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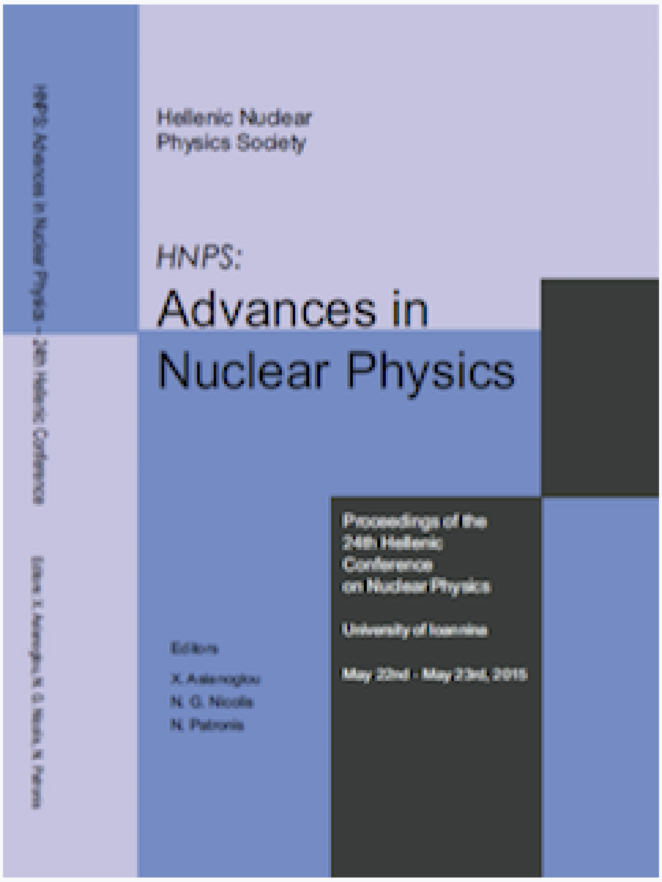

Probing electromagnetic neutrino properties within the tensor non-standard neutrino-nucleus interactions

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Probing electromagnetic neutrino properties within the tensor non-standard neutrino-nucleus interactions

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Abstract Non-standard coherent neutrino scattering off nuclei is extensively studied through realistic nuclear structure calculations performed within the framework of the quasi-particle random phase approximation (QRPA). More specifically, we focus on the accurate estimation of the number of events expected to be measured by the COHERENT experiment at the Spallation Neutron Source at Oak Ridge, as well as by the reactor neutrino experiments TEXONO and GEMMA. To this purpose our study concentrates on the relevant detector materials ^{20}Ne, ^{40}Ar, ^{76}Ge and ^{132}Xe. In this context, we obtain stringent constraints on the vector and tensor non-standard interaction parameters and examine their impact on various electromagnetic neutrino phenomena such as neutrino magnetic moments and neutrino milli-charges. Our results indicate that the aforementioned experiments offer significant prospects to probe neutrino properties predicted in theories beyond the Standard Model.

Keywords coherent neutrino-nucleus scattering, non-standard interactions, tensor coupling, electromagnetic neutrino properties, neutrino magnetic moment

INTRODUCTION

Exotic neutrino properties arise in neutrino-nucleus processes, occurring due to non-standard neutrino interactions (NSI) of the form [1,2]

$$\nu_\alpha(\bar{\nu}_\alpha) + (A,Z) \rightarrow \nu_\beta(\bar{\nu}_\beta) + (A,Z), \tag{1.1}$$

providing us with model independent constraints of various NSI parameters. In the current literature, even though only vector terms are mainly considered in the relevant Lagrangian, tensorial NSI terms have attracted the interest of studying the aforementioned processes, while robust constraints to the corresponding couplings have been extracted from neutrino-nucleus coherent scattering [3,4]. In addition, because tensor interaction does not obey the chirality constraint imposed by vector-type couplings, it allows a large class of interactions to be investigated [5]. More specifically from a particle physics point of view, tensor NSI terms are possible to be generated via Fierz reordering of the effective low-energy operators appearing in models with scalar leptoquarks as well as in R-parity-violating supersymmetry.

In this paper, we mainly focus on contributions to the neutrino-nucleus reactions of Eq. (1.1), due to tensorial terms of the NSI Lagrangian, paying special attention on the nuclear physics aspects of these exotic processes. The cross sections, that arise from the effective four fermion contact interaction Lagrangian, are expressed in terms of the nuclear proton and neutron form factors. Subsequently, the sensitivity on the tensor NSI parameters is obtained from a χ^2 analysis of the expected data from the COHERENT experiment [6] recently proposed to operate at the Spallation Neutron Source (SNS) at Oak Ridge [7] by using promising nuclear detectors as ^{20}Ne, ^{40}Ar, ^{76}Ge and ^{132}Xe. Constraints of this type translate into relevant sensitivities on the upper limits of the neutrino magnetic moment (NMM) predicted within the context of the tensor components entering the NSI Lagrangian. The latter can be compared with existing limits derived from $\nu_e - e$ scattering data coming out of reactor neutrino experiments , such as TEXONO [8] and GEMMA [9] experiments.

On the basis of our nuclear calculations (performed with quasi-particle RPA) for the dominant coherent process, we evaluate the number of events due to vector and tensor NSI parts of the neutrino-nucleus cross section, and estimate the contribution due to the NMM. Our results for the number of events, refer to the ^{76}Ge isotope which is the current detector medium of the TEXONO and GEMMA experiments.

FORMALISM

In general the search for potential existence of phenomena beyond the SM involving NSI at the four fermion approximation, becomes accessible through phenomenological low-energy effective Lagrangians as [3]

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{X} \sum_{f=q,\ell} \sum_{\alpha,\beta=e,\mu,\tau} \epsilon_{\alpha\beta}^{fX} \left[\bar{\nu}_\alpha \Gamma_X \nu_\beta\right]\left[\bar{f}\Gamma_X f\right], \qquad (1.2)$$

where, $X = \{V, A, S, P, T\}$, $\Gamma_x = \{\gamma_\mu, \gamma_\mu\gamma_5, 1, \gamma_5, \sigma_{\mu\nu}\}$ and $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. The magnitude of the NSI couplings $\epsilon_{\alpha\beta}^{fX}$ is taken with respect to the Fermi coupling constant G_F, ν_α denotes three light Majorana neutrinos and f is a quark q , or a charged lepton ℓ. In the present work, we focus on the tensorial neutrino-nucleus NSI described by the Lagrangian [4]

$$\mathcal{L}_{\mathrm{NSI}}^{T} = -2\sqrt{2}G_F \sum_{\alpha,\beta=e,\mu,\tau} \sum_{f=u,d} \epsilon_{\alpha\beta}^{fT} \left[\bar{\nu}_\alpha \sigma^{\mu\nu} \nu_\beta\right]\left[\bar{f}\sigma_{\mu\nu} f\right]. \qquad (1.3)$$

The extraction of the latter Lagrangian is illustrated in Fig.1 where the nuclear-level Feynman loop-diagram represents the photon exchange between a fermion and a quark generating a neutrino magnetic moment. The non-standard physics enters through the complicated leptonic vertex (see also Refs. [1,2]).

For neutral current processes, the vector NSI part of the effective Lagrngian (1.2) is parametrized in terms of the non-universial (NU) $\epsilon_{\alpha\alpha}^{fV}$ and flavor changing (FC) vector couplings $\epsilon_{\alpha\beta}^{fV}$ $(\alpha \neq \beta)$ [7]. For neutral current processes, the vector NSI part of the effective Lagrngian is parametrized in terms of the non-universial (NU) $\epsilon_{\alpha\alpha}^{fV}$ and flavor changing (FC) vector couplings $\epsilon_{\alpha\beta}^{fV}$ $(\alpha \neq \beta)$ [7] For coherent scattering, a nucleus of mass M recoils (no intrinsic excitation occurs) with energy which, in the approximation $T_N \ll E_\nu$ (low energy limit), is maximized as, $T_N^{max} = 2E_\nu^2/(M + 2E_\nu)$. Then, to a good approximation, the square of the three momentum transfer is equal to $q^2 = 2MT_N$, and the coherent vector NSI differential cross section with respect to T_N is written as [1,2]

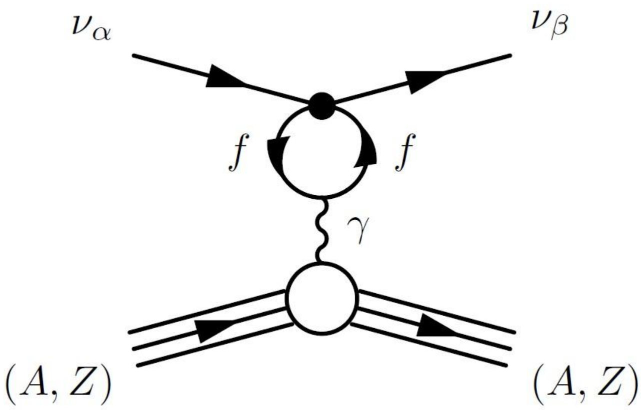

Fig.1 Nuclear level effective Feynman diagram for magnetic moment of a neutrino induced by tensorial NSI. The non-standard physics enters in the complicated vertex denoted by the large dot •.

$$\frac{d\sigma^{V}_{\mathrm{NSI},\nu_\alpha}}{dT_N} = \frac{G_F^2 M}{\pi}\left(1-\frac{M T_N}{2E_\nu^2}\right)\left|\langle gs \| G^{\mathrm{NSI}}_{V,\nu_\alpha}(q) \| gs\rangle\right|^2, \tag{1.4}$$

($\alpha = e,\ \mu, \tau$, denotes the flavour of incident neutrinos) where for even-even nuclei the nuclear ground state reads $|gs\rangle = |J^\pi\rangle = |0^+\rangle$. The corresponding nuclear matrix element can be found in Ref. [2].

For NSI scattering, the differential cross section with respect to the recoil energy T_N due to tensor interactions (at nuclear level) reads [3]

$$\frac{d\sigma^{T}_{\mathrm{NSI},\nu_\alpha}}{dT_N} = \frac{4G_F^2 M}{\pi}\left[\left(1-\frac{T_N}{2E_\nu}\right)^2 - \frac{MT_N}{4E_\nu^2}\right]\left|\langle gs \| G^{\mathrm{NSI}}_{T,\nu_\alpha}(q) \| gs\rangle\right|^2. \tag{1.5}$$

The corresponding tensorial NSI matrix element arising from the Lagrangian (1.3) takes the form [3]

$$\left|M^{\mathrm{NSI}}_{T,\nu_\alpha}\right|^2 \equiv \left|\langle gs \| G^{\mathrm{NSI}}_{T,\nu_\alpha}(q) \| gs\rangle\right|^2 = \left[\left(2\epsilon^{uT}_{\alpha\beta}+\epsilon^{dT}_{\alpha\beta}\right)ZF_Z(q^2)+\left(\epsilon^{uT}_{\alpha\beta}+2\epsilon^{dT}_{\alpha\beta}\right)NF_N(q^2)\right]^2, \tag{1.6}$$

there is no interference between the tensorial NSI and the SM amplitude [4] where $F_{Z(N)}(q^2)$ denote the nuclear (electromagnetic) form factors for protons and neutrons.

In flavor space $\alpha, \beta = e, \mu, \tau$ neutrini magnetic moments $\mu_{\alpha\beta}$ are generated by the tensorial part of the Hermitian magnetic form factor $f^M_{\alpha\beta}(0) = \mu_{\alpha\beta}$ in the effective neutrino EM current $-f^M_{\alpha\beta}(q^2)\bar{\nu}_\beta i\sigma_{\mu\nu}\nu_\alpha$ (for the relation of the NMM between the flavor basis $\mu_{\alpha\beta}$and the mass basis μ_{ij} with $i, j = 1,2,3$. In our convention the leading order con contribution to the NMM for neutrino-quark ($\nu_\alpha - q$) NSI is expressed as [3]

$$\mu_{\alpha\beta} = \sum_q 2\sqrt{2}G_F\epsilon^{qT}_{\alpha\beta}\frac{N_c Q_q}{\pi^2}m_e m_q \ln\left(2\sqrt{2}G_F m_q^2\right)\mu_B, \tag{1.7}$$

where m_q and Q_q are the quark mass and charge respectively, while N_c is the number of quark colours (see also Ref. [5]). Analogously, the NMM for neutrino-lepton ($\nu_\alpha - \ell$) NSI takes the form

$$\mu_{\alpha\beta} = -\sum_{\ell} 2\sqrt{2} G_F \epsilon_{\alpha\beta}^{\ell T} \frac{m_e m_\ell}{\pi^2} \ln\left(2\sqrt{2} G_F m_\ell^2\right) \mu_B, \tag{1.8}$$

with m_ℓ being the mass of the charged leptons.

The presence of a NMM yields an additional contribution to the weak interaction cross section. Thus, the differential EM cross section due to a tensor NSI (transition) magnetic moment is written as [3]

$$\frac{d\sigma_{\text{magn}}}{dT_N} = \frac{\pi a^2 \mu_{\alpha\beta}^2 Z^2}{m_e^2} \left(\frac{1 - T_N / E_\nu}{T_N} + \frac{T_N}{4E_\nu^2} \right) F_Z^2(q^2), \tag{1.9}$$

which contains the proton nuclear form factor. From the Lagrangian (1.2) the total cross section reads [3]

$$\frac{d\sigma_{\text{tot}}}{dT_N} = \frac{d\sigma_{\text{SM}}}{dT_N} + \frac{d\sigma_{\text{NSI}}^V}{dT_N} + \frac{d\sigma_{\text{NSI}}^T}{dT_N} + \frac{d\sigma_{\text{magn}}}{dT_N}, \tag{1.10}$$

RESULTS AND DISCUSSION

The COHERENT experiment [6] proposed to operate at the SNS (Oak Ridge) has excellent capabilities not only to measure, for the first time, coherent neutral-current neutrino-nucleus events, but also to search for new physics beyond the SM [7]. In general, any deviation from the SM predictions is interesting, therefore in the present study we explore the role of the sensitivity of the above experiment in putting stringent bounds on the tensor NSI, by taking advantage of our realistic nuclear structure calculations. We determine potential limits for the exotic parameters and compare them with available constraints reported in similar studies [4,5]

To this aim, we first evaluate the expected number of events, on various detector materials of the COHERENT experiment, through the integral [2]

$$N = K \int_{E_{\nu_{\min}}}^{E_{\nu_{\max}}} \eta^{\text{SNS}}(E_\nu) dE_\nu \int_{T_N^{\text{thres}}}^{T_{N_{\max}}} \frac{d\sigma}{dT_N}(E_\nu, T_N) dT_N, \tag{1.11}$$

where $K = N_{targ} \Phi^{SNS} t_{tot}$, N_{targ} being the number of atoms of the studied target nucleus, and t_{tot} the total time of exposure. The relevant neutrino energy distribution $\eta^{\text{SNS}}(E_\nu)$ and the neutrino fluxes Φ^{SNS} (strongly depended on the detector distances from the SNS source), are taken from Ref. [7].

To estimate the sensitivity on the tensorial parameters we adopt the futuristic statistical method for the χ^2 defined as [3,4]

$$\chi^2 = \left(\frac{N^{\mathrm{SM}}_{events} - N^{\mathrm{NSI}}_{events}}{\delta N_{events}} \right)^2 . \qquad (1.12)$$

Since the experiment is not running yet, the calculations are performed without binning the sample relying on statistical errors only (systematic errors are discussed in Ref. [7]. In Eq. (1.12) N^{SM}_{events} ($N^{\mathrm{NSI}}_{events}$) denotes the exact number of SM (tensorial NSI) events expected to be recorded by a COHERENT detector and the parameters $\epsilon^{qT}_{\alpha\beta}$ are varied so as to fit the hypothetical data. In our calculations we consider the promising target nuclei, ^{20}Ne, ^{40}Ar, ^{76}Ge, (^{132}Xe) at 20 m (40 m) from the SNS source, assuming an energy threshold of 1 keV and a detector mass of one ton. The considered time window of data taking is fixed to one year assuming perfect detection efficiency. For the sake of convenience, from the SNS delayed-beam we take into account only the ν_e component. This allows us also to compare our predictions with those of Ref. [4]. For the various target nuclei, the present results are illustrated in Fig.2 (left panel), from where we conclude that higher prospects are expected for ^{76}Ge. In principle, more severe constraints are expected for heavier target nuclei, however, the detector distance from the Spallation target plays crucial role, and thus, a light ^{20}Ne detector located at 20 m performs better than a heavy ^{132}Xe detector at 40 m. The corresponding sensitivity at 90% C.L. on the NSI couplings, coming out of the ν_e and the $\nu_\mu + \nu_\mu$ beams, are listed in Table 1. Furthermore, focusing on the ν-quark ($q = u, d$) tensor NSI involved in the Lagrangian (1.3), we exploit the constraints of Table 1 and utilise Eq. (1.7), in order to extract the sensitivity on the NMM (see Table 1). At this point, we consider useful to make a comparison between the results obtained through our nuclear calculations and those obtained by assuming zero momentum transfer (where $F_{N,Z}(0) = 1$) i.e when neglecting the nuclear physics details. This leads to the conclusion that, in the majority of the cases the obtained results differ by about 20% .

In recent years, it has been shown that, in order to constrain more than one parameters simultaneously, two detectors consisting of target material with maximally different ratio $k = (A+N)/(A+Z)$ are required [7]. To this purpose, we exploit the advantageous multi-target approach of the COHERENT experiment and in Fig. 2 (right panel) we illustrate the allowed regions in the $\epsilon^{dT}_{\alpha\beta} - \epsilon^{uT}_{\alpha\beta}$ plane at 68%, 90% and 99% C.L., obtained by varying both tensorial NSI parameters. As expected, the most restricted area corresponds to the delayed beam for which the number of events is larger.

CONCLUSIONS

Using our reliable cross sections for SM and NSI ν-processes, we have computed the number of neutrino scattering events expected to be measured at the Spallation Neutron Source experiments. To this purpose, we have chosen as target nuclei the ^{20}Ne, ^{40}Ar, ^{76}Ge and ^{132}Xe isotopes, that constitute the main detector materials of the planned COHERENT experiment

parameter	^{20}Ne	^{40}Ar	^{76}Ge	^{132}Xe
$\lvert\epsilon^{dT}_{e\beta}\rvert \times 10^{-3}$	8.6	7.6	6.8	8.8
$\lvert\epsilon^{uT}_{e\beta}\rvert \times 10^{-3}$	8.6	8.1	7.5	9.8
$\mu_{e\beta} \times 10^{-12}\mu_B$	3.0	2.7	2.5	3.2
$\lvert\epsilon^{dT}_{\mu\beta}\rvert \times 10^{-3}$	7.1	6.3	5.6	7.2
$\lvert\epsilon^{uT}_{\mu\beta}\rvert \times 10^{-3}$	7.1	6.7	6.2	8.1
$\mu_{\mu\beta} \times 10^{-12}\mu_B$	2.5	2.3	2.1	2.7

Table 1. Constraints on the tensor NSI parameter $\epsilon^{fT}_{\alpha\beta}$ at 90% C.L. for various potential detector materials of the COHERENT experiment. The sensitivity on transition neutrino magnetic moment is also shown at 90% C.L.

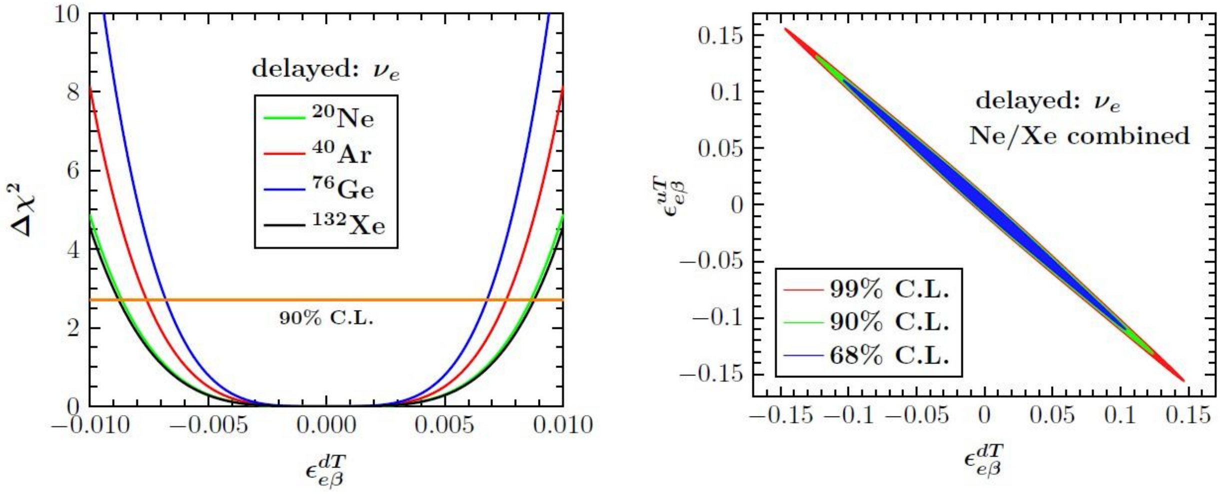

Fig 2. $\Delta\chi^2$ profiles as function of the $\epsilon^{dT}_{e\beta}$ NSI parameters, for potential nuclear detectors of the COHERENT experiment (left panel). Allowed regions in the $\epsilon^{dT}_{e\beta}-\epsilon^{uT}_{e\beta}$ (right panel) tensor NSI parameter space. Only statistical errors are taken into consideration

Through a χ^2-type analysis, we have estimated the sensitivity of the latter experiment on the tensor NSI parameters. We remark, that especially for the case of the $\epsilon_{\alpha\beta}^{fT}$ $(q = u, d)$ couplings, such bounds are presented here for the first time. Moreover, by exploiting these potential constraints, the resulted sensitivities on the transition neutrino magnetic moments lead to contributions which are of the same order of magnitude with existing limits coming from astrophysical observations. Furthermore, due to their large size, they are accessible by current experimental setups and therefore they may be testable with future experiments searching for coherent neutrino-nucleus scattering. We have also devoted special effort in obtaining precise predictions for the number of neutrino-nucleus events expected to be recorded by the promising TEXONO and GEMMA reactor -$\bar{\nu}_e$ experiments.

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References

[1] D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B728**, 482 (2014).
[2] D.K. Papoulias and T.S. Kosmas, Adv. High Energy Phys. **2015**, 763648 (2014).
[3] D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B747**, 454 (2015).
[4] J. Barranco et al., Int.J.Mod.Phys. **A27**, 1250147 (2012). [5] K. Healey et al., Phys.Rev. **D87**, 117301 (2013).
[6] D. Akimov et al. [COHERENT Collaboration], arXiv:1509.08702.
[7] K. Scholberg Phys.Rev. **D73** (2006) 033005.
[8] TEXONO Collaboration, H. Wong et al., Phys. Rev. **D75**, 012001 (2007).
[9] A. Beda et al. [GEMMA Collaboration], Adv. High Energy Phys. **2012**, 350150 (2012).