Projected sensitivities on sterile neutrino dipole portal with coherent elastic solar neutrino-nucleus scattering

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Abstract

Sterile neutrinos can be produced by neutrino beams electromagnetically upscattering on nuclei in the presence of a transition magnetic moment between active and sterile neutrinos. We investigate the active-sterile neutrino transition magnetic moment through this upscattering in the coherent elastic neutrino-nucleus scattering ($CE\nu NS$) process induced by solar neutrinos. We consider future projection scenarios taking into account expected experimental developments at direct detection facilities. We derive projected limits on the transition magnetic moment-sterile neutrino mass plane from these scenarios. We compare our results with available limits derived from other experiments.

Keywords: $CE\nu NS$, Solar neutrino, Sterile dipole portal
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1. INTRODUCTION

The interactions of low-energy neutrinos with nuclei supply a unique framework to probe various Standard Model (SM) and beyond the SM (BSM) processes. In particular, the coherent elastic neutrino-nucleus scattering ($CE\nu NS$), which has recently been observed, is a neutral current process induced by the exchange of the neutral Z-boson [1]. A relatively low-energy neutrino interacts with a nucleus as a whole in this process, followed by measurable nuclear recoil energy of the nucleus. This process was first observed by COHERENT collaboration [2] with a CsI[Na] scintillating crystal detector utilizing neutrinos from pion-decays-at-rest (πDAR). The experiment further detected the process with liquid argon and with a larger sample of CsI[Na] detector [3, 4]. In the near future, these attempts will improve the precision test of $CE\nu NS$in the SM and further give clues to search for BSM physics. One such BSM proposal is the scattering of active neutrinos with heavy sterile neutrinos through a transi- tion magnetic moment, which is called the Primakoff upscattering [5, 6]. It was first proposed to explain neutral-meson photoproduction in a nuclear electric field [7]. The sterile neutrino production by electromagnetically upscattering neutrino beams on nuclei may improve by the large transition magnetic moment [8]. This kind of dipole portal has been studied extensively in many experiments [9, 10, 11, 12, 13, 14, 15, 16, 17]. Experiments for dark matter (DM) direct detection (DD) are turning into excellent low-energy neutrino detectors. In this work, we provide future sensitivities of these experiments on the active-sterile neutrino transition magnetic moment through $CE\nu NS$ with solar neutrinos, based on our recent work [18]. Solar neutrinos can induce events of $CE\nu NS$ in direct detection experiments. We consider in this context future projections utilizing the latest data of the CDEX-10 [19] taking into account expected experimental developments. The experiment itself has a main goal of searching light DM candidate [20]. We give our projected sensitivities on the parameter plane of the transition magnetic moment and the sterile neutrino mass for next-generation and future scenarios. Also, we compare our obtained results with the available limits utilizing data from various experiments. In the rest of this study, we introduce the theoretical framework of the $CE\nu NS$ in both SM and the presence of active-sterile neutrino transition magnetic moment in Section 2. We next provide details of the data analysis in Section 3. After that, we present our results and give a conclusion in Section 4.

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2. THEORETICAL FRAMEWORK

The differential cross section of the $CE\nu NS$ process at tree level in the SM can be written as :

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{SM} = \frac{G_F m_N}{\pi}\left(Q_V^{SM}\right)^2 F^2(q^2)\left(1-\frac{m_N T_{nr}}{2E_\nu^2}\right) \quad (1)$$

The Fermi constant is represented by G_F while E_ν denotes the incoming energy of neutrinos, nuclear recoil energy, $q = \sqrt{2m_N T_{nr}}$ momentum transfer, and m_N the mass of the target nucleus. The weak charge of the nucleus is

$$Q_V^{SM} = g_V^p Z + g_V^n N \quad (2)$$

with $g_V^p = (2g_V^u + g_V^d)$and $g_V^n = (g_V^u + 2g_V^d)$. Here, g_V^u and g_V^d are the vector couplings for the up and down quarks,respectively. In view of the weak mixing angle θ_W at low momentum transfer, $g_V^p = -2\sin^2\theta_W + \frac{1}{2} \approx 0.0229$,$g_V^n = \frac{1}{2}$with $\sin^2\theta_W = 0.23857$ [21]. For the form factor $F(q^2)$, we use the Klein-Nystrand parametrization [22]. Note that the impact of the nuclear form factor can be negligible at small momentum transfer. The transition magnetic moment between active neutrinos and a sterile neutrino ν_4 gives rise to the possibility of observing the proposed BSM through an upscattered process. The Lagrangian that can explain this process is [12]

$$\mathcal{L}_{int} \supset \frac{\mu_{\nu l_4}}{2}\bar{\nu}_{lL}\sigma^{\mu\nu}P_4\nu_4 F_{\mu\nu} + h.c \quad (3)$$

$\mu_{\nu l_4}$ denotes the active-sterile transition magnetic moment, ν_{lL} an SM left-handed neutrino of flavor $l = e, \mu, \tau$, and $F_{\mu\nu}$ the electromagnetic strength tensor.This Lagrangian is valid only at energies below the electroweak (EW) scale, which is suitable for the $CE\nu NS$ process. In Figure 1, we show the representative diagram for the upscattering of $\nu_l N \to \nu_4 N$. Concerning the nucleus as spin-1/2 particle, the differential cross section can be written by

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{TMM} = \frac{\pi\alpha_{EM}^2}{m_e^2}\left|\frac{\mu_{\nu l4}}{\mu_B}\right|^2 Z^2F^2(|\vec{q}|^2)\left[\frac{1}{T_{nr}} - \frac{1}{E_\nu} - \frac{m_4^2}{2T_{nr}E_\nu m_N}\left(1-\frac{T_{nr}}{2E_\nu}+\frac{m_N}{2E_\nu}\right) - \frac{m_4^4}{8m_N T_{nr}^2 E_\nu^2}\left(1-\frac{T_{nr}}{m_N}\right)\right] \quad (4)$$

This contribution is coherently added with the SM case. Note that the subdominant scattering through the nuclear magnetic dipole moment is neglected. The active neutrino masses are negligibly small compared to the sterile neutrino mass m_4, the nuclear recoil energy, and the neutrino energy. Since only protons contribute to this process, the enhancement factor only depends on Z. The above formula turns to the active neutrino magnetic moment [23] for $m_4 = 0$. It should be noted that the sterile neutrino mass must satisfy the following kinematic constraint:

$$m_4^2 \leq 2m_N T_{nr}\left(\sqrt{\frac{2}{m_N T_{nr}}}E_\nu - 1\right) \quad (5)$$

3. ANALYSIS

The nuclear recoil event observed in the experiments is given by :

$$\frac{dR}{dT_{nr}} = \frac{\epsilon}{m_T}\Sigma_i \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi_{\nu l}^i(E_\nu)}{dE_\nu}\frac{d\sigma(E_\nu, T_{nr})}{dT_{nr}} \quad (6)$$

In this relation, ϵ denotes experimental exposure, m_T target mass, $\frac{d\Phi_{\nu l}^i(E_\nu)}{dE_\nu}$ solar neutrino flux ($cm^{-2}s^{-1}$), and $\frac{d\sigma(E_\nu,T_{nr})}{dT_{nr}}$ differential cross section. The minimum neutrino energy for active neutrinos is given by

$$E_\nu^{min} = \frac{T_{nr}}{2}\left(1+\sqrt{1+\frac{2m_N}{T_{nr}}}\right) \quad (7)$$

while for the sterile neutrino

$$E_{\nu 4}^{min} = \frac{m_4^2 + 2m_N T_{nr}}{2\sqrt{T_{nr}(T_{nr}+2m_N)} - T_{nr}} \quad (8)$$

Notice that the sterile neutrino case is higher than the active one. This indicates that higher energy neutrino could produce ν_4 with a larger mass. As for the solar neutrino fluxes, we consider standard solar model (SSM) BS05(OP) [24, 25]. In this work, we consider the ^8B and hep solar neutrino spectra. These give major contributions to the $CE\nu NS$ event rates. ince we are dealing with $CE\nu NS$, note that the observed data are given in units of electron equivalent energy T_{ee} as ionization signals. To convert the nuclear recoil energy T_{nr} into T_{ee}, we need a quenching factor $Y(T_{nr})$. These two quantities can be related by $T_{ee} = Y(T_{nr})T_{nr}$. Hence, in views of the electron equivalent energy, the differential rate can be given as :

$$\frac{dR}{dT_{ee}} = \frac{dR}{dT_{nr}}\frac{1}{Y(T_{nr}) + T_{nr}\frac{dY(T_{nr}}{dT_{nr}}} \quad (9)$$

In general, the Lindhard quenching factor [26] is used where it is acceptable in the region $T_{nr} > 0.254$ keV. In this work, since we are dealing with a low threshold, we take

$$Y(T_{nr}) = 0.18\left[1 - e^{\left(\frac{15-T_{nr}}{71.03}\right)}\right] \quad (10)$$

It is obtained from the “high” ionization-efficiency model for Ge target, which is acceptable for $0.015\ keV < T_{nr} < 0.254$ keV [27]. Solar neutrinos arrive at a detector on Earth since they oscillate when propagating from the Sun to the Earth, as a mixture of all possible flavor. We consider the survival probabilities for each flavor to be $\Phi_{\nu e}^i = \Phi_{\nu e}^i \odot P_{ee}, \Phi_{\nu\mu}^i = \Phi_{\nu\nu}^i \odot (1 - P_{ee})\cos^2\mathcal{V}_{23}$ and $\Phi_{\nu\tau}^i = \Phi_{\nu e}^i \odot (1-P_{ee})\sin^2\mathcal{V}_{23}$[28] . In our calculation, we take the day-night asymmetry due to the Earth matter effect. We consider the normal- ordering neutrino oscillation parameters from the $3-\nu$ oscillation of NuFit-5.3 [29]. Experimental advancements in DD facilities currently enter the multi-ton phase. Many facilities have the potential for detecting $CE\nu NS$ and exploring new physics scenarios in the future. Experiments with Xe targets have already been able to observe the $CE\nu NS$ process with solar neutrinos, such as PandaX-4T [30], XENONnT [31], and LZ [32], while a future facility at DARWIN [33] targets to reach up to 50 tons of liquid xenon. Moreover, others low-scale solid material targets using Si or Ge, such as EDELWEISS [34], Super CDMS [35], and SENSEI [36], aim to reach low threshold detectors. All these developments are expected to improve limits on low-mass WIMPs and to detect extremely low recoil energies of solar neutrino $CE\nu NS$ events that may allow more severe tests for BSM physics. The CDEX facility itself is currently developing the CDEX-50 phase [37]. The upgrade is expected to reduce the background to about 0.01 events keV^{-1} kg^{-1} day^{-1} with improved exposure up to 150 kg $\cdot$ year and 160eVee analysis threshold [37]. Additionally, the ultimate goal of the experiment is to set up a ton-scale mass Ge detector and reach a low sub-keV energy threshold. We consider two scenarios to investigate the near future experimental advancements of the active-sterile transition magnetic moment. These are termed next-generation and future scenarios. These two are based on the projected development of the DD facilities discussed above. The nextgeneration scenario is set to have exposure of 150 kg $\cdot$ year and the future scenario have 1.5 ton $\cdot$ year exposure. The threshold of the next-generation scenario is set to be 1 keVnr and the future 2 is 0.1 keVnr. We consider the target mass for the two scenarios to be 50 kg. We set a flat background of 0.01 events keV^{-1} kg^{-1} day^{-1} in both scenarios. These configurations are considered to reduce the uncertainty by a factor of 10 future scenario. With these considerations, we examine the relationship between the sterile neutrino mass bounds that can provide intuitive scaling from DD advancements. We derive our projected sensitivities by using χ^2 function with the pull approach [38]

$$\chi^2 = min_{(\zeta_j)}\Sigma_{i=1}^{20}\left(\frac{R_{obs}^i - R_{exp}^i - \Sigma_j\zeta_J c_J^i}{\Delta^i}\right)^2 + \Sigma_j\zeta_j^2 \quad (11)$$

The i-th energy bin of the observed and expected event rates are given by R_{obs}^i and R_{exp}^i , respectively. The experimental uncertainty is given by Δ^i , including the statistical and systematic uncertainties [20]. The solar neutrino flux uncertainty is denoted by the factor c_J^i . We minimize this to pull parameters ζ_j for the J-th neutrino flux.

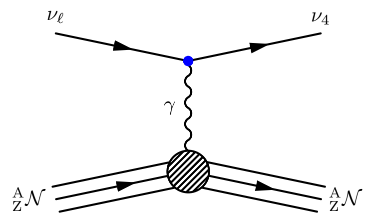

FIGURE 1: The up-scattering diagram of $\nu_l\mathcal{N} \to \nu_4\mathcal{N}$

4. RESULTS AND CONCLUSION

We present our derived projected limits on the plane of the transition magnetic moment and sterile neutrino mass. The projected sensitivities are obtained for next-generation and future scenario obtained by taking into account experimental developments (discussed in the previous section). We also compare the results with the existing limits in the literature. Figure 2(a) shows our projected sensitivities on the flavor-independent ν-sterile transition magnetic moment $\mu_{\nu l4}$. The upper limit of the $\mu_{\nu l4}$ from next-generation and future scenarios is around $\mu_{\nu l4} \leq 8.63 \times 10^{-10}\mu_B$ and $\mu_{\nu l4} \leq 2.9710^{-10}\mu_B$, respectively. We see that the future scenario provides about 65.54% more stringent limits than the next-generation scenario. In Figure. 2(b), we present a comparison with previous limits of$\mu_{\nu l4}$. It is observed that the projected scenarios may yield stronger constraints than some available derived limits. They fully cover the region of XENON1T [10, 11], NUCLEUS 1kg [12], Dresden-II [39], and COHERENT (ν_μ) limits [13]. Our results also reach previously unexplored region of the COHERENT (μ_e) [13], CENNS-750 [10], as well as LSND [14], SHiP main [14], DUNE ND (ν_e and ν_μ) [40], and IceCube/DeepCore [15]. Our results further improve the obtained BOREXINO [11] and TEXONO [10] limits for m_4 >0.5 MeV. Concerning the cosmological results, our results are complementary to the BBN [11] limit (for $m_4 < 1MeV$) and the limit of the SN1987A [11]. Lastly, we present the limit from the $\nu_4 \to \nu\gamma$ decay to complement our results. We have presented the active-sterile neutrino transition magnetic moments through $CE\nu NS$ induced by solar neutrinos at future experimental advancement. We studied the flavor-independent case of the process. Two scenarios are considered, which can be realized following further upgrades of DD experiments which potentially improve precision of the $CE\nu NS$ signal. Accordingly, we then compared our analysis with existing limits from previous works. From our results, we find that the projected sensitivities could cover sterile neutrino mass below 10 MeV, regions which were previously unexplored. The existing sterile neutrino proposal is interesting from a phenomenological standpoint, and we have demonstrated the utility of solar neutrinos in the framework of $CE\nu NS$ experiments to explore it. The low-energy neutrinos from the Sun enable us to derive constraints on the active-sterile neutrino transition magnetic moment and compare them with results from existing facilities. More opportunities in examining new physics from future experiments are expected and our results may provide clues for those endeavors.

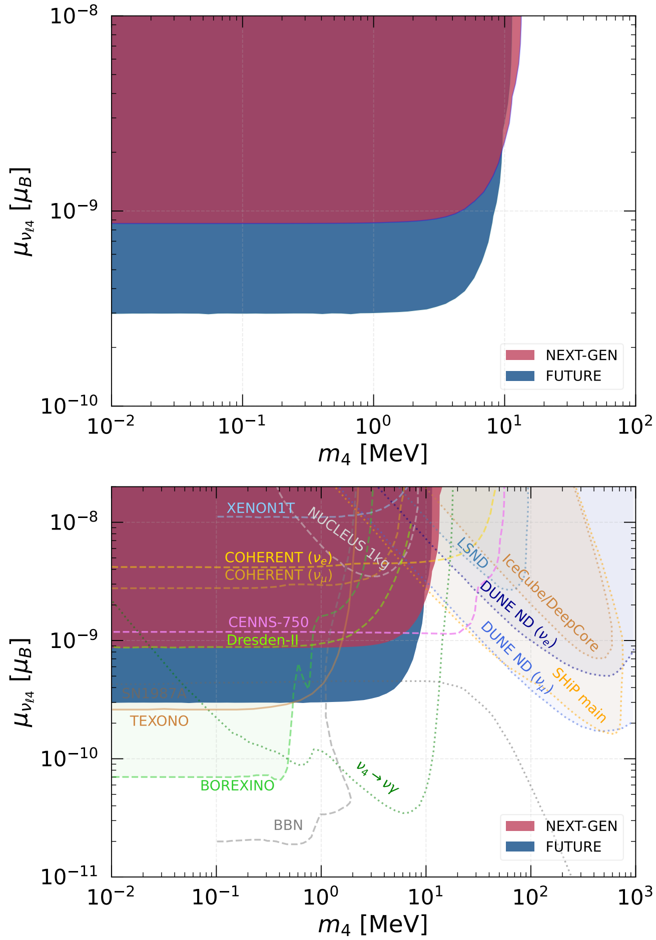

FIGURE 2: (a) Projected sensitivities at 90% C.L. on the plane of $\mu_{\nu l4} - m_4$ derived from the next-generation and future experimental scenarios, and (b) comparison with other available limits.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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