Probing Neutrino Magnetic Moment with Coherent Elastic Neutrino-Nucleus Scattering

M. Demirci, O. Başlı, and M. F. Mustamin

Department of Physics, Karadeniz Technical University, Trabzon, TR61080, Türkiye

Abstract

The observation of a nonzero value of the neutrino magnetic moment could be an important signature of physics beyond the Standard Model (SM), as well as determining either the Majorana or Dirac nature of neutrinos. We examine the effective neutrino magnetic moment via coherent elastic neutrino-nucleus scattering (CEνNS) for solar neutrinos. We show effect of the neutrino magnetic moment by incorporating it in signal of the SM using solar neutrino flux. We derive new constraints on the effective neutrino magnetic moment using the recent CDEX-10 data.

Keywords: CEνNS, solar neutrino, beyond the SM, neutrino magnetic moments
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1. INTRODUCTION

The Standard Model (SM) needs to be extended to account for neutrino masses. In some of the extensions of the SM, neutrinos can acquire electromagnetic properties [1] via quantum loop effects. These properties are neutrino charge radii, electric charges, dipole electric moment, magnetic moment, and anapole moment. Among these properties, the neutrino magnetic moment is actively searched in modern neutrino experiments and may be measured in the near future. Its value could not only support some theoretical scenarios beyond the SM (BSM), but could also be crucial for determining the Majorana or Dirac nature of neutrinos [2, 3, 4]. Indeed, its existence is predicted by many BSM theories, especially those that include right-handed neutrinos. Furthermore, it is phenomenologically significant for astrophysics since neutrinos with magnetic moments can interact with astrophysical magnetic fields leading to many important effects (see, review [2, 3]). In the SM, its value is predicted to be very small as follows [1, 5]:

$$\mu_\nu = \frac{3eG_F m_\nu}{8\sqrt{2}\pi^2} \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{1\,\text{eV}}\right) \mu_B, \tag{1}$$

while it can be much larger in new physics beyond the SM [6, 7, 8]. Here, G_F is the Fermi constant and μ_B is the Bohr magneton.

Coherent elastic neutrino-nucleus scattering (CEνNS), which occurs when neutrinos are scattered out of the nucleus as a whole [9], provides an important tool for probing the neutrino magnetic moment. CEνNS was firstly observed by the COHERENT experiment [10, 11]. Several constraints on neutrino magnetic moment are derived through CEνNS in [12, 13, 14, 15, 16]. However, the most stringent bounds were obtained as $\mu_{\nu e} \leq 2.9 \times 10^{-11}\,\mu_B$ through the anti-electron neutrino-electron scattering in the GEMMA experiment [17], and $\mu_\nu^{\text{eff}} < 2.8 \times 10^{-11}\,\mu_B$ (at 90% C.L.) with Borexino Phase-II solar neutrino data [18]. Furthermore, the best astrophysical limit was obtained as $\mu_\nu \leq 3 \times 10^{-12}\,\mu_B$ [19]. Utilizing solar neutrinos as a source of inducing CEνNS process would be an interesting framework, especially for studying BSM physics. 0ne of the most intensive natural neutrino sources on the earth is solar neutrinos. The Sun produces electron neutrinos through the nuclear fusion process in its core. Energy of the solar neutrinos that reach to the Earth is located in the range of a few MeV scale, relevant to study their interaction with matter. Since its first observation [20], it has been one of the widely worked subjects. The compact study of it is incorporated within the Standard Solar Model [21, 22, 23].

In the present work, we examine the neutrino magnetic moment through CEνNS with solar neutrinos. Neutrino magnetic moment contributions flip chirality and have not any interference term with the SM. Hence, its cross section can be incoherently added to SM CEνNS cross section. Accordingly, the scattering experiments can be utilized to study the neutrino magnetic moment by measuring deviations of the scattering cross section from the SM prediction.

We present new constraints on the neutrino magnetic moment through CEνNS using the recent CDEX-10 data [24, 25]. We have already derived new constraints for light mediator models through this CDEX-10 data in [26]. The CDEX experiment [27] has primary goal to observe light DM. It has recently detected neutrino-nucleus signals from solar neutrino flux using a germanium target. In the data, event rates are given according to the electron equivalent recoil energies. These values are converted to nuclear recoil signals using a quenching factor. Moreover, we compare our results with the existing constraints of previous works.

The remainder of this work is organized as follows. In Section 2, we review theoretical formulation of the CEνNS in the SM and in the presence of neutrino magnetic moment. In Section 3, we present the analysis method used for limit setting. In Section 4, we present expected event spectra of both the SM and the neutrino magnetic moment. We also show the upper-limits of the parameter space and compare these with previous available limits. Finally, in Section 5, we summarize our work.

2. THEORETICAL FRAMEWORK

In this section, we present analytical expressions of the CEνNS differential cross section in the SM and in the presence of the neutrino magnetic moment.

2.1. CEνNS in the SM

In the CEνNS process, a neutrino with initial energy E_ν scatters from a nucleus target and transmits a kinetic recoil energy T_{nr} to the nucleus. The process occurs as neutrino interact with nucleus as a whole. For the transfer momentum $|\vec{q}| \lesssim \frac{1}{R}$ with the typical nuclear size R, the coherent scattering will provide a cross section enhancement.

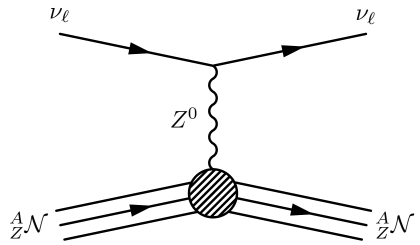


FIGURE 1: Feynman diagram for CEνNS in the SM.

The Feynman diagram for CEνNS in the SM is shown in Figure 1, where ${}^A_Z\mathcal{N}$ denotes to a nucleus with A nucleons (Z protons and $N = A - Z$ neutrons). The Z^0 represents the SM neutral vector boson. The subscript ℓ denotes to the neutrino flavour $\ell = e, \mu$ or τ. The differential cross-section of this process in the SM is given by

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{\mathrm{SM}} = \frac{G_F^2 m_{\mathcal{N}}}{\pi}\left(1 - \frac{m_{\mathcal{N}} T_{nr}}{2E_\nu^2}\right)\left[g_V^p Z F_Z\left(|\vec{q}|^2\right) + g_V^n N F_N\left(|\vec{q}|^2\right)\right]^2, \tag{2}$$

where $m_{\mathcal{N}}$ is the nucleus mass, and T_{nr} is the nuclear recoil energy. The proton and neutron vector couplings are defined by

$$g_V^p = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right), \quad g_V^n = -\frac{1}{2}, \tag{3}$$

respectively. For the weak-mixing angle, we use the value of $\sin^2\theta_W = 0.23863$ [28] (low momentum transfer in the $\overline{\mathrm{MS}}$ scheme). Furthermore, the SM cross section of the process is flavor independent at tree level. There are flavor dependencies in the small loop corrections, however they have no significant impact for the current sensitivities [29]. The weak nuclear form factors are given by $F_Z(|\vec{q}|^2)$ and $F_N(|\vec{q}|^2)$, which describe the nucleon complex structure of the target nucleus. We assume the same form factor for both proton and neutron, namely $F_Z \simeq F_N = F$, and use the Helm parametrization [30].

2.2. CEνNS in the Presence of Neutrino Magnetic Moment

In general, the magnetic moments for Dirac ($\mathcal{D}$) or Majorana ($\mathcal{M}$) neutrinos to interact with the electromagnetic field strength $F_{\mu\nu}$ are defined by the following Lagrangians [5, 6, 7]:

$$\mathcal{L}_{\mathcal{D}} = -\frac{1}{4}\bar{\nu}_{\ell R}\lambda^{\mathcal{D}}_{\ell k}\sigma^{\mu\nu}\nu_{kL}F_{\mu\nu}, \tag{4}$$

$$\mathcal{L}_{\mathcal{M}} = -\frac{1}{4}\bar{\nu}^C_{\ell R}\lambda^{\mathcal{M}}_{\ell k}\sigma^{\mu\nu}\nu_{kL}F_{\mu\nu}, \tag{5}$$

where the parameter $\lambda^{\mathcal{D}/\mathcal{M}} = \mu^{\mathcal{D}/\mathcal{M}} - i\epsilon^{\mathcal{D}/\mathcal{M}}$ is antisymmetric for Majorana neutrinos and hermitian for the Dirac neutrinos. In practice, no distinction between Dirac and Majorana neutrinos is possible since the neutrino flavor in final state during the scattering process is unknown.

For simplicity, the flavor diagonal cases for the electron, muon and tau neutrinos can be considered. In presence of neutrino magnetic moment, the differential cross section is given by [7]

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{\nu_\ell\mathrm{MM}} = \frac{\pi\alpha_{\mathrm{EM}}^2}{m_e^2}\mu_{\nu_\ell}^2\left(\frac{1}{T_{nr}} - \frac{1}{E_\nu}\right)\left[ZF_Z(|\vec{q}|)\right]^2, \tag{6}$$

where m_e is the electron mass, α_{EM} is fine structure constant and μ_{ν_ℓ} represents the effective neutrino magnetic moment in unit of Bohr magneton μ_B (see, [2]). The magnetic moment contribution changes the helicity of the final neutrino state. Hence, there is no interference with the SM, and the magnetic moment contribution adds to the SM cross-section. Namely, the complete cross section reads

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{\mathrm{SM}+\nu_\ell\mathrm{MM}} = \left[\frac{d\sigma}{dT_{nr}}\right]_{\mathrm{SM}} + \left[\frac{d\sigma}{dT_{nr}}\right]_{\nu_\ell\mathrm{MM}}. \tag{7}$$

It is clear that any deviation of the measured cross section of CEνNS under discussion from the well-known SM value (2) will give a signature of the physics beyond the SM.

We consider the solar neutrino survival probabilities. For the case of $\nu_e \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$, and $\nu_e \rightarrow \nu_\tau$ the probabilities are, respectively,

$$P_{ee} = P_{\text{eff}} \cos^4 \theta_{13} + \sin^4 \theta_{13}, \tag{8}$$

$$P_{e\mu} = (1 - P_{ee}) \cos^2 \theta_{23}, \tag{9}$$

$$P_{e\tau} = (1 - P_{ee}) \sin^2 \theta_{23}, \tag{10}$$

with the factor of the matter effect P_{eff} [31]

$$P_{\text{eff}} = 1 - \frac{1}{2} \sin\left(2\theta_{12}\right)^2 . \tag{11}$$

We consider this form for solar neutrino in a few MeV energy. The probabilities are evaluated using the best-fit central values of the recent oscillation parameters with normal ordering [32].

2.3. *Differential Rate*

We calculate the event rate by the convolution of cross section with neutrino flux as follows:

$$\frac{dR}{dT_{nr}} = N_T \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{d\Phi\left(E_\nu\right)}{dE_\nu} \frac{d\sigma\left(E_\nu, T_{nr}\right)}{dT_{nr}}, \tag{12}$$

where $d\Phi(E_\nu)/dE_\nu$ is the differential neutrino flux and $N_T = m_t N_A / m_A$. Here, m_t is the target mass, m_A is the molar mass of the nuclei and N_A is Avogadro's number. The minimum neutrino energy $E_\nu^{\min}$ satisfies

$$E_\nu^{\min} = \frac{T_{nr}}{2} \left(1 + \sqrt{1 + \frac{2m_{\mathcal{N}}}{T_{nr}}}\right), \tag{13}$$

while the maximum neutrino energy $E_\nu^{\max}$ is taken as the end point of the solar neutrino flux. Furthermore, the maximum value of nuclear recoil energy is

$$T_{nr}^{\max} = \frac{2E_\nu^2}{2E_\nu + m_{\mathcal{N}}}. \tag{14}$$

We consider solar neutrino flux from the BS05(OP) standard solar model (SSM) [33, 34]. There are eight neutrino fluxes which produced from proton-proton (pp) chain and Carbon-Nitrogen-Oxygen (CNO) cycle inside the sun. For the pp chain, neutrinos are produced from five nuclear reactions referred to the *pp*, *pep*, hep, ^{8}B, and ^{7}Be. Meanwhile in the CNO cycle, neutrinos are originated from decays of ^{13}N, ^{15}O, and ^{17}F.

In experiments, the observed physical quantity is different from the nuclear recoil energy signal as neutrinos scatter off the nuclei. When an isolated nuclear recoil occurs, the electron-equivalent nuclear recoil energy T_{ee} is observed in the detector. For relating these two quantities, quenching factor $Q(T_{nr})$ must be used. We consider the Lindhard quenching factor [35]

$$Q\left(T_{nr}\right) = \frac{\kappa g(\epsilon)}{1 + \kappa g(\epsilon)}, \tag{15}$$

where $\kappa = 0.162$ and $g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$ with $\epsilon = 11.5 Z^{-7/3} T_{nr}$. The value of κ is chosen to be closely matches the recent measurement in the low-energy range [36, 37]. We notice that the Linhard formula is acceptable for relatively high nuclear recoil energy, namely $T_{nr} > 0.254\,\text{keV}$. With the quenching factor, the nuclear recoil energy can be converted into electron equivalent using

$$T_{ee} = Q\left(T_{nr}\right) T_{nr}. \tag{16}$$

Thus, the differential rate can be expressed as

$$\frac{dR}{dT_{ee}} = \frac{dR}{dT_{nr}} \left[Q\left(T_{nr}\right) + T_{nr} \frac{dQ\left(T_{nr}\right)}{dT_{nr}}\right]^{-1}. \tag{17}$$

3. DATA ANALYSIS METHOD

We analysis the recent CDEX-10 data [25] with associated to coherent neutrino-nucleus scattering. The CDEX experiment, which is part of the China Jinping Underground Laboratory (CJPL) [27], have been dedicated for direct detection of DM, using ultra-low energy threshold pPCGe detectors. Since its first started, the experiment have been conducting some exotic physics searches such as WIMP, axion particle, and dark photon. The CDEX-10 experimental configuration has been described in [24]. The CEνNS, as well as neutrino-electron, process can enhance the observation limits of the light mediator models in the ROI of DM direct detection endeavors. In this regards, we use the recent CDEX-10 data (20 data points) related to neutrino-nucleus scattering. These data are given in terms of electron-equivalent recoil energy. We convert this into the nuclear recoil energy using the Linhard quenching factor in equation (15).

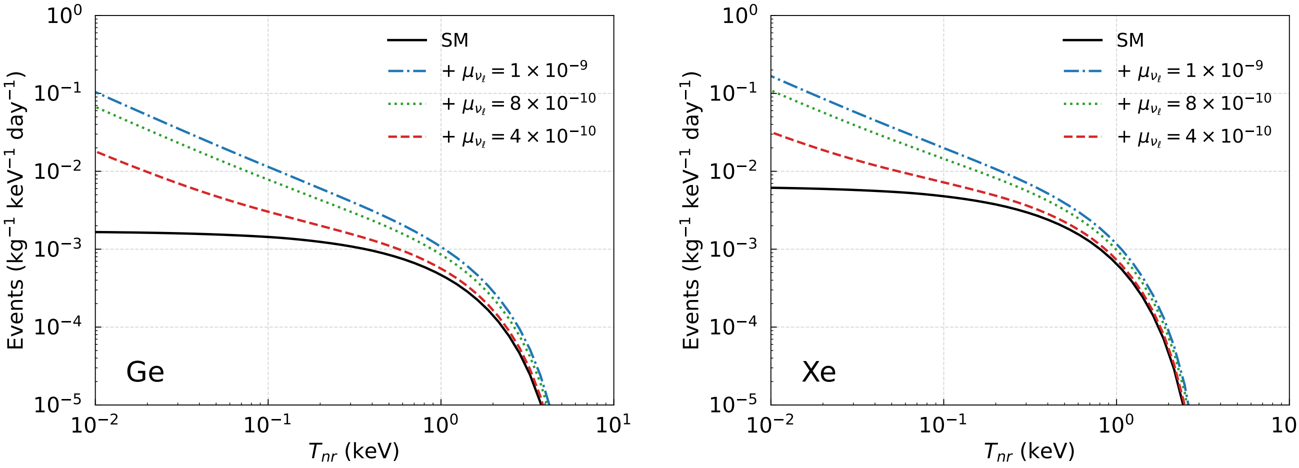
We adopt the pull approach of the χ^2 function [38]

$$\chi^2 = \min_{(\xi_j)} \sum_{i=1}^{20} \left(\frac{R^i_{\text{obs}} - R^i_{\text{exp}} - B - \sum_j \xi_j c^i_j}{\Delta^i} \right)^2 + \sum_j \xi_j^2 \tag{18}$$

for constraining the corresponding model parameters. Here, R^i_{obs} and R^i_{exp} are the observed and expected event rates (that consists of SM plus new physics contribution) respectively, in the i-th energy bin. Δ^i denotes the experimental uncertainty which includes statistical and systematic uncertainties, for the i-th energy bin. The function is minimized with respect to all pull parameters ξ_j [38]. The solar neutrino flux uncertainty is represented by c^i_j. Using this function, we derive the 90% C.L. with 2 d.o.f. limits of our considered models and further compare it with previous related works that is explained in the next section.

4. NUMERICAL RESULTS

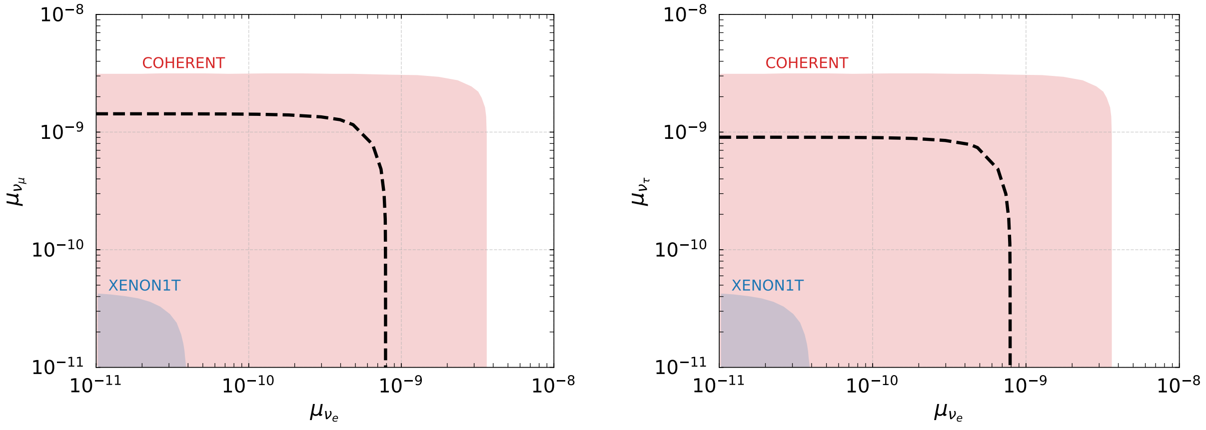
The predicted CEνNS rates in the SM and the contribution of neutrino magnetic moments in terms of T_{nr} are given in Figure 2. The rates are normalized in kg^{-1} keV^{-1} day^{-1}. We consider three values of μ_{ν_ℓ} as follows $\mu_{\nu_\ell} = 1 \times 10^{-9}, 8 \times 10^{-10}, 4 \times 10^{-10}$, to show their predicted contribution to the SM process for Ge and and Xe targets in Figures 2(a) and 2(b), respectively. We witness that heavier target provide a larger predicted event rates. The contribution of neutrino magnetic moment is clearly seen in the low-recoil energy region as $T_{nr} < 1$ keV. These effects are clearly observed for larger value of μ_{ν_ℓ}. As neutrino magnetic moment becomes smaller, these contributions are approaching the SM signal and they are hardly separated in the region with high nuclear recoil energy. We note that since it has no interference term with the weak neutral current of Z-boson, neutrino magnetic moment contribution is added incoherently to the SM CEνNS.



(a) (b)

FIGURE 2: Predicted CEνNS rates as a function of nuclear recoil energy in the SM (solid black) and contributions of neutrino magnetic moments for (a) Ge and (b) Xe targets. Here, ^{8}B neutrino flux which has a large energy spectrum on the Earth is considered.

We present new limits on the neutrino magnetic-moments using CDEX-10 data in Figure 3. We show 90% C.L. allowed regions of μ_{ν_e} vs μ_{ν_μ} and μ_{ν_e} vs μ_{ν_τ} when two effective neutrino magnetic moments are taken simultaneously. We derive the following limits $\mu_{\nu_e} < 7.88 \times 10^{-10}$, $\mu_{\nu_\mu} < 1.43 \times 10^{-10}$, and $\mu_{\nu_\tau} < 9.05 \times 10^{-10}$ for electron-, muon-, and tau-neutrino magnetic moments, respectively. These limits can be obtained directly from Figure 3. We further compare our results with the allowed region derived from COHERENT and XENON1T from excees of electron recoil for μ_{ν_e} with effective case that combine μ_{ν_μ} and μ_{ν_τ}. It is seen that our result is more stringent than limit from the COHERENT (red-regions) which combined CsI and Ar data [12]. Meanwhile, the parameter space of excess from the electron recoil of XENON1T (blue-regions), such as studied in [39], is yet to be reached.



(a)

(b)

FIGURE 3: Upper-limits with 90% C.L. of the flavor dependent neutrino magnetic moments on the space of (a) μ_{ν_e} vs μ_{ν_μ} and (b) μ_{ν_e} vs μ_{ν_τ}. The allowed regions from COHERENT and XENON1T are shown for comparison.

5. SUMMARY AND CONCLUSIONS

We have studied contribution of neutrino magnetic moment in the framework of CEνNS with solar neutrino. This electromagnetic property of neutrino is an interesting consequence of the discovery of massive neutrino. It has no interference with the SM CEνNS, hence its contribution is directly added with the SM cross section. The event rates of the process is obtained by convoluting solar neutrino flux with the cross section. For the analysis, we considered recent CDEX-10 data. In doing so, the nuclear recoil energy is converted into electron-equivalent energy with the use of Linhard quenching factor.

We have numerically presented event rates and analysis result. The event rates are shown for two nuclear Ge and Xe targets with different values of neutrino magnetic moments as a benchmark. The effect of this electromagnetic property enhances the spectrum in the low-region of nuclear recoil energy. For the considered benchmark, smaller values contribute a small effect to the SM signal. Furthermore, heavier target provide larger spectrum as expected from the dependency on number of nucleon of the processes. Regarding the analysis, we have shown our obtained limit of neutrino magnetic moment with 90% C.L. when two effective neutrino magnetic moments are taken simultaneously. We have compared our results with the allowed regions derived from COHERENT and XENON1T. A tighter limit than the former can be seen, while our results still yet to reach the latter case.

We have demonstrated that effect of neutrino magnetic moment within CEνNS could be studied with solar neutrino source. Our results could be utilized to study new physics signals, particularly for neutrino electromagnetic properties, by current and future experiments.

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References

[1] B. Kayser, "Majorana Neutrinos and their Electromagnetic Properties," Phys. Rev. D 26, 1662 (1982).
[2] C. Giunti and A. Studenikin, Rev. Mod. Phys. 87,531 (2015).
[3] C. Giunti, K. A. Kouzakov, Y.-F. Li, A. V. Lokhov, A. I. Studenikin, S. Zhou, "Electromagnetic neutrinos in laboratory experiments and astrophysics," Ann. Phys. (Berlin) 528, 198 (2016).
[4] A. I. Studenikin and K. A. Kouzakov, Moscow UniversityPhysics Bulletin, Vol. 75, No. 5 (2020).
[5] K. Fujikawa and R. Shrock, "The Magnetic Moment of a Massive Neutrino and Neutrino Spin Rotation," Phys. Rev. Lett. 45, 963 (1980).
[6] R. E. Shrock, "Electromagnetic Properties and Decays of Dirac and Majorana Neutrinos in aGeneral Class of Gauge Theories," Nucl. Phys. B 206,359 (1982).
[7] P. Vogel and J. Engel, Phys. Rev. D 39, 3378 (1989).
[8] K. S. Babu, S. Jana and M. Lindner, "Large Neutrino Magnetic Moments in the Light of RecentExperiments," JHEP 10, 040 (2020).
[9] D. Z. Freedman, "Coherent Neutrino Nucleus Scattering as a Probe of the Weak Neutral Current," Phys. Rev. D **9**, 1389–1392 (1974).
[10] D. Akimov et al. [COHERENT], "Observation of Coherent Elastic Neutrino-Nucleus Scattering," Science **357**, 1123–1126 (2017).
[11] D. Akimov et al. [COHERENT], "First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon," Phys. Rev. Lett. **126** 012002, (2021).
[12] M. Cadeddu, F. Dordei, C. Giunti, Y. F. Li, E. Picciau, and Y. Y. Zhang, "Physics results from the first COHERENT observation of coherent elastic neutrino-nucleus scattering in argon and their combination with cesium-iodide data," Phys. Rev. D **102**, 015030 (2020).
[13] M. Atzori Corona, M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, Y. F. Li, C. A. Ternes, and Y. Y. Zhang, "Impact of the Dresden-II and COHERENT neutrino scattering data on neutrino electromagnetic properties and electroweak physics." JHEP **09**, 164 (2022).

[14] A. N. Khan, "Neutrino millicharge and other electromagnetic interactions with COHERENT-2021 data," Nucl. Phys. B **986**, 116064 (2023).

[15] A. N. Khan, "Light new physics and neutrino electromagnetic interactions in XENONnT," Phys. Lett. B **837**, 137650 (2023).

[16] V. De Romeri, O. G. Miranda, D.K. Papoulias, G. S. Garcia, M. Tortola, and J. W. F. Valle, "Physics implications of a combined analysis of COHERENT CsI and LAr data." J. High Energ. Phys. 2023, 35 (2023).

[17] A. G. Beda, V. B. Brudanin, V. G. Egorov, D. V. Medvedev, V. S. Pogosov, M. V. Shirchenko, and A. S. Starostin, "The results of search for the neutrino magnetic moment in GEMMA experiment," Adv. High Energy Phys. 2012 (2012) 350150.

[18] M. Agostini et al. [Borexino], "Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data," Phys. Rev. D 96, 091103 (2017).

[19] G. G. Raffelt, "New bound on neutrino dipole moments from globular-cluster stars," Phys. Rev. Lett. 64, 2856 (1990).

[20] R. Davis, Jr., D. S. Harmer, and K. C. Hoffman, "Search for neutrinos from the sun," Phys. Rev. Lett. **20**, 1205–1209 (1968).

[21] J. N. Bahcall, M. H. Pinsonneault, and S. Basu, "Solar models: Current epoch and time dependences, neutrinos, and helioseismological properties," Astrophys. J. **555**, 990–1012 (2001).

[22] N. Vinyoles, et al., "A new Generation of Standard Solar Models," Astrophys. J. **835**, 202 (2017).

[23] E. Vitagliano, I. Tamborra, and G. Raffelt, "Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components," Rev. Mod. Phys. **92**, 45006 (2020).

[24] H. Jiang et al. [CDEX], "Limits on Light Weakly Interacting Massive Particles from the First 102.8 kg × day Data of the CDEX-10 Experiment," Phys. Rev. Lett. **120**, 241301 (2018).

[25] X. P. Geng et al. [CDEX], "Search for exotic neutrino interactions using solar neutrinos in the CDEX-10 experiment," Phys. Rev. D **107**, 112002 (2023).

[26] M. Demirci and M. F. Mustamin, "Solar neutrino constraints on light mediators through coherent elastic neutrino-nucleus scattering," Phys. Rev. D **109**, 015021 (2024).

[27] K. J. Kang et al. [CDEX], "Introduction to the CDEX experiment," Front. Phys. (Beijing) **8**, 412–437 (2013).

[28] R. L. Workman et al. [Particle Data Group], "Review of Particle Physics," PTEP **2022**, 083C01 (2022) .

[29] O. Tomalak, P. Machado, V. Pandey, and R. Plestid, "Flavor-dependent radiative corrections in coherent elastic neutrino-nucleus scattering," JHEP **02**, 097 (2021).

[30] R. H. Helm, "Inelastic and Elastic Scattering of 187-Mev Electrons from Selected Even-Even Nuclei," Phys. Rev. **104**, 1466–1475 (1956).

[31] C. Giunti and C. A. Ternes, "Testing neutrino electromagnetic properties at current and future dark matter experiments," Phys. Rev. D **108**, 095044 (2023).

[32] P. F. de Salas, et al., "2020 global reassessment of the neutrino oscillation picture," JHEP **02**, 071 (2021).

[33] J. N. Bahcall and A. M. Serenelli, "How do uncertainties in the surface chemical abundances of the Sun affect the predicted solar neutrino fluxes?," Astrophys. J **626**, 530 (2005).

[34] J. N. Bahcall, A. M. Serenelli, and S. Basu, "New solar opacities, abundances, helioseismology, and neutrino fluxes," Astrophys. J. Lett. **621**, L85–L88 (2005).

[35] J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, "Integral Equations Governing Radiation Effects (Notes on Atomic collisions, III)," Kgl. Danske Videnskab., Selskab. Mat. Fys. Medd. 33, 1, (1963).

[36] A. Bonhomme, et al., "Direct measurement of the ionization quenching factor of nuclear recoils in germanium in the keV energy range," Eur. Phys. J. C **82**, 815 (2022).

[37] T. Schwemberger and T. T. Yu, "Detecting beyond the standard model interactions of solar neutrinos in low-threshold dark matter detectors," Phys. Rev. D **106**, 015002 (2022).

[38] G. L. Fogli, et al., "Getting the most from the statistical analysis of solar neutrino oscillations," Phys. Rev. D **66**, 053010 (2002).

[39] B. Yue, J. Liao, and J. Ling, "Probing neutrino magnetic moment at the Jinping neutrino experiment," JHEP **08**, 068 (2021).