

## Sensitivities to neutrino electromagnetic properties at the TEXONO experiment

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### Abstract

The possibility of measuring neutral-current coherent elastic neutrino-nucleus scattering (CENNS) at the TEXONO experiment has opened high expectations towards probing exotic neutrino properties. Focusing on low threshold Germanium-based targets with kg-scale mass, we find a remarkable efficiency not only for detecting CENNS events due to the weak interaction, but also for probing novel electromagnetic neutrino interactions. Specifically, we demonstrate that such experiments are complementary in performing precision Standard Model tests as well as in shedding light on sub-leading effects due to neutrino magnetic moment and neutrino charge radius. This work employs realistic nuclear structure calculations based on the quasi-particle random phase approximation (QRPA) and takes into consideration the crucial quenching effect corrections. Such a treatment, in conjunction with a simple statistical analysis, shows that the attainable sensitivities are improved by one order of magnitude as compared to previous studies.

*Keywords:* Reactor neutrinos, Coherent elastic neutrino-nucleus scattering (CENNS), Weak mixing angle, Neutrino magnetic moment, Neutrino charge radius, Quenching factor

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# 1 Introduction

The robust discovery of neutrino oscillations in the propagation of solar and atmospheric neutrinos [1, 2], confirmed at accelerator and reactor neutrino sources [3, 4] has provided us with a rather solid proof for the existence of neutrino masses and mixing [5, 6] and hence the clearest evidence for the need of physics beyond the Standard Model (SM) [7]. These results have prompted a great rush to produce adequate SM extensions with small neutrino masses [8].

Underpinning the ultimate origin of neutrino mass stands out as one of the biggest challenges in particle physics [9]. A generic feature of many such schemes is the presence of non-vanishing neutrino electromagnetic (EM) properties [10, 11, 12, 13, 14, 15]. While the neutrino masses indicated by oscillation data are perhaps too small to induce sizeable magnetic moments, this issue is rather model dependent, and one cannot exclude this possibility on general grounds [16]. If large enough, these may still play an important sub-leading role in precision neutrino studies [17], despite the good agreement found within the three-neutrino oscillation picture. Non-zero diagonal magnetic moments exist for massive Dirac neutrinos. In contrast, in the general Majorana neutrino case all magnetic moments are transition-type. Therefore, the study of neutrino magnetic moments would be a powerful tool towards distinguishing their Dirac or Majorana character [18, 19].

The detection of neutral-current (NC) coherent elastic neutrino-nucleus scattering (CENNS) processes by measuring the nuclear recoil spectrum of the scattered nucleus has by now become feasible [20]. As a concrete example, the newly formed COHERENT Collaboration at the Spallation Neutron Source (SNS) has excellent prospects [21, 22], motivating also theoretical effort [23, 24]. In this work, we consider the possibility of revealing signs of new physics through a detailed study of CENNS at the TEXONO experiment [25, 26, 27]. We demonstrate that the use of sub-keV Germanium-based kg-scale detectors [28, 29, 30], provides a favourable experimental set up with good prospects for performing precision SM tests, as well as probing EM neutrino properties [31], such as the neutrino magnetic moment [18, 19, 32, 33] and the neutrino charge radius [34, 35, 36, 37, 38]. The total number of events expected in an experiment searching for CENNS depends strongly on the energy threshold  $T_{thres}$ , as well as the total mass of the detector [23, 24]. For low energy thresholds and more massive detectors, the total number of events expected is significantly larger and, therefore, the attainable sensitivities are higher. In addition, this work highlights that the present calculations become more realistic by considering quenching effect corrections [39, 40, 41]. The sensitivity is evaluated by assuming that a given experiment searching for CENNS events will measure exactly the SM expectation. Thus, any deviation [42, 43, 44] is understood as a signature of new physics [45, 46, 47, 48, 49].

Apart from the possibility of the first ever detection of CENNS events, our present results emphasise the potentiality of discovering neutrino interactions beyond the SM expectations [50]. In our estimates we perform nuclear structure calculations within the context of the quasi-particle random phase approximation (QRPA) that uses realistic nuclear forces [51, 52, 53, 54, 55], and employ a  $\chi^2$ -type statistical analysis. We find that the prospects for improving current bounds on  $\mu_{\nu_e}$  are rather promising and complementary to future sensitivities on the muon neutrino magnetic moment,  $\mu_{\nu_\mu}$  [24].

## 2 Coherent elastic neutrino-nucleus scattering

The coherent elastic scattering of neutrinos upon a nucleus is described within the SM starting from the neutrino-quark NC interaction Lagrangian. However, as mentioned above, one has good reasons to expect corrections coming from new physics [1], such as non-standard interactions (NSI) [42, 43, 44, 45, 46, 47, 49] or non-trivial neutrino EM properties [10, 11, 12, 13, 14, 15, 16, 32, 33, 36].

### 2.1 Standard model prediction

Within the context of SM, for low energies ( $E_\nu \ll M_W$ ) accessible to neutrino experiments, the weak neutral-current CENNS can be naturally studied by considering the  $V \pm A$  interaction of four-fermion  $\nu\nu f f$  type operators entering the effective Lagrangian,  $\mathcal{L}_{\text{SM}}$ , written as [43]

$$\mathcal{L}_{\text{SM}} = -2\sqrt{2}G_F \sum_{\substack{P=L,R \\ f=u,d \\ \alpha=e,\mu,\tau}} g_{\alpha\alpha}^{f,P} [\bar{\nu}_\alpha \gamma_\rho L \nu_\alpha] [\bar{f} \gamma^\rho P f] . \quad (1)$$

In this Lagrangian, the chiral structure of the SM weak interaction is expressed by the projectors  $P = \{L, R\}$ , while  $\alpha$  denotes the neutrino flavour and  $f$  refers to the first-generation quarks. The relative strength of the left- and right-handed couplings for  $u$ -

and  $d$ -quark to the  $Z$ -boson with respect to the Fermi constant  $G_F$  are given as

$$\begin{aligned}
g_{\alpha\alpha}^{u,L} &= \rho_{\nu N}^{NC} \left( \frac{1}{2} - \frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{u,L}, \\
g_{\alpha\alpha}^{d,L} &= \rho_{\nu N}^{NC} \left( -\frac{1}{2} + \frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{d,L}, \\
g_{\alpha\alpha}^{u,R} &= \rho_{\nu N}^{NC} \left( -\frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{u,R}, \\
g_{\alpha\alpha}^{d,R} &= \rho_{\nu N}^{NC} \left( \frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{d,R}.
\end{aligned} \tag{2}$$

In the latter expressions, after including the relevant radiative corrections, we have  $\hat{s}_Z^2 = \sin^2 \theta_W = 0.23120$ ,  $\rho_{\nu N}^{NC} = 1.0086$ ,  $\hat{\kappa}_{\nu N} = 0.9978$ ,  $\lambda^{u,L} = -0.0031$ ,  $\lambda^{d,L} = -0.0025$  and  $\lambda^{d,R} = 2\lambda^{u,R} = 7.5 \times 10^{-5}$  [17]. From the effective Lagrangian in Eq. (1), the differential cross section with respect to the nuclear recoil-energy,  $T$ , for the case of a CENNS off a spherical spin-zero nucleus of mass  $M$ , reads

$$\left( \frac{d\sigma}{dT} \right)_{\text{SM}} = \frac{G_F^2 M}{2\pi} \left[ 1 - \frac{MT}{E_\nu^2} + \left( 1 - \frac{T}{E_\nu} \right)^2 \right] \left| \langle gs || \hat{\mathcal{M}}_0(q) || gs \rangle \right|^2. \tag{3}$$

For  $gs \rightarrow gs$  transitions, the corresponding coherent nuclear matrix element takes the form [48, 23]

$$\begin{aligned}
\langle gs || \hat{\mathcal{M}}_0(q) || gs \rangle &= [2(g_{\alpha\alpha}^{u,L} + g_{\alpha\alpha}^{u,R}) + (g_{\alpha\alpha}^{d,L} + g_{\alpha\alpha}^{d,R})] ZF_Z(q^2) \\
&+ [(g_{\alpha\alpha}^{u,L} + g_{\alpha\alpha}^{u,R}) + 2(g_{\alpha\alpha}^{d,L} + g_{\alpha\alpha}^{d,R})] NF_N(q^2).
\end{aligned} \tag{4}$$

Note that, due to the smallness of the coupling of protons with the  $Z$ -boson, the main contribution to the CENNS cross section essentially scales with the square of the neutron number  $N$  of the target nucleus (see e.g. [48]). We stress that the differential cross section is evaluated with high significance by weighting the nuclear matrix element with corrections provided by the proton (neutron) nuclear form factors  $F_{Z(N)}(q^2)$ . This way the finite nuclear size is taken into account with respect to the typical momentum transfer,  $q \simeq \sqrt{2MT}$ . Furthermore, the  $N^2$  enhancement of the CENNS cross section makes the relevant experiments favourable facilities to probe the neutron form factor of the target nucleus at low energies [20, 21, 22].

From a nuclear theory point of view, the reliability of the present CENNS cross sections calculations is maximised in terms of accuracy by performing nuclear structure calculations in the context of QRPA [52, 53]. Motivated by its successful application

on similar calculations for various semi-leptonic nuclear processes [54, 55], in this work we construct explicitly the nuclear ground state,  $|gs\rangle \equiv |0^+\rangle$ , of the relevant even-even isotope through the solution of the BCS equations (for a detailed description see Ref. [23]).

## 2.2 Electromagnetic neutrino-nucleus cross sections

The existence of neutrino masses is well-established thanks to the current neutrino oscillation data, implying that they could have exotic properties, such as non-zero neutrino magnetic moments. In this framework, potential neutrino-nucleus interactions of EM nature have been considered [10, 11, 12, 13, 14, 15], resulting in corrections to the weak CENNS cross section of the form [31]

$$\left(\frac{d\sigma}{dT}\right)_{\text{tot}} = \left(\frac{d\sigma}{dT}\right)_{\text{SM}} + \left(\frac{d\sigma}{dT}\right)_{\text{EM}}. \quad (5)$$

Here, the helicity-violating EM contribution to the neutrino-nucleus cross section can be parametrised in terms of the proton nuclear form factor, the fine structure constant  $a_{em}$  and the electron mass  $m_e$  as [16]

$$\left(\frac{d\sigma}{dT}\right)_{\text{EM}} = \frac{\pi a_{em}^2 \mu_{eff}^2 Z^2}{m_e^2} \left(\frac{1 - T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right) F_Z^2(q^2). \quad (6)$$

Note, that additional corrections are incorporated in Eqs. (3), (6), compared to Ref. [24].

If the neutrino is of Dirac-type as in the SM, then the magnetic moment is undetectably small due to its proportionality to the neutrino mass. Even though from oscillation data the latter is well-known to be small, one cannot rule out the possibility of sizeable neutrino magnetic moments. Indeed, in general scenarios where neutrinos are Majorana fermions, as expected on general grounds, larger transition magnetic moments are possible. For example, relatively sizeable contributions may be predicted in models involving NSI [16]. From experimental perspectives, a potential signal will be detected as a distortion of the nuclear recoil spectrum at very low energies where the EM cross section dominates due to its  $\sim 1/T$  dependence. For this reason, such challenging technological constraints require innovative experimental advances towards reducing the threshold to the sub-keV region.

Despite having vanishing electric charge, the first derivative in the expansion of the neutrino electric form factor entering the decomposition of the leptonic matrix element may provide non-trivial information concerning other neutrino electric properties [15]. More specifically, the gauge-invariant definition of the neutrino root mean square charge-radius  $\langle r_{\nu_\alpha}^2 \rangle$ ,  $\alpha = \{e, \mu, \tau\}$  [34, 35] leads to corrections to the weak mixing angle [36, 37, 38]

$$\sin^2 \theta_W \rightarrow \sin^2 \overline{\theta}_W + \frac{\sqrt{2}\pi a_{em} \langle r_{\nu\alpha}^2 \rangle}{3G_F}. \quad (7)$$

### 3 The TEXONO experiment

In the present work we explore how well one can probe neutrino EM phenomena with the TEXONO experiment [25, 26, 27] through low-energy CENNS measurements near the Kuo-Sheng Nuclear Power Station. Towards this purpose, the TEXONO Collaboration has pursued a research program aiming at detecting neutrino-nucleus events by using high purity Germanium-based detectors HPGe with sub-keV threshold [28, 29, 30]. According to the proposal, we consider a 1 kg  $^{76}\text{Ge}$ -detector operating with a threshold as low as  $T_{thres} = 100 \text{ eV}_{ee}$ . Due to the absence of precise information regarding the fuel composition of the reactor core, we only include the dominant  $^{235}\text{U}$  component of the anti-neutrino spectrum. In this respect, for the present study we assume a typical neutrino flux of  $\Phi_{\bar{\nu}_e} = 10^{13} \text{ } \nu \text{ s}^{-1} \text{ cm}^{-2}$  for a detector location at 28 m from the reactor core. In order to estimate the reactor antineutrino energy-distribution  $\eta_{\bar{\nu}_e}(E_\nu)$  for energies above 2 MeV, existing experimental data from Ref. [56] are employed. We stress that the main part of reactor anti-neutrinos is released with energies  $E_{\bar{\nu}_e} < 2 \text{ MeV}$ , thus their contribution is crucial and must be taken into account. For their description we adopt the theoretical estimates given in Ref. [57]. This will bring about improved sensitivities on the neutrino magnetic moment.

## 4 Results and discussion

### 4.1 Signal cross sections

First we present and discuss the individual weak and electromagnetic differential and total CENNS cross sections (see Eq. 5) weighted over experimental reactor anti-neutrino spectra [56, 57]. These convoluted cross sections determine the neutrino signals expected to be recorded at a nuclear detector (e.g. the  $^{76}\text{Ge}$  of the TEXONO experiment). For each interaction channel  $x$ , [ $x = \text{SM, EM, tot}$ ] the energy-integrated differential cross section,  $\langle d\sigma/dT \rangle_x$ , is defined as

$$\langle \frac{d\sigma}{dT} \rangle_x = \int dE_\nu \left( \frac{d\sigma}{dT}(E_\nu, T) \right)_x \eta_{\bar{\nu}_e}(E_\nu), \quad (8)$$

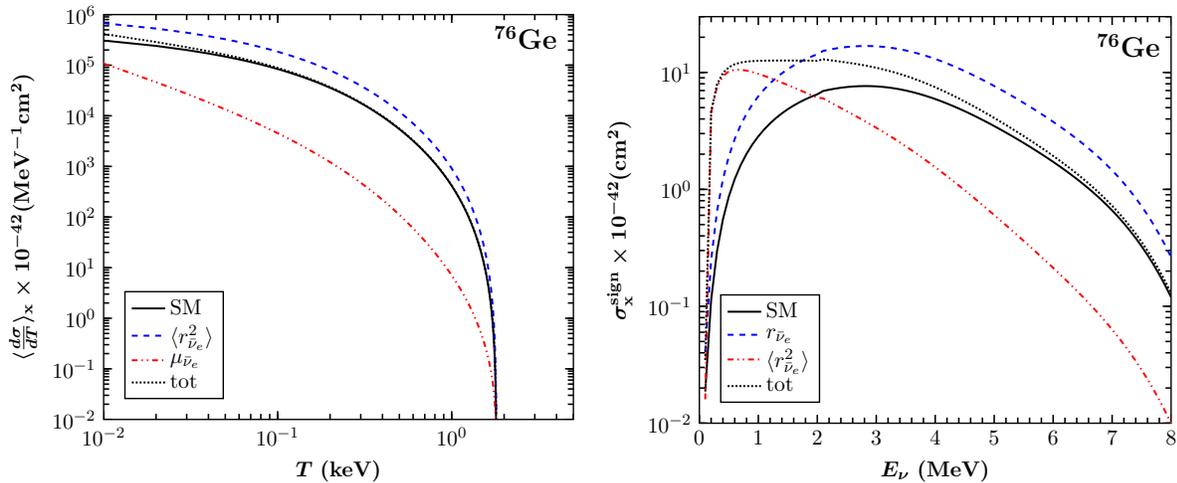


Figure 1: Weak and electromagnetic differential (*left panel*) and total (*right panel*) cross sections convoluted with reactor  $\bar{\nu}_e$ -spectra.

where  $\eta_{\bar{\nu}_e}(E_\nu)$  denotes the normalised neutrino energy-distribution. The corresponding signal cross section  $\sigma_x^{\text{sign}}$  reads

$$\sigma_x^{\text{sign}}(E_\nu) = \int dT \left( \frac{d\sigma}{dT}(E_\nu, T) \right)_x \eta_{\bar{\nu}_e}(E_\nu). \quad (9)$$

For the  $^{76}\text{Ge}$  detector, assuming the experimental constraints placed recently by TEXONO ( $\mu_{\bar{\nu}_e} = 7.4 \times 10^{-11} \mu_B$  [25] and  $\langle r_{\bar{\nu}_e}^2 \rangle = 6.6 \times 10^{-32} \text{cm}^2$  [26]), the computed results are illustrated in Fig. 1. One sees that in the case of  $\sigma_x^{\text{sign}}$ , the curve involving neutrino magnetic moment contribution exceeds that of the pure SM weak rate at low neutrino energies,  $E_\nu$ . The curve containing neutrino charge radius contributions through Eq. 7 is showing a similar behaviour as the pure SM (the photon propagator cancellation leads to 4-fermion contact interaction [30, 50]).

## 4.2 Statistical analysis

Our present analysis is strongly based on the estimation of the number of CENNS events. Therefore, we first provide a brief description of the conventions and approximations we use in our calculations. For each interaction channel  $x$ , the number of CENNS events

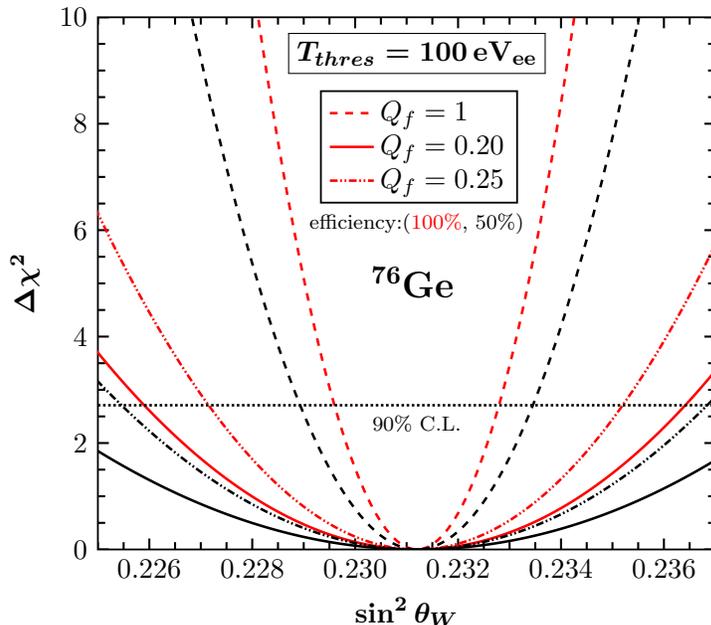


Figure 2:  $\Delta\chi^2$  sensitivity profile as a function of the weak mixing angle  $\theta_W$  at TEXONO. The results are presented for two detector efficiencies 100% (50%) shown with red (black) colour and three values of the quenching factors  $Q_f = (1, 0.20, 0.25)$  indicated with (dashed, solid, dashdotted) lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

above a minimum nuclear recoil-energy,  $T_{min}$ , reads [43]

$$N_x = K \int_{E_{\nu_{min}}}^{E_{\nu_{max}}} \eta_{\bar{\nu}_e}(E_\nu) dE_\nu \int_{T_{min}}^{T_{max}} \left( \frac{d\sigma}{dT}(E_\nu, T) \right)_x dT. \quad (10)$$

In the above expression,  $K = N_{\text{targ}} t_{\text{tot}} \Phi_{\bar{\nu}_e}$ , with  $N_{\text{targ}}$  being the total number of atoms in the detector and  $t_{\text{tot}}$  the relevant irradiation period. Note that potential effects due to neutrino oscillation in propagation are neglected, since this is well satisfied for the short-baselines considered here. The numerical results throughout this work refer to a 1 kg  $^{76}\text{Ge}$ -detector, one year of data taking and a detector threshold of 100 eV<sub>ee</sub>. In addition, we consider two different detector efficiencies including an optimistic approach of a perfectly efficient detection capability and the more realistic scenario assuming a recoil acceptance of 50%.

The present calculations take into consideration the fact that the nuclear recoil events are quenched [39] (in Ref. [24], where for each target the calculation is referred to the

Table 1: Summary of the sensitivities obtained for  $\sin^2 \theta_W$  ( $1\sigma$ ) and for the EM neutrino parameters (90% C.L.) at the TEXONO experiment. The results refer to various sensitivities and quenching factors. Comparing with Ref. [24] one sees that a substantial improvement in the sensitivity for the weak mixing angle  $\sin^2 \theta_W$ , the magnetic moment  $\mu_{\bar{\nu}_e}$  parameter and the neutrino charge-radius  $\langle r_{\bar{\nu}_e}^2 \rangle$  w.r.t. the COHERENT proposal.

(Target, Threshold)	COHERENT [24] (100 kg $^{76}\text{Ge}$ , 10 keV $_{ee}$ )		TEXONO (this work) (1 kg $^{76}\text{Ge}$ , 100 eV $_{ee}$ )				
	67%	100%	100%			50%	
Quenching	$Q_f = 1$	$Q_f = 1$	$Q_f = 0.20$	$Q_f = 0.25$	$Q_f = 1$	$Q_f = 0.20$	$Q_f = 0.25$
$\delta s_W^2(\bar{\nu}_e)$	0.0055	0.0010	0.0033	0.0025	0.0014	0.0046	0.0035
Uncer. (100%)	2.36	0.43	1.41	1.08	0.61	1.97	1.51
$\mu_{\bar{\nu}_e} \times 10^{-10} \mu_B$	9.46	0.40	0.98	0.83	0.47	1.17	0.99
$\langle r_{\bar{\nu}_e}^2 \rangle \times 10^{-32} \text{cm}^2$	-0.38 - 0.37	-0.07 - 0.07	-0.22 - 0.22	-0.17 - 0.17	-0.10 - 0.10	-0.32 - 0.31	-0.24 - 0.24

nuclear recoil-energy window [21], such a treatment is not necessary). Corrections of this type are crucial since for a given ionisation detector the observed energy (equivalent to an electron energy) is lower than the total nuclear recoil-energy, i.e. much energy is converted to heat (phonons) which is not measured, especially at low energies [40]. To convert from nuclear recoil-energy (eV $_{nr}$ ) to electron equivalent energy (eV $_{ee}$ ), we multiply the energy scale by a quenching factor,  $Q_f$ . In principle  $Q_f$  varies with the nuclear-recoil energy [41] and has to be determined experimentally, however for the sub-keV Germanium-based targets considered here it can be well-approximated as constant with typical values in the range 0.20-0.25 [28]. Thus, the TEXONO threshold  $T_{thres} = 100 \text{ eV}_{ee}$  corresponds to nuclear recoil-energy  $T_{min} = 500 \text{ eV}_{nr}$  for  $Q_f = 0.20$  and  $T_{min} = 400 \text{ eV}_{nr}$  for  $Q_f = 0.25$ , correspondingly the maximum nuclear recoil-energy  $T_{max} = 1.81 \text{ keV}_{nr}$ , is restricted to a maximum observable energy of 362 and 452 eV $_{ee}$ .

The sensitivity of the TEXONO experiment to the SM weak mixing angle  $\sin^2 \theta_W$  is quantitatively determined on the basis of a  $\chi^2$ -type analysis relying on statistical errors only [24]

$$\chi^2 = \left( \frac{N_{SM} - N_{SM}(\sin^2 \theta_W)}{\delta N_{SM}} \right)^2. \quad (11)$$

In our calculational procedure we have assumed that the TEXONO experiment will detect the precise number of SM events,  $N_{SM}$ , by fixing the electroweak mixing parameter to the PDG value i.e.  $\hat{s}_Z^2 = 0.23120$  [17]. We estimate the expected events  $N_{SM} = (27962, 2586, 4415)$  assuming  $Q_f = (1, 0.20, 0.25)$  and a detection threshold 100 eV $_{ee}$ , in good agreement with Ref. [29]. The  $\chi^2$  function is then minimised with respect to  $\sin^2 \theta_W$ , by varying this parameter around its central value, taken as the value reported by the PDG.

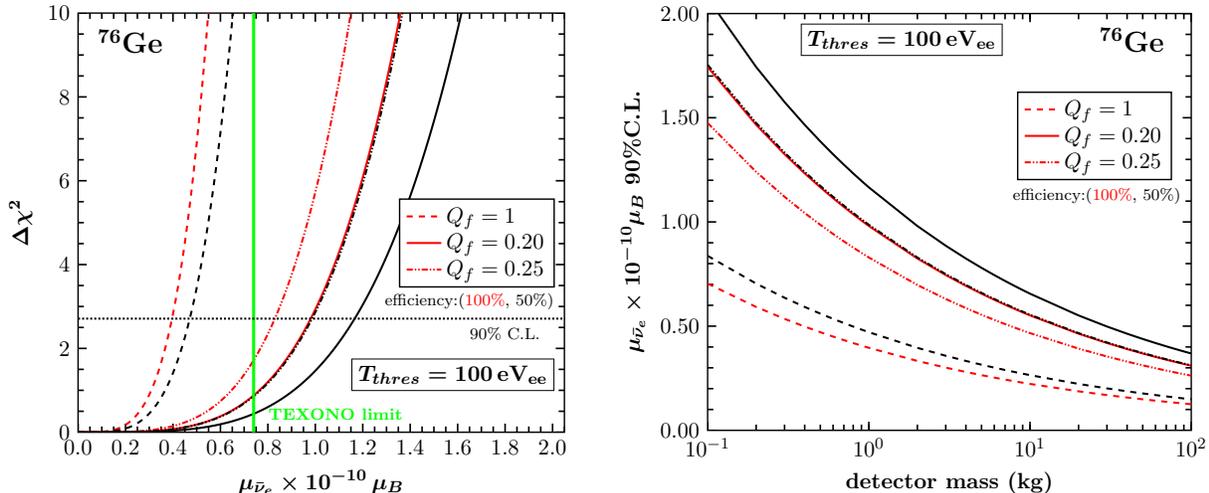


Figure 3: (*Left panel*)  $\Delta\chi^2$  profiles in terms of the neutrino magnetic moment parameter  $\mu_{\bar{\nu}_e}$  in units of  $10^{-10}\mu_B$  at TEXONO. (*Right panel*) Sensitivity to  $\mu_{\bar{\nu}_e}$  at 90% C.L. as a function of the detector mass. Same conventions as in Fig. 2 are used.

We have explicitly verified that there are good prospects for making precision tests of the SM by using low-energy  $^{76}\text{Ge}$  detectors. Our results for the TEXONO sensitivity to the weak mixing angle are presented in Fig. 2. Furthermore, we have also evaluated the  $1\sigma$  error band on  $\sin^2\theta_W$  defined as  $\delta\sin^2\theta_W \equiv \delta s_W^2 = (s_{Wmax}^2 - s_{Wmin}^2)/2$  as well as the corresponding uncertainty  $\delta s_W^2/\hat{s}_Z^2$ , with  $s_{Wmax}^2$  ( $s_{Wmin}^2$ ) being the respective upper (lower) bound. The resulting sensitivities are shown in Table 1. Specifically, neglecting the quenching corrections ( $Q_f = 1$ ), the improvement upon previous results [24] is up to 82% (74% when realistic efficiencies are taken into account). Furthermore, the effect for  $Q_f = 0.20$  (0.25) leads to reduction of  $\delta\sin^2\theta_W$  sensitivity by a factor of 3.3 (2.5) for both detection efficiencies.

Prompted by the upcoming generation of low-threshold nuclear detectors, we have made an effort to identify possible deviations from the SM neutrino-quark interaction cross section originated by non-standard neutrino EM properties. In particular, analysing their sensitivity to electromagnetic CENNS events we have found that important deviations may be induced by the presence of a non-zero transition neutrino magnetic moment  $\mu_{eff} \equiv \mu_{\bar{\nu}_e}$ . In order to determine this sensitivity we use a  $\chi^2$  function of the form [19]

$$\chi^2 = \left( \frac{N_{\text{SM}} - N_{\text{tot}}(\mu_{\bar{\nu}_e})}{\delta N_{\text{SM}}} \right)^2. \quad (12)$$

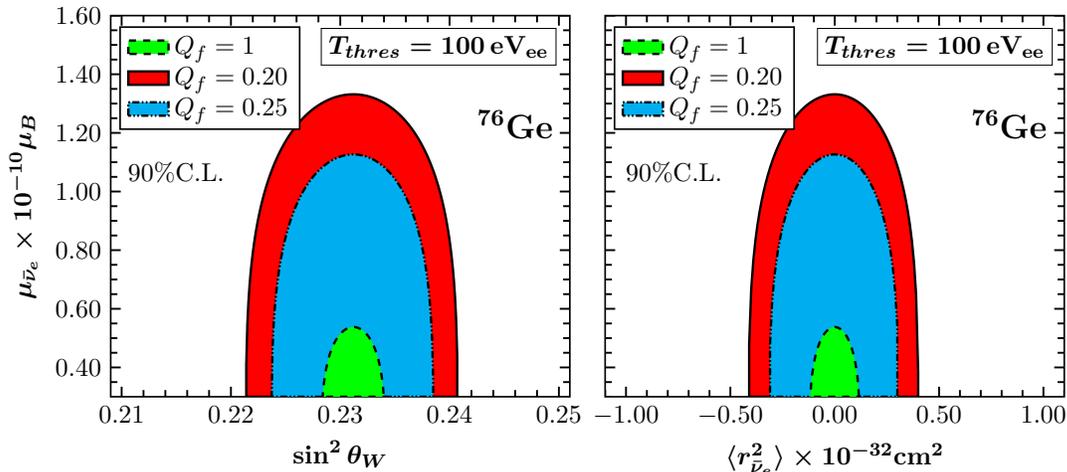


Figure 4: 90% C.L. allowed regions in the  $(\sin^2 \theta_W - \mu_{\bar{\nu}_e})$  plane (*left panel*) and the  $(\langle r_{\bar{\nu}_e}^2 \rangle - \mu_{\bar{\nu}_e})$  plane (*right panel*) from a two parameter combined analysis. See the text for more details.

In Eq. (12), we substitute the SM cross section by the one given in Eq. (5) in order to account for possible events,  $N_{\text{tot}}$ , originating from the corrections associated to the non-trivial structure of the neutrino EM current, as discussed previously. The corresponding results obtained by varying the effective transition neutrino magnetic moment,  $\mu_{\bar{\nu}_e}$ , are presented in Fig. 3 (left panel). The experimental TEXONO limit from  $\bar{\nu}_e - e$  scattering,  $\mu_{\bar{\nu}_e} = 7.4 \times 10^{-11} \mu_B$  [25], is also shown for comparison (the most stringent bound on the neutrino magnetic moment comes from the reactor experiment GEMMA as  $\mu_{\bar{\nu}_e} = 2.9 \times 10^{-11} \mu_B$  at 90% C.L. [58]). One sees that the prospects are very promising. Indeed, from Table 1, we find that the attainable sensitivities are improved by about one order of magnitude compared to the corresponding expectations at a SNS facility, considered recently in [24]. Note however, that experiments at the SNS are not optimised to measure electron-neutrino properties.

Moreover, it is worth mentioning that for the case of a  $100 \text{ eV}_{\text{ee}}$  threshold and  $Q_f = 1$ , the resulting sensitivity is by 46% (36% for the case of realistic efficiency) better than the existing limits derived from  $\bar{\nu}_e - e$  scattering TEXONO data [25]. However, assuming  $Q_f = 0.20$  (0.25) the above sensitivity reduces by a factor of 2.5 (2.1) for both recoil acceptances. From our calculations we have also found that neglecting quenching corrections the sensitivity to  $\mu_{\bar{\nu}_e}$  of a given detector with mass  $m$  is roughly equivalent to that of a detector with ten times bigger mass for the case of  $Q_f = 0.25$ . The results concerning this point are shown in Fig. 3 (right panel).

In view of our previous discussion, the TEXONO sensitivity to  $\langle r_{\bar{\nu}_e}^2 \rangle$ -related searches is estimated through the definition of the  $\chi^2$  given in Eq. (11) by replacing  $\sin^2 \theta_W$  with that of Eq. (7) and fixing  $\sin^2 \bar{\theta}_W$  to the PDG value. After the  $\chi^2$  minimisation we find that the TEXONO experiment is expected to be very sensitive to EM contributions of this type. The estimated 90% C.L. sensitivities are presented in Table 1. In the particular case of  $Q_f = 0.25$  we see that thanks to the observation of CENNS events, TEXONO can reach an improvement of the order of 35% or more, with respect to similar calculations [24]. Again, this sensitivity reduces by a factor of 3.2 (2.4) when quenching corrections  $Q_f = 0.20$  (0.25) are taken into account. Moreover, it is worth noting that the latter sensitivities are by one order of magnitude better than the current TEXONO constraint obtained from  $\bar{\nu}_e - e$  scattering [26].

Finally, it is also interesting to show the combined sensitivities obtained by varying two of the above parameters ( $\sin^2 \theta_W$ ,  $\mu_{\bar{\nu}_e}$  and  $\langle r_{\bar{\nu}_e}^2 \rangle$ ) simultaneously. The 90% C.L. allowed regions in the  $(\sin^2 \theta_W - \mu_{\bar{\nu}_e})$  and  $(\langle r_{\bar{\nu}_e}^2 \rangle - \mu_{\bar{\nu}_e})$  plane are shown in the left and right panel of Fig. 4, respectively for different quenching factors. One notices that the resulting parameter space is substantially reduced with respect to the corresponding sensitivity regions for muon neutrinos at a SNS experiment (see e.g. Ref. [24]). The latter is a direct consequence of the low-threshold TEXONO detectors adopted in the present study.

## 5 Summary and conclusions

In this work we have explored the possibility of performing Standard Model precision studies and probing for new physics through low energy neutral-current coherent elastic neutrino-nucleus scattering (CENNS) at the TEXONO experiment. Moreover, we have presented a comprehensive analysis for the case of potential sub-leading neutrino EM interactions. The calculated convoluted cross sections, clearly indicate the need for novel detector technologies with sub-keV sensitivities. Furthermore, from a nuclear physics point of view, the reactor neutrino beam induces transitions in the bound nuclear spectrum while the Spallation Neutron Source (SNS) beam may excite in addition much higher transitions of the nuclear detector. We conclude that, apart from providing the first ever detection of CENNS events, low threshold Germanium-based kg-scale detectors, e.g. TEXONO, will bring substantial improvements on precision SM tests as well as sensitivities on neutrino EM properties, such as the neutrino magnetic moment and the neutrino charge radius. We show explicitly that the sensitivities improve by up to one order of magnitude with respect to previous estimates. In this paper we have used realistic nuclear structure calculations within the context of the quasi-particle random

phase approximation (QRPA) and a simple  $\chi^2$ -type analysis taking into account quenching effects. We have also checked that our sensitivities are determined mainly by the number of events: a binned sample would result in differences less than percent. It is also worth mentioning that a global fit including an experiment at the SNS added to the TEXONO experiment will not essentially improve these results, since SNS provides the best sensitivities for the case of muonic neutrinos. Hence, the two experiments are clearly complementary.

## Acknowledgements

This work was supported by Spanish MINECO under grants FPA2014-58183-P, Multidark CSD2009-00064 (Consolider-Ingenio 2010 Programme), by EPLANET, by the CONACYT grant 166639 (Mexico) and the PROMETEOII/2014/084 grant from Generalitat Valenciana. DKP was supported by "*Prometeu per a grups d' investigació d' Excel·lència de la Conselleria d' Educació, Cultura i Esport, CPI-14-289*" (*GV PROMETEOII2014-084*). MT is also supported by a Ramon y Cajal contract of the Spanish MINECO (grant SEV-2014-0398 (MINECO)). TSK wishes to thank Prof. H.T. Wong for the useful discussion on TEXONO experiment during attending the NDM-15 conference. DKP is indebted to Prof. J.D. Vergados for stimulating discussions.

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