Scalar Non-Standard Interactions in Neutrino Oscillation

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Scalar nonstandard interactions (NSI) can introduce a matter effect for neutrinos propagating through medium and modify the behavior of neutrino oscillations. In contrast to the conventional one induced by the nonstandard interactions with vector mediator, the scalar NSI contributes as correction to the neutrino mass matrix rather than potential. Consequently, the effect of scalar NSI is energy independent while the one of vector NSI scales linearly with neutrino energy. This leads to significantly different phenomenological consequences in reactor, solar, atmospheric, and accelerator neutrino oscillation experiments. Especially the recent Borexino data prefers a nonzero scalar NSI $\eta_{ee} = -0.16$. A synergy of different types of experiments, especially those with matter density variation, can identify the scalar NSI and help to guarantee the measurement of CP violation at accelerator experiments.

\textit{Introduction} – Neutrino oscillations was originally proposed in vacuum due to the presence of nontrivial neutrino mass matrix [1]. The matter potential that neutrinos experience when propagating through matter medium was recognized in 1978 [2]. If the matter density times neutrino energy is at the right value, mixing angles can resonant to the maximal value and significantly change the oscillation behavior [3]. The MSW effect [2, 3] successfully explains the observed solar neutrino fluxes [4] and make a consistent picture with the terrestrial experiments [5]. Matter effects have played a very important role in our understanding of neutrino oscillations.

In the very first paper [2] on neutrino matter effect, Wolfenstein introduced non-standard interactions with generally parametrized vector and axial-vector currents. This opens up the possibility of using neutrino oscillation to probe additional new physics beyond the Standard Model (SM), in addition to neutrino mass [6]. The effect of NSI creates issues for the Dirac CP phase measurement. Both real diagonal and complex off-diagonal elements can fake the CP violation effect and hence disguise the genuine Dirac CP phase [7].

Not only the ordinary matter can induce matter effect to modify the neutrino oscillation, but also dark sector medium such as dark energy [8], or MaVaNs (Mass Varying Neutrinos) [9], fuzzy dark matter (DM) [10], or with a stand-alone particle [11]. Although the dark sector density is much lower than the ordinary matter density in Sun or Earth, a large enough effect is possible for super-light mediators. In the extreme environments of supernova, NSIs can affect the collective oscillation of neutrinos [12].

Coming back to the effect of NSI induced by ordinary matter on neutrino oscillations, the discussion so far has been focusing on a vector mediator. Neutrinos can couple to not only vector field, but also scalar field. To some extent, neutrino coupling with scalar field is an even more natural scenario than the vector one. Due to the observed oscillation, at least two of the three light neutrinos are massive. A natural mechanism for neutrinos to acquire masses is via coupling with a scalar that has nonzero vacuum expectation values. The coupling with a vector gauge boson beyond SM would not have such benefit. Such a possibility cannot be easily excluded. Since the left-handed neutrino belongs to $SU(2)_L$ doublets and hence the scalar coupling with neutrino may also couple with charged leptons, it is natural to see matter effect induced by such a scalar particle.

We point out in this letter that the scalar NSI can introduce a rich phenomenology in reactor, solar, atmospheric, and accelerator experiments. It is inevitable to use a synergy of multiple experiments to test scalar NSI for the purpose of guaranteeing the Dirac CP phase measurement. Although matter effect can also arise due to scalar mediator in MaVaNs [13] and fuzzy dark matter [10] scenarios, its size is not proportional to ordinary matter density. Either the matter effect is modulated by dark energy, neutrino, or dark matter densities, or is proportional to a nontrivial function of matter density such as $\tanh \rho$. In contrast, we make model-independent study of scalar NSI that scales with constant proportionality to the density of ordinary matter and has rich phenomenological consequences.

\textit{Matter Potential and NSI} – Before exploring the details of scalar NSI, let us first take a look how vector interactions can introduce the matter effect in neutrino oscillations [14]. In SM, the matter potential can be induced by both charged and neutral currents. Using Fierz identities [15], the effective Lagrangian contributed by charged current $\propto |\bar{e}(p_1)\gamma^\mu P_L \nu_e(p_2)| |\bar{\nu}_e(p_3)\gamma^\nu P_L e(p_4)|$ can be transformed into the neutral current form [16]

$$L_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} |\bar{\nu}_e(p_3)\gamma_\mu P_L \nu_e(p_2)| |\bar{e}(p_1)\gamma^\nu P_L e(p_4)|.$$ \hspace{1cm} (1)

Here we use electron as matter for illustration and the same thing applies for the matter effect induced by neutral gauge boson mediation with proton or neutron. The contribution that can affect neutrino oscillation comes
from forward scattering with $p_1 = p_4 \equiv p_0$, and $p_2 = p_3 \equiv p_1$, and hence becomes independent of neutrino momentum. We can obtain the matter potential by sandwiching the effective Lagrangian with in and out states,

$$V_{cc} = -\langle \nu_e(p_e,s_e) | \mathcal{L}_{\text{eff}}^\nu | \nu_e(p_e,s_e) \rangle,$$

$$V_{cc} = -\langle \nu_e(p_e,s_e) | \mathcal{L}_{\text{eff}}^\nu | \nu_e(p_e,s_e) \rangle,$$

for neutrino and anti-neutrino cases, respectively. Since the neutrino and electron spinors are separated into two terms, we can focus on the neutrino part, $\langle \nu_e | \mathcal{P}_c \gamma_\mu P_L \nu_e | \nu_e \rangle$ and $| \bar{\nu}_e | \mathcal{P}_c \gamma_\mu P_L \bar{\nu}_e \rangle$. The neutrino spinor can be quantized as $\nu_e = a u + b^\dagger v$ where $a$ and $b$ are the annihilation operators of neutrino and anti-neutrino, respectively. Correspondingly, the external states are defined as $| \nu_e \rangle \equiv a | 0 \rangle$ and $| \bar{\nu}_e \rangle \equiv b^\dagger | 0 \rangle$. The anti-commutation property of neutrino operators leads to opposite sign between the neutrino and anti-neutrino matter potentials $V_{cc} = -V_{cc} = \sqrt{3}G_F \bar{\nu}_e e$. For NSI, the only difference is introducing extra vector mediator between various neutrino flavors. In all these cases, the matter effect contributes to the $\bar{\nu} \gamma^0 \nu$ term,

$$\bar{\nu}_\beta \left[ (i \partial_t + V^{(1)}_{\alpha \beta}) \gamma_0 - i \nu \cdot \gamma - M_{\beta \alpha} \right] \nu_\alpha = 0,$$

with $-V_{\alpha \beta}$ for neutrino and $V^{(1)}_{\alpha \beta}$ for anti-neutrino. When written in terms of Hamiltonian and expanded to linear order

$$\mathcal{H} \approx E_\nu + \frac{M M^\dagger}{2 E_\nu} \pm (V_{SI} + V_{NSI}),$$

where the neutrino mass matrix $M$, the standard interaction (SI) matter potential $V_{SI}$, and NSI matter potential $V_{NSI}$ are $3 \times 3$ matrices. Since neutrino $\nu_\alpha$ ($\bar{\nu}_\beta$) appears on the right (left) side of the kinetic term in (3), the oscillation of neutrons (anti-neutrinos) is described by $\mathcal{H}$ ($\mathcal{H}^\nu$), respectively. The matter effect appears as an extra term added to the Hamiltonian or energy. In this sense, the SM and vector-boson-mediated NSI act as matter potential. For matter potential to be important, the neutrino energy or the matter density should be large enough, $2 E_\nu V \gtrsim \Delta m^2_{ij}$ where the latter has two typical values, $\Delta m^2_{21} = 7.5 \times 10^{-5} \text{eV}^2$ and $\Delta m^2_{31} = 2.7 \times 10^{-3} \text{eV}^2$.

**Scalar NSI** – The scalar NSI effect is no longer a matter potential. This is because the effective Lagrangian (1) is no longer vector current but scalar Yukawa term for Dirac neutrinos

$$\mathcal{L}_{\text{eff}}^\nu \propto [\bar{\nu}_\alpha(p_1)e(p_2)] [\mathcal{P}(p_1)e(p_2)],$$

which cannot convert to vector currents [17]. In the nonrelativistic limit the electron spinor reduces to $u_e = (\xi, \xi)^T$ where $\xi = (1,0)^T$ or $\xi = (0,1)^T$ for the two spin polarizations. Consequently, $\bar{\nu}_e u_e = \bar{\nu}_e \gamma^0 u_e = 2 \xi \xi = n_e$. The correction to the Dirac equation (3) would then shift to the mass term

$$\bar{\nu}_\beta \left[ [i \partial_t + \gamma^\mu Y_{\alpha \beta}] \gamma^\mu + \left( M_{\beta \alpha} + \frac{\nu_e y_e Y_{\alpha \beta}}{m_\beta^2} \right) \right] \nu_\alpha = 0,$$

where $y_e$ is the Yukawa coupling of the scalar mediator $S$ of with electron, and $Y_{\alpha \beta}$ is the Yukawa coupling of scalar $\phi$ with neutrinos, $Y_{\alpha \beta} = \bar{\nu}_\alpha u_\beta + h.c.$ Due to the hermit conjugation, the Yukawa coupling matrix is constrained as $Y = Y^\dagger$ for a real scalar mediators. For convenience, we define $M_S \equiv n_e y_e Y / m_\phi^2$. Then, the effective Hamiltonian (4) becomes

$$\mathcal{H} \approx E_\nu + \frac{(M + M_S)(M + M_S)^\dagger}{2 E_\nu} \pm V_{SI},$$

where $V_{SI}$ is the matter potential from SM interactions. The scalar NSI effect appears as correction to neutrino mass, rather than potential. Since matter effect is inversely proportional to the mediator mass, $M_S$, is proportional to $1/m_\phi^2$ due to zero momentum exchange, large enough $M_S$ can be generated by a light enough scalar mediator that can survive current constraints from supernova [18], meson and lepton decays [19], neutrino electron scattering [20], neutrino trident production [21], Big Bang Nucleosynthesis [22], coherent scattering [23], and other various observables [24]. None of them can exclude the parameter region with both mediator mass and coupling being tiny.

Of the neutrino mass matrix $M = V_\nu D_\nu V_\nu^\dagger$, where $D_\nu \equiv \text{diag}(m_1, m_2, m_3)$ is the diagonal mass matrix and the mixing matrix $V_\nu \equiv P_\nu U_\nu Q_\nu$, has two diagonal rephasing matrices $P_\nu$ and $Q_\nu$ in addition to the PMNS matrix $U_\nu$, the rephasing phases in $P_\nu$ would also affect neutrino oscillation. But their effect can be rotated into the scalar NSI contribution, $M \rightarrow M = U_\nu D_\nu U_\nu^\dagger$ and $M_S \rightarrow M_S = P_\nu M_S P_\nu$. For easy comparison with the true mass term, we parametrize the scalar NSI as

$$M_S \equiv \sqrt{\Delta m^2_{31}} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\nu} & \eta_{\nu\mu} & \eta_{\nu\tau} \\ \eta_{\tau\nu} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix},$$

where $\eta_{\alpha \beta}$ are dimensionless parameters. Note that those phases in $M_S$ is a combination of the unphysical phases from the neutrino mass matrix $M$ and the scalar NSI matrix $M_S$. In presence of scalar NSI, the unphysical phases of $M$ may also have physical consequences on neutrino oscillation. In addition, the absolute mass scale of neutrinos can be subtracted from the $M M^\dagger$ in (7) as a common $m^2_{ij}$ term. Nevertheless, it is always associated with the scalar NSI contribution as $M M^\dagger + M^\dagger M_S$. The scalar NSI is totally different from the vector NSI.

Note that the matter effect from vector mediator always conserves neutrino helicity and consequently has to associate with $\gamma^\mu$ matrices. In addition, since the matter effect comes from coherent scattering it is consequently
insensitive to direction and only the $\gamma_0$ term can survive. This is why the matter effect from vector mediator appears as matter potential. For scalar mediator, neutrino helicity is no longer conserved [25] and the corresponding matter effect can only appear as correction to neutrino mass which flips helicity. Neutrino matter effect needs not to conserve helicity.

Phenomenological Consequences – Neutrino oscillation probes not only neutrino mixing but also the neutrino interactions with medium. Wolfenstein pointed out that “even if all neutrinos are massless it is possible to have oscillations occur when neutrinos pass through matter” [2]. He estimated “the oscillation length in matter of normal density is of the order $10^9$ cm ($10^4$ km) which is inversely proportional to the matter potential. In absence of true mass term, the vector NSI leads to oscillation phase as $e^{iV_L}$ and hence the oscillation length $L \propto 1/V$ is independent of the neutrino energy but only a function of the medium density.

Nowadays, we have already measured neutrino oscillation due to mass splittings which leads to oscillation phase as $e^{i\Delta m^2_{ij}L/4E}$ where the oscillation length is proportional to the neutrino energy, $L \propto E_\nu/\Delta m^2_{ij}$. But the question is whether the mass splittings are the true one $M$ from the fundamental Lagrangian or the faked mass matrix $M_S$ by scalar NSI. Even in absence of true mass matrix, oscillation can still be present due to scalar NSI [26]. Most importantly there is no essential difference between the true mass and the one induced by scalar NSI.

Its dependence on the matter density can help us to identify the scalar NSI. While the true mass matrix $M$ is independent of environmental conditions, the scalar NSI contribution $M_S$ scales with matter density. If the matter density changes along the baseline, the oscillation probabilities would be different. For short baseline terrestrial experiments, the variation in matter density can be ignored and one combination of $M$ and $M_S$ can be redefined as the effectively measured mass matrix. Since reactor experiments such as KamLAND [27], Daya Bay [28], and RENO [29] gives the most precise measurements, not to say the future JUNO [30], we choose the reactor anti-neutrino for matter density subtraction at $\rho_s = 3$ g/cm$^3$,

$$\tilde{M} \rightarrow \tilde{M} + \tilde{M}_S \frac{\rho - \rho_s}{\rho} [1 - \delta(\rho)], \quad (9)$$

for both neutrino and anti-neutrino modes. With $\rho = \rho_s$, the effective mass matrix is exactly the one $\tilde{M} = U_{\nu} D_{\nu U_{\nu}^\dagger}$ reconstructed from the measured oscillation parameters. In Fig. 1 we show the effect of scalar NSI before and after subtraction, simulated by the NuPro package [31]. The density subtraction in (9) is a simplified treatment. An effort of global fit is necessary to establish the “reconstructed” mass matrix. In the rest of this paper, we discuss the nontrivial effects of of scalar NSI on these experiments. Due to significant density variation along the path of solar neutrinos [32], the oscillation probabilities of solar neutrinos may not approach the SI case in the same way as the reactor neutrinos shown in Fig. 1. Based on density subtraction, we show the effect of scalar NSI on solar neutrino conversion in Fig. 2, with a similar plot of vector NSI for comparison. Different from the vector NSI, the scalar NSI is energy independent and hence not suppressed, in contrary to previous studies [33]. In addition, SNO neutrino experiences much higher matter density than the KamLAND reactor neutrino. This provides a possibility of explaining the discrepancy in the KamLAND [27] and SNO [34] measurements of neutrino mass splitting $\Delta m^2_{23}$.

Last year, the Borexino experiment has made first simultaneous measurement of the $pp$, $^7$Be, and $pep$ fluxes.

![FIG. 2: The solar neutrino conversion probabilities with (a) vector and (b) scalar NSI, together with the Borexino measurement [35] of the $pp$, $^7$Be, and $pep$ fluxes.](image)

![FIG. 3: The $\chi^2$ fit of scalar NSI to the Borexino data [35].](image)
As a naive estimation, we plot the $\chi^2$ function for these three data points in Fig. 3. The $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ elements are effectively the same for solar neutrinos and their best fit is the SM scenario. But for the $\eta_{ee}$ element, there is a local minimal around $\eta_{ee} = -0.16$ beyond which the $\chi^2$ curve has a sharp increase due to flip of mass eigenvalues. The lastest Borexino data [35] does favor a nonzero scalar NSI. We show the oscillation probability curve with $\eta_{ee} = -0.16$ in Fig. 2 for comparison. The preferred nonzero $\eta_{ee}$ is mainly fixed by the smaller central value of the $\text{pep}$ flux than the SI prediction. Although the curve shape is quite different from the standard case, it is still consistent with the Borexino data, including the $8\beta$ flux from earlier measurement [36]. The future SNO+ [37] and Jinping [38] neutrino experiments can help to pin this down.

The atmospheric neutrino oscillation can also experience matter density variation and hence help identifying scalar NSI. In Fig. 4 we show the atmospheric neutrino oscillogram and its modification by vector or scalar NSI. Those neutrinos crossing the Earth core experience the most significant matter density variation. Consequently, the core region ($\cos \theta_z \lesssim -0.8$) shows the largest effect where the difference in $P_{\mu\mu}$ can be as large as 0.14 between SI and scalar NSI. Note that the maximal value of $P_{\mu\mu}$ is around 0.5 which can be clearly seen in the decomposition formalism [39]. The relative change can be as large as 1 in the energy range $E_\nu \lesssim 5\text{ GeV}$. We can expect PINGU [40], ORCA [41], and INO [42] to put some constraints on scalar NSI. In addition, lower energy threshold with Super-PINGU [43] can further enhance the sensitivity to scalar NSI whose effect can surpass matter potential with smaller neutrino energy.

For accelerator neutrino experiments, whose main purpose is for the Dirac CP phase measurement, the situation is a little more intricate. Since the effective mass matrix is modified by the scalar NSI, the effective Dirac CP phase can be quite different from the genuine one. We show the oscillation probabilities $P_{\mu\mu}$ at TNT2K [44], including the neutrino mode $\nu$T2K and the anti-neutrino mode $\bar{\nu}$SK, and both modes at DUNE [45] in Fig. 5. To make the faked CP effect explicit, we remove the matter density subtraction so that the effect of scalar NSI appears in both neutrino and anti-neutrino modes. Although the neutrino energy varies a lot, all experiments receive comparable modification from scalar NSI, totally different from the vector case. If the complex phases and off-diagonal elements $\eta_{\alpha\beta}$ with $\alpha \neq \beta$ are also introduced, the situation would become even more complicated. Degeneracy between the genuine Dirac CP phase and the scalar NSI would make the CP measurement more difficult, in the same way as the vector NSI [7] and non-unitary mixing [46].

**Summary and Discussions** – We point out that scalar NSI has totally different features and phenomenological consequences from the vector one. The scalar NSI contributes as correction to the neutrino mass matrix and hence its effect is independent of neutrino energy. Even for low energy neutrino experiment, such as reactor, solar, and muon decay at rest ($\mu$DAR) experiments, the effect of scalar NSI cannot be ignored. In addition, the scalar NSI can fake CP effect and becomes a trouble to the on-going and future CP measurement at T2(H)K [47], NO$\nu$A [48], and DUNE [45]. A global effort of using matter-density-varying oscillation, such as solar and atmospheric neutrino experiments, is then needed for precision measurement of the leptonic Dirac CP phase which is in preparation.
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