New Physics with Scalar and Dark Non-Standard Interactions in Neutrino Oscillation

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Abstract. The neutrino oscillation can arise from not just the genuine neutrino mass term but also neutrino non-standard interactions with the environmental matter or dark matter (DM). It is true that neutrino oscillation indicates some new physics beyond the Standard Model, but it is not necessarily a genuine neutrino mass term. We point out two possibilities of the scalar or dark non-standard interactions (NSI), both of which can induce correction to the neutrino mass term in the effective Hamiltonian that describes neutrino oscillation and hence opens the possibility of faking the neutrino mass term.

1. Introduction

The neutrino oscillation was first proposed by B. Pontecorvo in 1958 to happen in the vacuum. Later in 1978, L. Wolfenstein introduced the matter effect into the study of neutrino oscillation [1]. In the same paper, Wolfenstein pointed out that "*even if all neutrinos are massless it is possible to have oscillations occur when neutrinos pass through matter*"[1]. This matter effect latter leads to the discovery of the MSW effect which is the key of resolving the "*missing solar neutrino*" problem. The matter effect is as important as the neutrino mass, if not more.

Again, the same paper by Wolfenstein has also discussed the vector-type NSI, although subject to the permutation symmetry among different neutrino flavors. For generality, we parametrize the vector mediation as

$$\mathcal{L}_{\text{vector NSI}}^{\text{eff}} = \frac{g_{\alpha\beta}g_{\rho\sigma}^*}{2} \frac{1}{q_V^2 - m_V^2} \left(\overline{\nu_\alpha}\gamma_\mu P_L \nu_\beta\right) \left(\overline{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right) , \tag{1}$$

where q_V^2 is the momentum transfer. As indicated by the vector-vector-current form, this effective vertex is mediated by some vector boson. Considering only neutral vector mediator, the induced matter potential from forward scattering has vanishing momentum transfer, $q^2 = 0$, by definition. Correspondingly, the effective Hamiltonian for describing the neutrino oscillation receives an extra matter potential

$$\mathcal{H} = \frac{M_\nu M_\nu^\dagger}{2E_\nu} + V_{\text{cc}} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \equiv \frac{M_\nu M_\nu^\dagger}{2E_\nu} + V_{\text{SI}} + V_{\text{NSI}} , \tag{2}$$

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[1] Slightly different from the oscillation driven by neutrino mass, "*the oscillation length in mass of normal density is of the order 10^9 cm or larger*".

where $V_{\text{SI}} \equiv V_{\text{cc}}\text{diag}\{1,0,0\}$ stands for the matter potential induced by the SM interactions while V_{NSI} for those by the vector NSI as parameterized by the $\epsilon_{\alpha\beta}$ parameters.

2. The Scalar NSI

It is then natural to ask the question whether a scalar mediator can also induce some NSI. We are not the first to ask such question. But some earlier studies concluded that the scalar NSI should have exactly the same consequences on neutrino oscillation as the vector NSI and hence needs not to be studied separately. When talking about the nonstandard matter effect, usually only the name "NSI" is used with the vector NSI as a protocol.

We found that this is very misleading since the scalar NSI actually has totally different phenomenological consequences from the vector NSI. Similar to (1), we can parametrize the scalar mediation as

$$\mathcal{L}_{\text{scalar NSI}}^{\text{eff}} = \frac{y_{\alpha\beta}y_{\rho\sigma}^*}{q_S^2 - m_S^2}\left(\overline{\nu_\alpha}\nu_\beta\right)\left(\overline{\ell}_\sigma\ell_\rho\right)\,, \tag{3}$$

where $y_{\alpha\beta}$ are Yukawa couplings. Intuitively thinking, the effect induced by a scalar mediator should appear as correction to the neutrino mass term,

$$\mathcal{H} = \frac{(M + \delta M)(M + \delta M)^\dagger}{2E_\nu} + V_{\text{SI}} + V_{\text{NSI}}\,, \tag{4}$$

which is verifiable by explicit derivations [2]. The mass correction is proportional to Yukawa couplings and inversely proportional to the mediator mass, $\delta M \propto y^2/m_S^2$. To obtain certain size effect, the coupling and the mediator mass can proportionally adjust with large enough parameter space.
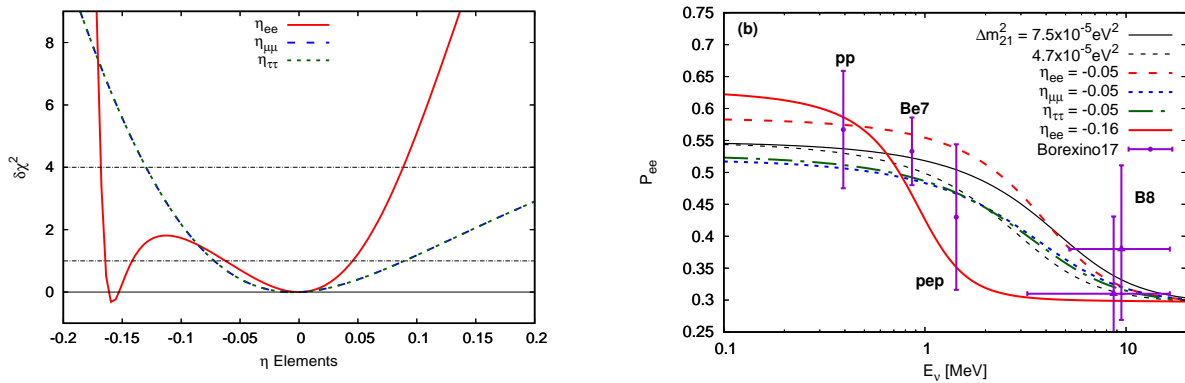
Figure 1. (Left) The χ^2 fit of the scalar NSI to the Borexino 2017 data and (Right) the effect on the solar neutrino oscillation probability P_{ee}. The scalar NSI elements are parametrized as $\delta M_{\alpha\beta} \equiv \sqrt{|\Delta m_{31}^2|}\eta_{\alpha\beta}$.

For comparison, we also keep the vector NSI term V_{NSI} in (4). The fact that the vector and scalar NSI appear at different places lead to totally different phenomenological consequences. While the effect of the vector NSI is proportional to the neutrino energy E_ν, the effect of the scalar NSI is independent of E_ν. Consequently, the vector NSI is important only at high energy neutrino oscillation experiments while the scalar NSI is important regardless of the neutrino energy. The recent low-energy Borexino 2017 data prefers nonzero scalar NSI, $\eta_{ee} = -0.16$, see the left panel of Fig. 1.

Since the scalar NSI comes from the forward scattering with the ordinary matter, its size is proportional to the matter density. Consequently, it is possible to distinguish the constant

genuine neutrino mass from the effective neutrino mass induced by the scalar NSI that can vary with matter density. The neutrino oscillation that experiences variation of matter density, such as the atmospheric or solar neutrino oscillations, can then provide a way of detecting the scalar NSI. It is then very important to have a synergy of different types of neutrino oscillation experiments to disentangle the genuine neutrino mass matrix and the scalar NSI. In this way, the measurement of the neutrino mixing parameters can be unambiguous.

3. The Dark NSI

The space is filled with not just the ordinary matter but also DM which is strongly supported by various evidences from astrophysics and cosmology. The propagating neutrinos can also feel extra NSI if there is interaction between neutrinos and DM. For a bosonic (scalar ϕ or vector V) DM with (Yukawa or gauge) coupling with neutrinos, the forward scattering in Fig. 2 can happen and neutrino oscillation receives the dark NSI.
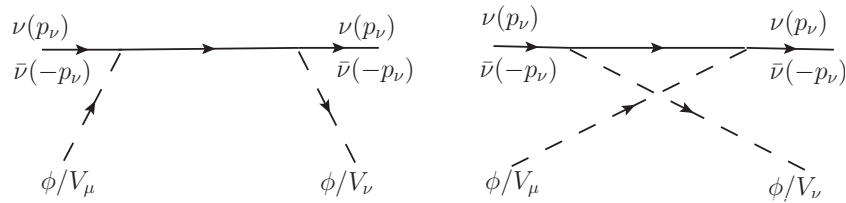
Figure 2. The neutrino forward scattering with scalar ϕ or vector (V) DM particles.

For both the scalar and vector DM cases, the dark NSI appear as correction to the neutrino mass squared term,

$$\mathcal{H} = \frac{MM^\dagger}{2E_\nu} - \frac{1}{E_\nu}\sum_j y_{\alpha j}y_{j\beta}^* \frac{\rho_\chi}{m_\phi^2} \equiv \frac{MM^\dagger + \delta M^2}{2E_\nu}, \tag{5}$$

where $\rho_\chi \approx 0.47\,\mathrm{GeV/cm^3}$ is the DM mass density. Similar to the scalar NSI, the effect of the mass-squared correction δM^2 is also independent of the neutrino energy E_ν and hence can be important for all neutrino oscillation experiments. For the scalar DM case, the two Yukawa vertices can flip the chirality twice, conserving the neutrino chirality, and hence contradicts with the mass correction δM^2 that seems to flip the chirality. This is not a problem at all. The $\delta M^2/2E_\nu$ actually comes from potential correction associated with γ_0 that does conserve chirality and gets promoted as mass-squared correction only because of the $1/E_\nu$ dependence.

Assuming that the measured neutrino mass matrix is the genuine one and adding the dark NSI as perturbations, a nonzero dark NSI, $\eta_{e\mu} = -\eta_{e\tau} \approx -0.016$ is also preferred by the recent Borexino 2017 and SK-IV data, shown as the χ^2 in the left panel of Fig. 3. At the 2σ confidence level, $\eta_{e\mu}$ and $\epsilon_{e\tau}$ can be as large as ± 0.03 and can further relax to ± 0.1 at the 3σ confidence level. This estimation is very conservative. Especially, all neutrino oscillation experiments until now are done within the solar system where the DM density is almost constant. The environmental dark NSI δM^2 can readily fake the neutrino mass term. Turning off the genuine mass term M^2, the environmental δM^2 alone can perfectly fit all the neutrino oscillation data. Neutrino oscillation cannot uniquely point to the genuine neutrino mass term.

4. Comparison and Conclusion

Putting everything together, (4) becomes

$$\mathcal{H} = \frac{(M + \delta M)(M + \delta M)^\dagger + \delta M^2}{2E_\nu} + V_{\mathrm{SI}} + V_{\mathrm{NSI}}, \tag{6}$$
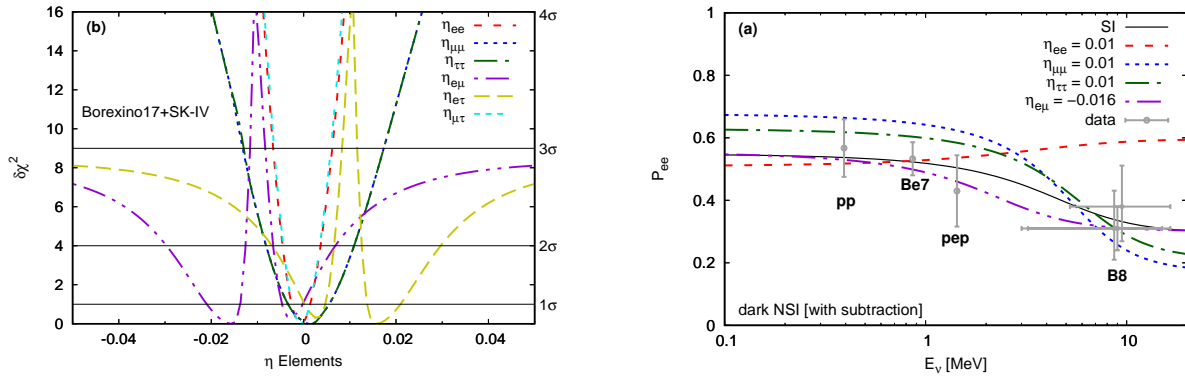
Figure 3. (Left) The χ^2 fit of the dark NSI to the Borexino 2017 + SK-IV data and (Right) the effect on the solar neutrino oscillation probability P_{ee}. The dark NSI elements are parametrized as $\delta M_{\alpha\beta}^2 \equiv |\Delta m_{31}^2|\eta_{\alpha\beta}$.

which exhausts the possible corrections to the effective Hamiltonian for neutrino oscillation, unless there is some correction to the neutrino energy E_ν in the denominator. Here, we focus on the phenomenological consequences of the scalar and dark NSI on neutrino oscillation, without involving the concrete model construction. The effect is proportional to coupling and inversely proportional to mass, $\delta M \propto y^2/m_S^2$ for the scalar NSI and $\delta M^2 \propto g^2/m_\chi^2$ for the dark NSI, with large parameter space. In addition, only neutrino oscillation can probe the forward scattering without momentum transfer. Any other process involves sizable momentum transfer or phase space and hence contributes as $\propto y^2/(q^2 - m^2)$. For very tiny mass, $|q^2| \gg m^2$, the effect is then inversely proportional to the momentum transfer, y^2/q^2, rather than the mass. Consequently, the effect can be naturally suppressed than its counterpart in neutrino oscillation, $y^2/q^2 \ll y^2/m^2$. In other words, neutrino oscillation can easily probe the region with proportionally tiny coupling and mass that no other measurements can reach.

The neutrino oscillation does mean that there is some new physics beyond the SM. But it is not necessarily the genuine neutrino mass term but rather an effective mass as environmental effect. We provide two alternative possibilities of the scalar and dark NSI's. Both of them can contribute as correction to the neutrino mass term, in either the linear form δM or the quadratic form δM^2. The recent Borexino 2017 data does support such alternatives. Especially for the dark NSI, the constant neutrino mass term can be readily faked due to the homogeneous distribution of DM in the solar system. In other to consolidate the neutrino mass as the only explanation of neutrino oscillation, it is necessary to design new experimental configurations. This is equally important for the mixing parameter measurements, such as the leptonic Dirac CP phase or so, since faking neutrino mass term is equivalent to faking the mixing parameters.

References
[1] L. Wolfenstein, "*Neutrino Oscillations in Matter,*" Phys. Rev. D **17**, 2369 (1978).
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[3] S. F. Ge and H. Murayama, "*Apparent CPT Violation in Neutrino Oscillation from Dark Non-Standard Interactions,*" [arXiv:1904.02518 [hep-ph]].