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SFP effect on Majorana type solar neutrinos in the presence of nonstandard neutrino interactions

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Abstract: Assuming neutrinos are Majorana particles, neutrino oscillation is examined in the case of spin flavor precession (SFP) and nonstandard neutrino interaction (NSI). It is seen that the combined effect of them (SFP and NSI) is not ignorable for the neutrino oscillation.

Key words: Nonstandard neutrino interaction, spin-flavor precession, solar neutrinos, Majorana

1. Introduction

Various solar, atmospheric, and reactor neutrino experiments were established to confirm the neutrino oscillation over the last two decades [1–10]. The so-called LOW region ($\delta m_{12}^2 \sim 10^{-7} eV^2$) and the so-called LMA region ($\delta m_{12}^2 \sim 10^{-5} eV^2$) in the neutrino parameter space are identified from combined analysis of the solar neutrino experiments, while the KamLAND reactor neutrino experiment indicates only the LMA region. The confirmation of the neutrino oscillation by the experiments established that neutrinos have mass, which is one of the implications of physics beyond the minimal standard model. In a minimal extension of the standard model, neutrinos have also magnetic moment. For Dirac neutrinos, one writes the following:

$$\mu_\upsilon = \frac{3eG_f m_\upsilon}{8\pi^2\sqrt{2}} = \frac{3eG_f m_e m_\upsilon}{4\pi^2\sqrt{2}}\mu_B, \tag{1}$$

where G_f is the Fermi constant; m_e and m_ν are the masses of electron and neutrino, respectively; e is the proton charge; and μ_B is the Bohr magneton. Besides the limits on the neutrino magnetic moment obtained by astrophysical arguments [11], solar neutrino experiments combined with the KamLAND data [12], and the reactor neutrino experiments [13,14], the new limit recently was obtained by the GEMMA experiment: $\mu_\nu < 2.9 \times 10^{-11}\mu_B$ at 90% CL [15]. Detailed discussion on neutrino magnetic moment is given in [16].

Since neutrinos have magnetic moment, they can be affected by the magnetic fields throughout the sun. This effect together with matter effect, called spin flavor precession (SFP), can also be responsible for the solar electron neutrino deficit by changing flavor and type of the neutrinos: a left-handed neutrino becomes a right-handed type of neutrino [17–20]. As distinct from the Dirac case, the right-handed neutrino is called an antineutrino in the Majorana case. Even though the information about the solar magnetic field is not well known, some bounds and different profiles can be found in the literature [21–23]. The SFP effect has been investigated by several studies in different aspects [24–29].

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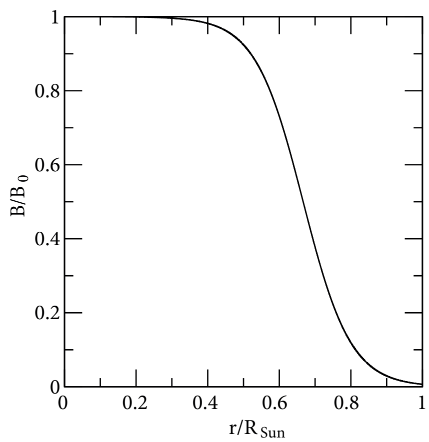

Figure 1. Magnetic field profile.

Solar neutrinos can also be used for the analysing the physics beyond the standard model of particle physics, such as flavor-changing neutral currents [30], mass-varying neutrinos [31] and long-range leptonic forces [32]. It is found that the MSW parameters in the LMA region are affected in the presence of nonstandard neutrino interaction (NSI) [33].

In this paper, neutrinos are assumed to be Majorana type. Combined effect of SFP and NSI for the LMA region is investigated in the case of two neutrino generations. Magnetic field profile is taken to be the Woods–Saxon shape of the form.

2. Formalism and analysis

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

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \overline{\nu}_e \\ \overline{\nu}_\mu \end{pmatrix} = \begin{pmatrix} H_{MSW}+H_{NSI} & H^{\dagger}_{Mag} \\ H_{Mag} & \overline{H}_{MSW}+\overline{H}_{NSI} \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \overline{\nu}_e \\ \overline{\nu}_\mu \end{pmatrix}, \tag{2}$$

where H_{MSW}, H_{NSI}, and H_{Mag} (and also those with bars) are 2×2 submatrices. The MSW part is given by

$$H_{MSW} = \begin{pmatrix} V_c + V_n + \frac{\delta m^2_{12}}{2E} sin^2\theta_{12} & \frac{\delta m^2_{12}}{4E} sin2\theta_{12} \\ \frac{\delta m^2_{12}}{4E} sin2\theta_{12} & V_n + \frac{\delta m^2_{12}}{2E} cos^2\theta_{12} \end{pmatrix}. \tag{3}$$

The matter potentials are given as

$$V_c = \sqrt{2}G_F N_e \quad V_n = -\frac{G_F}{\sqrt{2}}N_n, \tag{4}$$

where N_e and N_n are electron and neutron density, respectively, and G_F is the Fermi constant.

The neutrino NSI part is

$$H_{NSI} = V_c \begin{pmatrix} 0 & \epsilon^*_{12} \\ \epsilon_{12} & \epsilon_{11} \end{pmatrix}, \tag{5}$$

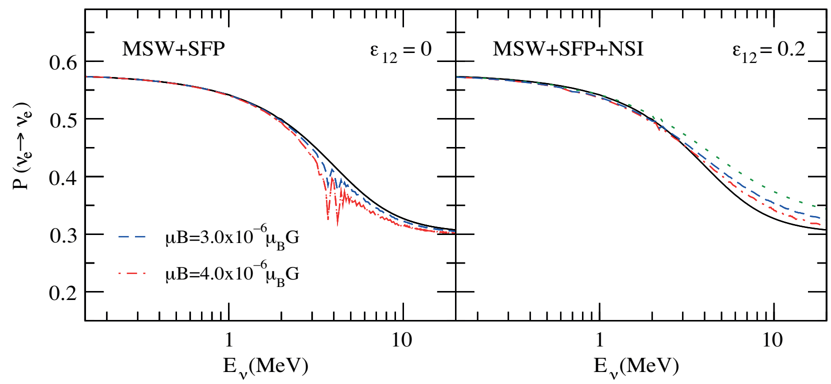

Figure 2. Survival probabilities with (left panel) and without (right panel) NSI parameter in the SFP framework. Solid line represents the MSW-LMA prediction alone in both panels. μB values are taken to be $\mu B = 3.0 \times 10^{-6} \mu_B G$ (dashed lines) and $\mu B = 4.0 \times 10^{-6} \mu_B G$ (dotted-dashed lines). Dotted line in right panel represents NSI effect alone for $\epsilon_{12} = 0.2$.

where ϵ_{11} and ϵ_{12} are the contributions from the new physics given as

$$\epsilon_{11} = \epsilon_{ee} - \epsilon_{\tau\tau} sin^2\theta_{23}, \;\; \epsilon_{12} = -2\epsilon_{e\tau} sin\theta_{23}.$$

Here $\epsilon_{\alpha\beta}$ is the NSI matter effect between the neutrinos of flavors α and β, which depends on the chemical composition of the medium [30]. $\overline{H}_{MSW}$ and $\overline{H}_{NSI}$ can be found by replacing $V_{c,n}$ with $-V_{c,n}$ in H_{MSW} and H_{NSI}.

The magnetic part of Eq. (2) is

$$H_{Mag} = \begin{pmatrix} 0 & -\mu B \\ \mu B & 0 \end{pmatrix}, \tag{6}$$

where μ and B are the transition magnetic moment and the magnetic field, respectively. Unlike the Dirac neutrinos that have diagonal and off-diagonal magnetic moments, Majorana neutrinos have only off-diagonal magnetic moments. The magnetic field is choosen as a Woods–Saxon shape of the form throughout the sun, given in Figure 1.

3. Conclusion

In this analysis it is assumed that the neutrinos are Majorana type and the magnetic field extends over the entire sun for profile of the Woods–Saxon shape given in Figure 1. MSW-LMA best fit values are used in the calculations: $\delta m^2_{12} = 7.54 \times 10^{-5} eV^2$ and $sin^2\theta_{12} = 0.308$ [34]. The effect of NSI and SFP on the solar electron neutrino survival probability is examined. The NSI parameters are choosen within the allowed regions calculated in [35]: $(\epsilon_{11}, \epsilon_{12}) = (0, 0.2)$. The results are shown in Figure 2. In that figure, electron neutrino survival probabilities are plotted as a function of energy for all situations. Namely, while the SFP cases for $\mu B = 3.0 \times 10^{-6} \mu_B G$ (dashed) and $4.0 \times 10^{-6} \mu_B G$ (dotted-dashed) values are shown only in the left panel, total effects of NSI and SFP are shown in the right panel. The solid lines represent the MSW-LMA prediction alone in both panels and the dotted line in the right panel represents NSI effect alone. Dashed lines and dotted-dashed lines in the right panel represent the combined effect of NSI and SFP for $\epsilon_{12} = 0.2$ at

$\mu B = 3.0 \times 10^{-6}\mu_B G$ and $4.0 \times 10^{-6}\mu_B G$, respectively. As seen in Figure 2, the new physics effect changes the standard MSW survival probability at the region of $E \gtrsim 3$ MeV, well examined by the solar neutrino experiments SNO and SK. When considering the SFP and NSI effects together, the change in the curve gets close to the standard curve at that region. Although we have not had strong bounds on the NSI parameters yet, one can generalize this study for other values of $(\epsilon_{11}, \epsilon_{12})$ and μB. The evidence of new physics is expected to be observed in the the range of 1MeV $\lesssim E \lesssim 3$ MeV by new experiments such as the SNO+ experiment. Thus, the stronger limits can be obtained from the low energy solar neutrino experiments and neutrino phenomenology. In summary, even though the solar magnetic field is not well known inside the sun and despite the loose bounds on the NSI parameters, it is seen that the SFP effect has an important role on electron neutrino survival probability affected by NSI. Therefore, one can say that the combined effect of them (SFP and NSI) is not ignorable for the neutrino oscillation.

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