFP effect seen for all neutrino energies, the new physics effects change the standard MSW-LMA curve especially at the energies of $E \gtrsim 1 \text{ MeV}$ in which the region of $E \gtrsim 3.5 \text{ MeV}$ is well examined by the solar neutrino experiments SNO and SK. When the combined effect of them (SFP + NSI) is considered, the curves get closer to the standard curve than the curves affected by them individually for some values of the parameters (ϵ_{11} , ϵ_{12} , and μB). A similar result was found in another analysis examined for Majorana neutrinos for only one NSI parameter, ϵ_{12} [58]. However, compared to the Dirac case presented here, SFP effect is seen at almost ten times larger μB values in the Majorana case.

The allowed regions obtained by using the SNO results [73] are shown in Figure 3 in the $(\epsilon_{11}, \mu B)$ and $(\epsilon_{12}, \mu B)$ planes at 90% CL for 10 MeV neutrino energy. Even though

the values of NSI parameters are expected to be very small ($\lesssim 10^{-2}$), the large values of them are in the allowed regions when considering the SFP and NSI effects together. It is seen that the current solar neutrino data constrain the μB and $(\epsilon_{11}, \epsilon_{12})$ values poorly. A practical limit on them can be expected from the data obtained by the new low energy ($1 \text{ MeV} \lesssim E \lesssim 4 \text{ MeV}$) solar neutrino experiments such as SNO+ [74] probing the evidence of new physics effect. However, as it can be seen from the analysis presented here, the combined effect of SFP and NSI needs to be taken into account when the solar electron neutrino data obtained by new solar neutrino experiments is analyzed.

Competing Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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