Nonstandard neutrino interactions and transition magnetic moments

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Abstract

We constrain generic nonstandard neutrino interactions with existing experimental data on neutrino transition magnetic moments and derive strong bounds on tensorial couplings of neutrinos to charged fermions. We also discuss how some of these tensorial couplings can be constrained by other experiments, e.g., on neutrino-electron and neutrino-nucleus scattering.

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Neutrinos have long been a prime vehicle for testing the standard model (SM) of particle interactions. They played instrumental role in measurements of parton distribution functions [1], quark mixing parameters [2] and other important quantities. Neutrino oscillations provided the first glimpse of the physics beyond the minimal standard model by establishing that neutrinos have mass [3]. It would not be entirely surprising if other signs of new physics (NP) would be revealed in the precision studies of neutrino properties. It is therefore important to study deviations of neutrino interaction parameters with other SM particles from their SM expectations. There have been many analyses of nonstandard neutrino interactions, often acronymed as NSIs, in neutrino scattering and oscillation experiments [4–10]. They have been particularly important in the studies leading up to a possible future neutrino factory. In this letter we point out that it is possible to constrain NSIs using existing measurements of neutrino transition magnetic moments.

It has been seen that the nonstandard neutrino interactions play a subdominant role in neutrino scattering. Provided that the scale of new physics M is large compared to the electroweak scale, the easiest parameterization of NSIs of $\nu\nu ff$ type at low energy scales accessible in neutrino experiments would be naturally written in terms of effective four-fermion operators of dimension six [6, 8, 11–13],

$$-\mathcal{L}_{\text{eff}} = \sum_a \frac{\epsilon_{\alpha\beta}^{fa}}{M^2} (\bar{\nu}_\beta \Gamma_a \nu_\alpha)(\bar{f}\Gamma_a f) + \text{h.c.,} \tag{1}$$

where $\epsilon_{\alpha\beta}^{fa}$ are NSI couplings, f denotes the component of an arbitrary weak doublet (often a quark field for studies of νNSI in matter), $\Gamma_a = \{I, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$, $a = \{S, P, V, A, T\}$ and $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. Effective non-standard neutrino interactions, expressed by the four-fermion operators as in Eq. (1), are widely discussed in the literature, see [8–10] for recent reviews. Typically only left-handed neutrinos are considered, which allows to study NSI impact on solar, atmospheric and reactor neutrinos, as well as on neutrino-nucleus scattering. Also, oftentimes, only left-handed or right-handed *vectorial* interactions are considered.

It is important to note that this restriction removes from the consideration a large class of models where neutrino interactions could violate lepton number, e.g., models with leptoquarks and R-parity-violating supersymmetric theories. The effective low-energy operators that are generated in those models include

$$-\mathcal{L}_{\text{eff}} \subset \sum_a \frac{\tilde{\epsilon}_{\alpha\beta}^{fa}}{M^2} (\bar{\nu}_\beta \Gamma_a f)(\bar{f}\Gamma_a \nu_\alpha) + \text{h.c.} \tag{2}$$

Using Fierz identities, Eq. (2) can be rewritten in the form of Eq. (1) if all effective operators, including the tensor ones, are considered. It is therefore important to consider effective Lagrangian that also includes tensorial interactions. The chirality constraint that allows $\nu\nu ff$ interaction only of $V \pm A$ type can not describe possible important neutrino phenomena, such as neutrino magnetic moment (NMM). It is the tensor interactions of neutrinos that we will attempt to constrain in this paper.

Neutrino magnetic moment $\mu_{\alpha\beta}$ can be defined by the Hermitian form factor $f_{\alpha\beta}^M(0) \equiv \mu_{\alpha\beta}$ of the term [14]

$$-f_{\alpha\beta}^M(q^2)\, \bar{\nu}_\beta(p_2)\, i\sigma_{\mu\nu}q^\nu \nu_\alpha(p_1) \tag{3}$$

in the effective neutrino electromagnetic current, where $\alpha, \beta = e, \mu, \tau$ are flavor indices, $q = p_2 - p_1$. The relation between NMMs in the flavor basis and in the mass basis can be written as [14–16]

$$\mu_{\alpha\beta}^2 = \sum_{i,j,k} U_{\alpha j}^* U_{\beta k} e^{-i\Delta m_{jk}^2 L/2E} \mu_{ij}\mu_{ik}, \tag{4}$$

where $i, j, k = 1, 2, 3$, $\Delta m_{jk}^2 = m_j^2 - m_k^2$ are the neutrino squared-mass differences, $U_{\ell i}$ is the leptonic mixing matrix, E is the neutrino energy, L is the baseline, and for simplicity we omitted the electric dipole moment contribution.

In the SM, minimally extended to include Dirac neutrino masses, NMM is suppressed by small masses of observable neutrinos [3] due to the left-handed nature of weak interaction. The diagonal and transition magnetic moments are calculated in the SM to be [4, 14, 15, 17–22]

$$\mu_{ii}^{\rm SM} \approx 3.2 \times 10^{-20} \left(\frac{m_i}{0.1\ \rm eV}\right)\ \mu_B \tag{5}$$

and

$$\mu_{ij}^{\rm SM} \approx -4 \times 10^{-24} \left(\frac{m_i + m_j}{0.1\ \rm eV}\right) \sum_{\ell=e,\mu,\tau} \left(\frac{m_\ell}{m_\tau}\right)^2 U_{\ell i}^* U_{\ell j}\ \mu_B, \tag{6}$$

respectively, where $\mu_B = e/(2m_e) = 5.788 \times 10^{-5}\ \rm eV\,T^{-1}$ is the Bohr magneton.

Currently, the strongest experimental bound on NMM is far from the SM value [23],

$$\mu_\nu < 3 \times 10^{-12}\ \mu_B. \tag{7}$$

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It has been obtained from the constraint on energy loss from globular cluster red giants, which can be cooled faster by the plasmon decays due to NMM [24] that delays the helium ignition. This bound can be applied to all diagonal and transition NMMs.

The best present terrestrial laboratory constraints on NMM, derived in $\bar{\nu}_e$-e elastic scattering experiments TEXONO [25],

$$\mu_{\bar{\nu}_e} < 7.4 \times 10^{-11} \, \mu_B \qquad (90\% \text{ C.L.}), \qquad (8)$$

and GEMMA [26],

$$\mu_{\bar{\nu}_e} < 2.9 \times 10^{-11} \, \mu_B \qquad (90\% \text{ C.L.}), \qquad (9)$$

apply to the diagonal μ_{ee} moment, and can be translated to the transition $\mu_{e\mu}$ and $\mu_{e\tau}$ moments. However these bounds are much weaker than one in Eq. (7). The global fit [27, 28] of NMM data from the reactor and solar neutrino experiments produces limits on the neutrino transition moments [15]

$$\mu_{12}, \mu_{23}, \mu_{31} < 1.8 \times 10^{-10} \, \mu_B \qquad (90\% \text{ C.L.}). \qquad (10)$$

NMM generically induces a radiative correction to the neutrino mass, which constrains NMM [29–31]. In the case of diagonal NMM, which is possible only for Dirac neutrinos, the correspondent bound $\mu_{\alpha\alpha} \lesssim 10^{-14} \, \mu_B$ is significantly stronger than in Eq. (7). However, the transition NMM $\mu_{\alpha\beta}$, which is possible for both Dirac and Majorana neutrino types, is antisymmetric in the flavor indices, while the neutrino mass terms $m^\nu_{\alpha\beta}$ are symmetric. This may lead to suppression of $\mu_{\alpha\beta}$ contribution to $m^\nu_{\alpha\beta}$, e.g., by the SM Yukawas, which makes the bound on NMM much weaker than in Eq. (7): $\mu_{\alpha\beta} \lesssim 10^{-9} \, \mu_B$ [30, 31]. Alternatively Majorana neutrino masses may have spin suppression comparing with NMM [32].

Large NMM compared with Eqs. (5) and (6) may be generated in many theories, e.g., models with left-right symmetry [33], scalar leptoquarks [34], R-parity violating supersymmetry [35], and large extra dimensions [36]. In this work we consider generation of the neutrino transition magnetic moments, using general $\nu\nu ff$ parametrization, which includes the scalar and tensor terms. And using the best present constraint on NMM, we get the bounds on the effective couplings.

We have found that among all possible $\nu_\alpha \nu_\beta ff$ interactions in Eq. (1), the lowest order contribution to NMM can be generated through the one-loop diagram, shown in Fig. 1, with
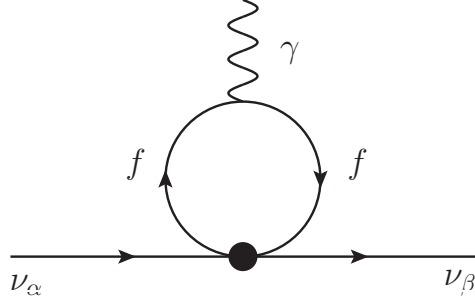
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FIG. 1: Effective diagram for magnetic moment of neutrino induced by tensorial NSI, indicated by the large dot.

the tensor dimension 6 operator,

$$\frac{\epsilon^{fT}_{\alpha\beta}}{M^2}(\bar{\nu}_\beta\sigma_{\mu\nu}\nu_\alpha)(\bar{f}\sigma^{\mu\nu}f), \tag{11}$$

where in the case of Majorana neutrinos $\bar{\nu}_\beta = \bar{\nu}^c_\beta$. In particular, interactions of neutrinos with quarks q via the operator

$$\frac{\epsilon^{q}_{\alpha\beta}}{M^2}(\bar{\nu}_\beta\sigma_{\mu\nu}\nu_\alpha)(\bar{q}\sigma^{\mu\nu}q), \tag{12}$$

where $\epsilon^q_{\alpha\beta} \equiv \epsilon^{qT}_{\alpha\beta}$ is real, generate NMMs

$$\mu_{\alpha\beta} = \mu^0_{\alpha\beta} - \sum_q \epsilon^q_{\alpha\beta}\frac{N_c Q_q}{\pi^2}\frac{m_e m_q}{M^2}\ln\left(\frac{M^2}{m_q^2}\right)\mu_B, \tag{13}$$

where $N_c = 3$ is the number of colors, Q_q and m_q are electric charge and mass of the quark, respectively. Here and later $\mu^0_{\alpha\beta}$ denotes the subleading part of the NMM that is not enhanced by the large logarithm. We note that this formula reproduces the leading order in the exact result, which can be derived in the model with scalar LQs, see Ref. [34] for the exact expressions of diagonal NMMs.

Similarly, for the interactions of neutrinos with charged leptons ℓ,

$$\frac{\epsilon^{\ell}_{\alpha\beta}}{M^2}(\bar{\nu}_\beta\sigma_{\mu\nu}\nu_\alpha)(\bar{\ell}\sigma^{\mu\nu}\ell) \tag{14}$$

with $\epsilon^\ell_{\alpha\beta} \equiv \epsilon^{\ell T}_{\alpha\beta}$, we have

$$\mu_{\alpha\beta} = \mu^0_{\alpha\beta} + \sum_\ell \frac{\epsilon^\ell_{\alpha\beta}}{\pi^2}\frac{m_e m_\ell}{M^2}\ln\left(\frac{M^2}{m_\ell^2}\right)\mu_B. \tag{15}$$

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We notice that the dominant logarithmic terms, such as in Eqs. (13) and (15), may not contribute to NMM in a certain models, e.g., in the SM, due to a mutual compensation between the relevant diagrams [19, 20].

For $M = 1$ TeV, using Eq. (7) and taking one nonzero $\epsilon_{\alpha\beta}^f$ at a time, we obtained the constraints shown in Table. I

TABLE I: Upper bounds on the couplings $\epsilon_{\alpha\beta}^f$.

$|\epsilon_{\alpha\beta}^e|$	3.9	$|\epsilon_{\alpha\beta}^d|$	0.25	$|\epsilon_{\alpha\beta}^u|$	0.49
$|\epsilon_{\alpha\beta}^\mu|$	3.0×10^{-2}	$|\epsilon_{\alpha\beta}^s|$	1.6×10^{-2}	$|\epsilon_{\alpha\beta}^c|$	1.7×10^{-3}
$|\epsilon_{\alpha\beta}^\tau|$	2.6×10^{-3}	$|\epsilon_{\alpha\beta}^b|$	5.8×10^{-4}	$|\epsilon_{\alpha\beta}^t|$	4.8×10^{-5}

Besides the limits on NMM, the neutrino-electron and neutrino-nucleus scattering [7] as well as the matter effects in the neutrino oscillations [6] constrain the tensorial NSI. However the limit on $|\epsilon_{e\beta}^f|$ from supernova and solar neutrino oscillations is suppressed by the small average polarization of the matter particles [6, 37].

The tensorial contributions to the differential cross sections of $\bar{\nu}_e$-e elastic scattering and $\bar{\nu}_e$-nucleus coherent scattering can be written as [7]

$$\frac{d\sigma_T^{\nu e}}{dE_e} = \sum_{\beta=\mu,\tau} \left(\epsilon_{e\beta}^e\right)^2 \frac{m_e}{2\pi M^4} \left[\left(1 - \frac{E_e}{2E_\nu}\right)^2 - \frac{m_e E_e}{4E_\nu^2} \right], \tag{16}$$

and

$$\frac{d\sigma_T^{\nu N}}{dE_N} = [\epsilon_{e\beta}^u(2Z + N) + \epsilon_{e\beta}^d(Z + 2N)]^2 \frac{m_N}{2\pi M^4} \left[\left(1 - \frac{E_N}{2E_\nu}\right)^2 - \frac{m_N E_N}{4E_\nu^2} \right], \tag{17}$$

where m_e (E_e) and m_N (E_N) are the mass (recoil energy) of the electron and nucleus, respectively; E_ν is the incident neutrino energy, and Z (N) is the number of protons (neutrons) in the nucleus.

Using the cross-section for the $\bar{\nu}_e$-e scattering, published by the TEXONO collaboration [38, 39] and taking $M = 1$ TeV, the bound $|\epsilon_{e\beta}^e| < 6.6$ at 90% C.L. can be obtained [7]. Using Eqs. (8) and (9), this bound can be rescaled to the GEMMA sensitivity as

$$|\epsilon_{e\beta}^e| < 2.7 \qquad (90\% \text{ C.L.}). \tag{18}$$

The planned $\bar{\nu}_e$-nucleus coherent scattering experiments, e.g., part of the TEXONO low-energy neutrino program [40], can reach the sensitivity of $|\epsilon_{e\beta}^{u,d}| < 0.2 \ (M/1\,\text{TeV})^2$ at 90% C.L. [7], which will also improve the respective bounds in Table I.

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[1] See, for example, J. Gao, *et al.*, "The CT10 NNLO Global Analysis of QCD," arXiv:1302.6246 [hep-ph]; M. E. Peskin and D. V. Schroeder, "An Introduction to quantum field theory," Reading, USA: Addison-Wesley (1995) 842 pages. See Section 17.3.

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