PROCEEDINGS OF SCIENCE

Electromagnetic properties of neutrinos

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Within the Standard Model, neutrinos exhibit no direct coupling to photons. Nonetheless, quantum loop corrections can give rise to electromagnetic properties in neutrinos, such as magnetic moments, electric dipole moments, electric charge, and charge-radius. This proceeding systematically addresses three pivotal components: firstly, the neutrino magnetic moment, an unequivocal consequence of neutrino masses, and establishing a one-to-one correlation. This connection yields definite predictions for neutrino magnetic moments when constructing models for neutrino masses. Subsequently, exploration extends to new leptonic symmetries that uncouple mass from the magnetic moment of neutrinos, elucidating both theoretical foundations and phenomenological implications. Secondly, an examination ensues into the anomalous electromagnetic properties shared between charged leptons and neutrinos, revealing potential correlations. Finally, the proceeding concludes with an examination of the astrophysical ramifications stemming from the electromagnetic properties of neutrinos. This proceeding is based on results obtained in Refs. [1–7].

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1. Introduction

Observations of sunspot activity in the late 1980s and early 1990s [8] sparked interest in neutrino magnetic moments, which had been studied for seven decades [9], prior to the discovery of the neutrino. Later, several studies investigated neutrino magnetic moments in more detail. There is a growing interest in studying neutrino magnetic moments because they have the potential to solve many unsolved mysteries, such as the excess of electron recoil events at XENON1T [10], the ANITA anomalous events [11, 12], the long-standing MiniBooNE [13] and muon $g-2$ anomalies [2, 14]. Strong bounds on neutrino magnetic moment can arise from astrophysical setups as well [6, 15–17]. The presence of a non-zero neutrino magnetic moment allows for direct coupling between neutrinos and photons, thereby allowing for neutrino radiative decays, as well as plasmon decays to neutrino-antineutrino pairs. The strongest bounds usually arise from globular cluster stars, where plasmon decay can delay helium ignition, leading to anomalous cooling of stars. Absence of any such observational evidence leads to $\mu_\nu \leq 3\times 10^{-12}\mu_B$ [18]. However, it has been recently pointed out that this astrophysical limit can be relaxed by considering "neutrino trapping mechanism" [1, 2]. From a theoretical standpoint, the anticipated magnetic moments of neutrinos are imperceptibly tiny in many neutrino mass models that generate the known neutrino masses and mixings. However, it is conceivable to construct theories consistent with neutrino mass generation that have quite large neutrino magnetic moments [1]. Thus, understanding the neutrino magnetic moment may give valuable insight into the process by which neutrinos acquire mass and other characteristics.

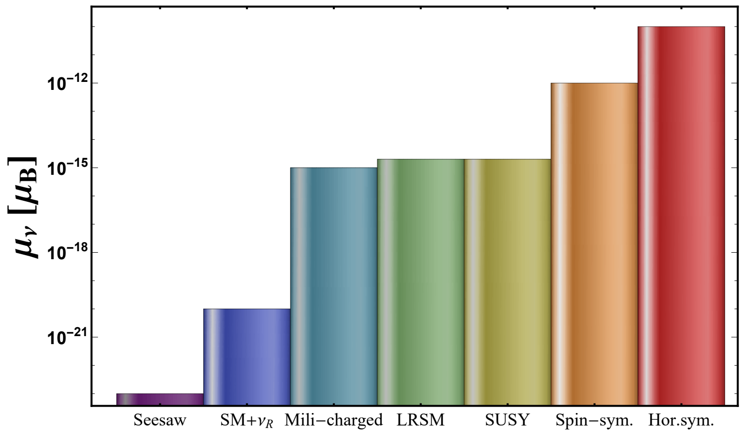

Figure 1: Theoretical predictions of the neutrino magnetic moments in different neutrino mass models. For details, see Ref. [1].

2. Model

Here, I present a simplified model [1] for large transition magnetic moment $\mu_{\nu_e\nu_\mu}$ based on an *approximate* $SU(2)_H$ horizontal symmetry acting on the electron and the muon families. The simplification is that the symmetry is only approximate, broken explicitly by electron and muon masses. Fewer new particles would then suffice to complete the model. The explicit breaking of

$SU(2)_H$ by the lepton masses is analogous to chiral symmetry breaking in the strong interaction sector by masses of the light quarks. Such breaking will have to be included in the neutrino sector as well. The one-loop corrections to the neutrino mass from these explicit breaking terms have been computed, and it has been found that they are small enough so as not to upset the large magnetic moment solution.

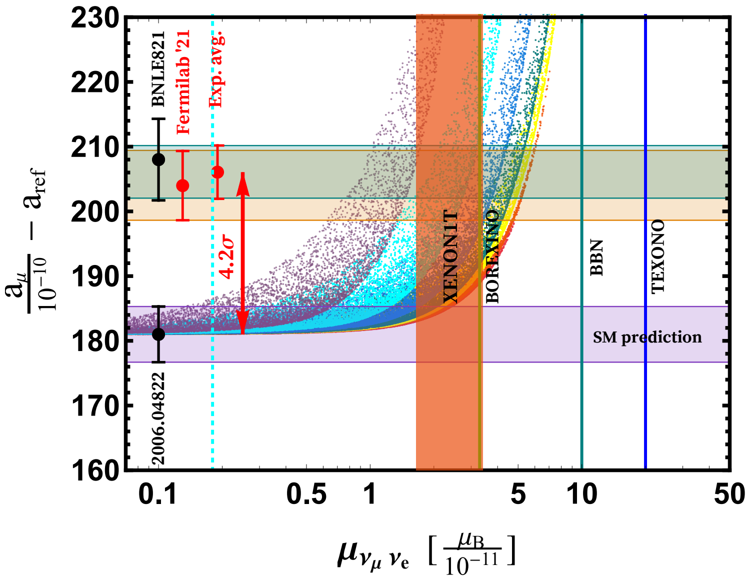

Figure 2: Theoretical predictions and experimental measurements of the muon anomalous magnetic moment and the neutrino transition magnetic moment. For details, see [2].

The Lagrangian of the model does not respect the lepton number. The $SU(2)_H$ limit of the model, however, respects $L_e - L_\mu$ symmetry. This allows a nonzero transition magnetic moment $\mu_{\nu_e \nu_\mu}$, while neutrino mass terms are forbidden – except for a loop-induced τ neutrino mass. Owing to the $SU(2)_H$ symmetry of the model, the two diagrams add in their contributions to the magnetic moment, while they subtract in their contributions to neutrino mass when the photon line is removed from these diagrams (for details, see Ref. [1]). The resulting neutrino magnetic moment is given by [1]

$$\mu_{\nu_\mu \nu_e} = \frac{f f'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2} \left\{ \ln \frac{m_{h^+}^2}{m_\tau^2} - 1 \right\} - \frac{1}{m_{H^+}^2} \left\{ \ln \frac{m_{H^+}^2}{m_\tau^2} - 1 \right\} \right] . \tag{1}$$

Predictions of neutrino magnetic moments (maximum achievable) for different neutrino mass models are summarized in Fig 1.

3. Correlation with charged-lepton magnetic moments

I have also shown that the models that induce neutrino magnetic moments while maintaining their small masses naturally also predict observable shifts in the muon anomalous magnetic moment [2, 3]. This shift is of the right magnitude to be consistent with the Brookhaven measurement as well as the recent Fermilab measurement of the muon $g - 2$. This points out the direct correlation between the magnetic moment of SM-charged lepton and neutral lepton (neutrino) by showing that the measurement of muon $g-2$ by the Fermilab experiment can be an in-direct and novel test of the neutrino magnetic-moment hypothesis, which can be as sensitive as other ongoing-neutrino/dark matter experiments. Such a correlation between muon $g-2$ and the neutrino magnetic moment is generic in models employing leptonic family symmetry to explain a naturally large neutrino magnetic moment. In Fig. 2, there is a direct correlation between the muon anomalous magnetic moment and neutrino magnetic moment.

4. Astrophysical implications

The neutronization burst phase of a core-collapse supernova, which lasts for a few tens of milliseconds post-bounce, is dominated by electron neutrinos and can offer exceptional discovery potential for neutrino transition magnetic moments. The neutrino spectra from the burst phase have been computed in forthcoming neutrino experiments like the Deep Underground Neutrino Experiment and the Hyper-Kamiokande, by taking into account spin-flavour conversions of supernova neutrinos caused by interactions with ambient magnetic fields. The sensitivities to neutrino transition magnetic moments are an order to several orders of magnitude better than the current terrestrial and astrophysical limits. This realization might shed light on the nature of Dirac/Majorana and the neutrino mass-generation mechanism. Investigations into electromagnetic interactions involving neutrinos can also be explored through collider experiments and forthcoming neutrino telescopes, see Refs. [19–23].

5. Final renarks

The theoretical and experimental investigation of neutrino electromagnetic interactions can serve as a powerful tool in the search for the fundamental theory behind the neutrino mass generation mechanism.

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