https://doi.org/10.15407/ujpe71.2.124

SUDIP JANA

Harish-Chandra Research Institute, A CI of Homi Bhabha National Institute
(Chhatnag Road, Jhunsi, Prayagraj 211019, India; e-mail: sudip.jana@okstate.edu)

FROM MATTER TO LIGHT: UNVEILING NEUTRINO NON-STANDARD INTERACTIONS [1]

After a brief introduction to neutrino non-standard interactions, I focus on neutrino electromagnetic properties and the correlation between the neutrino magnetic moment and neutrino mass mechanism. Then, I discuss that the models that induce large neutrino magnetic moments naturally maintaining small neutrino masses also predict observable shifts in the anomalous magnetic moments of charged leptons. The promising new possibilities for probing neutrino NSI and electromagnetic properties in future experiments in future terrestrial and astrophysical experiments are also discussed.

Keywords: neutrino, NSI, magnetic moments, supernova, neutrino mass.

1. Introduction

The discovery of neutrino oscillations firmly established the necessity for physics beyond the Standard Model, demonstrating that neutrinos are massive and may possess interactions not accounted for within the conventional framework. Such new physics can manifest either as non-standard neutrino interactions or as electromagnetic properties generated through quantum loop effects, including magnetic moments, charge radii, and electric dipole moments.

Neutrino electromagnetic properties, – especially magnetic moments, – have long been explored as potential windows into new physics. Renewed interest over the past decades has been driven by their possible role in explaining various experimental anomalies and by the fact that even tiny magnetic moments can significantly influence astrophysical processes. In stars, for example, a non-zero magnetic moment enables neutrino–photon interactions that alter energy-loss mechanisms, providing some of the strongest constraints on these properties.

While most standard neutrino mass models predict magnetic moments too small to detect, well-motivated extensions of these models can naturally accommodate much larger values without conflicting with known neutrino masses. Therefore, studying neutrino magnetic moments remains a powerful probe of new physics, capable of shedding light on unexplained observations and offering insight into the deeper mechanisms responsible for neutrino mass and identity. This talk is based on results obtained in Refs. [1–9].

2. Large Neutrino Non-Standard Interactions in Neutrino Mass Models

In constructing theories of neutrino mass, it is common for new neutrino interactions to arise alongside the mass-generation mechanism. These additional interactions can significantly influence neutrino oscillations, their propagation in matter, and consequently the interpretation of both astrophysical and terrestrial experiments. It is therefore essential to identify which classes of neutrino mass models naturally give rise to non-standard interactions (NSI) and to examine their phenomenological impact. I will begin by outlining the types of neutrino mass frameworks that can generate such interactions.

The conventional explanation for tiny neutrino masses is the high-scale seesaw mechanism, which generates the effective operator

$$\mathcal{O}_1 = \frac{LLHH}{\Lambda},$$

implying $\Lambda \sim 10^{14}$ GeV, far beyond experimental accessibility. Radiative models provide an appealing al-

Citation: Jana S. From matter to light: unveiling neutrino non-standard interactions. *Ukr. J. Phys.* **71**, No. 2, 124 (2026). https://doi.org/10.15407/ujpe71.2.124.

[1] This work is based on the results presented at the 2025 "New Trends in High-Energy Physics" Conference.

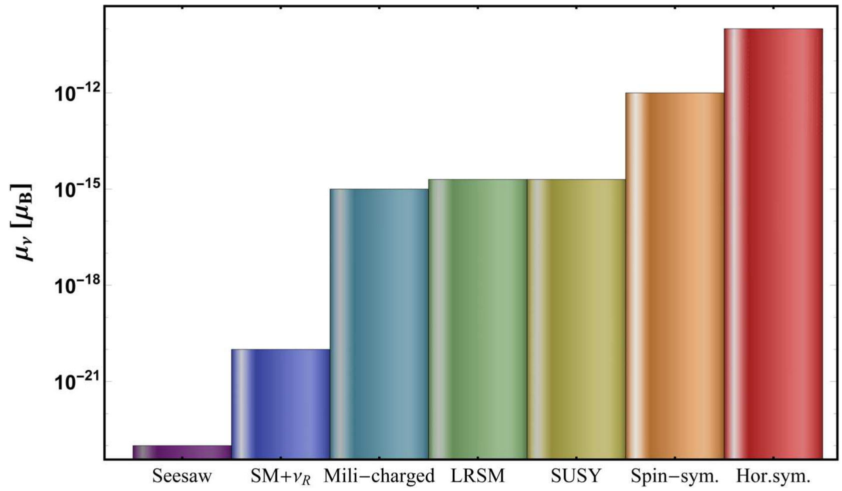

Fig. 1. Theoretical predictions of neutrino magnetic moments in different neutrino mass models. For details, see Ref. [1]

ternative: neutrinos are massless at tree level, and small Majorana masses arise only through loop effects, with lepton number violated by new scalar fields. Loop and chirality suppression naturally allow the new-physics scale to lie in the TeV range.

Radiative models can be grouped into two broad classes [9]:

Type-I radiative models: These correspond to scenarios that can be represented by higher-dimensional $\Delta L = 2$ operators. New scalar fields couple directly to Standard Model fermions, and the induced masses contain both loop and charged-lepton mass suppressions. With new scalars near the TeV scale, these models can yield sizable neutrino non-standard interactions.

Type-II radiative models: Here, the loop diagrams contain only new, non-SM particles and cannot be reduced to effective $\Delta L = 2$ operators. Although loop suppressed, the masses do not depend on light fermion masses. These models often incorporate dark matter candidates but generate negligible non-standard interactions, as neutrinos couple only to heavy new states.

Thus, for phenomenological studies of neutrino non-standard interactions, type-I radiative models are the most relevant.

3. Large Neutrino Magnetic Moments in Neutrino Mass Models

In addition to inducing new interactions with matter fields, many neutrino mass models also generate couplings between neutrinos and photons, leading to effective electromagnetic interactions. These can arise through magnetic and electric dipole moments, induced charges, and related loop-level operators.

A particularly illustrative case is a minimal framework in which an approximate horizontal symmetry, $SU(2)_H$, acts on the electron–muon sector. In this construction, the symmetry is not exact; it is explicitly broken by the charged-lepton masses. Treating $SU(2)_H$ as only approximate greatly streamlines the model, as no additional fields are required solely to complete the symmetry structure.

The explicit breaking of $SU(2)_H$ by lepton masses plays a role analogous to the breaking of chiral symmetry in QCD by the light-quark masses, and this breaking naturally extends to the neutrino sector. One-loop corrections to neutrino masses induced by these terms remain sufficiently suppressed, allowing the model to accommodate a large transition magnetic moment $\mu_{\nu_e \nu_\mu}$ without generating unacceptably large neutrino masses.

While the full Lagrangian violates total lepton number, the $SU(2)_H$-symmetric limit preserves the difference $L_e - L_\mu$. This feature permits a non-zero transition magnetic moment between ν_e and ν_μ, while forbidding neutrino mass terms except for a small radiative contribution to the ν_τ mass. Owing to the symmetry structure, the loop diagrams add constructively to the magnetic moment but cancel when the photon is removed, yielding strongly suppressed mass corrections. A comparison of the maximal transition magnetic moments predicted in various neutrino mass frameworks is shown in Fig. 1.

4. Correlation with Charged-Lepton Magnetic Moments

It has further been shown that theoretical frameworks capable of producing sizable neutrino magnetic moments–while still maintaining naturally small neutrino masses–also tend to induce measurable contributions to the anomalous magnetic moment of the muon [2, 3]. Remarkably, the magnitude of these contributions falls within the range indicated by both the earlier Brookhaven results and the more recent measurements from Fermilab. This establishes a compelling link between the electromagnetic properties of charged leptons in the Standard Model and those of neutral leptons.

In this context, the Fermilab determination of the muon $g-2$ serves as an indirect probe of enhanced neutrino magnetic moments, offering a level of sensitivity comparable to that of dedicated neutrino and dark matter searches. Such an interplay between the muon anomalous magnetic moment and neutrino magnetic moments naturally emerges in models that invoke leptonic family symmetries to amplify transition moments. As illustrated in Fig. 2, these frameworks predict a clear one-to-one correlation between the two observables.

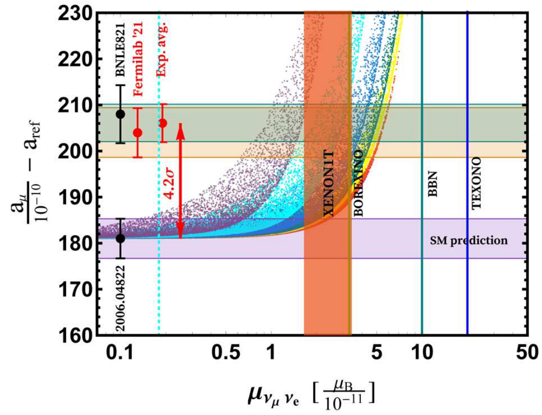

Fig. 2. Theoretical predictions and experimental measurements of the muon anomalous magnetic moment and the neutrino transition magnetic moment. For details, see [2]

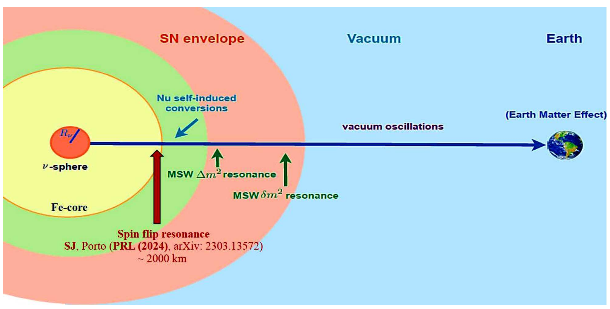

Fig. 3. Schematic illustration of flavor transformations of supernova neutrinos in the presence of magnetic moments. For details, see Ref. [10]

5. Implications for Terrestrial Experiments

Future lepton colliders such as the ILC, CLIC, and FCC-ee offer powerful complementary probes of NSI [11]. In these setups, NSI can manifest through monophoton signatures, closely resembling typical dark matter signals. When NSI originate from heavy mediators above the electroweak scale, lepton colliders can achieve sensitivities that surpass those of traditional neutrino experiments over a wide range of mediator masses. An important consequence is that collider measurements can break parameter degeneracies that commonly appear in oscillation analyses.

In particular, NSI scenarios invoked to alleviate the tension between T2K and NOνA can be decisively tested at upcoming lepton collider facilities. We further show that proton-proton colliders such as the FCC-hh, employing lepton parton distribution functions, can also probe leptonic NSI. At the LHC, NSI may appear as mono-jet–like signatures [12]. On a different front, high-energy neutrino telescopes provide an additional complementary window, exhibiting distinctive astrophysical signatures sensitive to NSI effects [13–16].

6. Astrophysical Implications

The neutronization burst of a core–collapse supernova, a brief interval lasting only a few tens of milliseconds after core bounce, is characterized by an intense flux of electron neutrinos. This phase provides an exceptional setting for probing neutrino transition magnetic moments. Detailed simulations of the corresponding neutrino spectra for next–generation detectors–including DUNE and Hyper–Kamiokande (HK)-have incorporated spin–flavor transitions driven by interactions with supernova magnetic fields. These analyses show that the resulting sensitivity to transition magnetic moments can exceed current laboratory and astrophysical bounds by several orders of magnitude, offering a powerful diagnostic of both the Dirac versus Majorana nature of neutrinos and the mechanisms responsible for neutrino mass generation. A particularly interesting possibility arises when the supernova magnetic field possesses a twisting or rotating configuration. In such environments, the field's rotation along the neutrino propagation path can trigger resonant spin–flavor transitions (see Fig. 3), leading to substantial modifications in the expected event rates at DUNE and HK. For Dirac neutrinos with sizeable transition magnetic moments, these resonances form an especially efficient avenue for identifying the relevant underlying physics. Furthermore, the study of neutrino electromagnetic properties may be broadened to include signatures at high-energy colliders and future neutrino telescopes. Distinctive gravitational–wave signals could also arise in scenarios where neutrinos experience non-standard interactions, offering an additional complementary probe of such effects [17]. For further details, see Refs. [12–15, 18, 19].

7. Conclusions

Theoretical and experimental studies of neutrino NSI and electromagnetic interactions offer a compelling approach to uncovering the fundamental theory underlying the mechanism of neutrino mass generation.

1. K.S. Babu, S. Jana, M. Lindner. Large neutrino magnetic moments in the light of recent experiments. *Journal of High Energy Physics* **10**, 040 (2020).
2. K.S. Babu, S. Jana, M. Lindner, P.K. Vishnu. Muon g - 2 anomaly and neutrino magnetic moments. *Journal of High Energy Physics* **10**, 240 (2021).
3. S. Jana, K.S. Babu, M. Lindner, P.K. Vishnu. Correlating muon $g-2$ anomaly with neutrino magnetic moments. *Proc. of Science "The European Physical Society Conference on High Energy Physics (EPS-HEP2021)", 26–30 July 2021* **398**, 189 (2022).
4. S. Jana. Horizontal symmetry and large neutrino magnetic moments. *Proc. of Science "7th Symposium on Prospects in the Physics of Discrete Symmetries, (DISCRETE2020-2021)", June 2022*, **405**, 037 (2022).
5. S. Jana, Y.P. Porto-Silva, M. Sen. Signal of neutrino magnetic moments from a galactic supernova burst at upcoming detectors. *Proc. of Science "41st International Conference on High Energy physics (ICHEP2022)", 6–13 July, 2022, Bologna, Italy*, **414**, 597 (2022).
6. S. Jana, Y.P. Porto-Silva, M. Sen. Exploiting a future galactic supernova to probe neutrino magnetic moments. *J. Cosmol. Astropart. Phys.* **09**, 079 (2022).
7. S. Jana, Y. Porto. Resonances of supernova neutrinos in twisting magnetic fields. *Phys. Rev. Lett.* **132**, 101005 (2024).
8. S. Jana, Electromagnetic Properties of Neutrinos. *XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023), 28-08—01-09-2023, University of Vienna*, **441**, 184 (2024).
9. K.S. Babu, P.S.B. Dev, S. Jana, A. Thapa. Non-standard interactions in radiative neutrino mass models. *Journal of High Energy Physics* **03**, 006 (2020).
10. S. Jana, Y. Porto. Non-standard interactions of supernova neutrinos and mass ordering ambiguity at DUNE. arxiv: 2407.06251.
11. S. Jana, S. Kundu, S.K. Rai. Tracing neutrino non-standard interactions through charged lepton collisions. arxiv: 2507.10703.
12. K.S. Babu, D. Gonçalves, S. Jana, P.A.N. Machado. Neutrino non-standard interactions: Complementarity between LHC and oscillation experiments. *Phys. Lett. B* **815**, 136131 (2021).
13. K.S. Babu, P.S. Dev, S. Jana, Y. Sui. Zee-burst: A new probe of neutrino nonstandard interactions at IceCube. *Phys. Rev. Lett.* **124**, 041805 (2020).
14. K.S. Babu, P.S.B. Dev, S. Jana. Probing neutrino mass models through resonances at neutrino telescopes. *Int. J. Mod. Phys. A* **37**, 2230003 (2022).
15. G.-y. Huang, S. Jana, M. Lindner, W. Rodejohann. Probing heavy sterile neutrinos at neutrino telescopes via the dipole portal. *Phys. Lett. B* **840**, 137842 (2023).
16. G.-y. Huang, S. Jana, M. Lindner, W. Rodejohann. Probing new physics at future tau neutrino telescopes. *J. Cosmol. Astropart. Phys.* (02), 038 (2022).
17. S. Jana, S. Manna, V.P. K, Gravitational wave signature and the nature of neutrino masses: Majorana, Dirac, or Pseudo-Dirac? arxiv: 2509.10456.
18. A. Ismail, S. Jana, R.M. Abraham. Neutrino up-scattering via the dipole portal at forward LHC detectors. *Phys. Rev. D* **105**, 055008 (2022).
19. S. Jana, M. Klasen, V.P. K, How Charged Can Neutrinos Be? arxiv: 2504.20044.

Received 19.11.25

С. Джана

ВІД МАТЕРІЇ ДО СВІТЛА: РОЗКРИТТЯ НЕСТАНДАРТНИХ ВЗАЄМОДІЙ НЕЙТРИНО

Після короткого вступу до нестандартних взаємодій нейтрино, зосереджуюсь на електромагнітних властивостях нейтрино та кореляції між магнітним моментом нейтрино та механізмом маси нейтрино. Потім обговорюю те, що моделі, які індукують великі магнітні моменти нейтрино, зберігаючи при цьому малі маси, також природним чином передбачають спостережувані зрушення аномального магнітного моменту заряджених лептонів. Також обговорювалися перспективні нові можливості для дослідження NSI та електромагнітних властивостей нейтрино в майбутніх експериментах, заснованих на наземних дослідженнях та астрофізичних міркуваннях.

Ключові слова: нейтрино, NSI, магнітні моменти, наднова, маса нейтрино.