Tensorial NSI and Unparticle physics in neutrino scattering

J. Barranco\textsuperscript{1,2}

\textsuperscript{1}Instituto de Astronomía, Universidad Nacional Autónoma de México, México, DF 04510, Mexico

\textsuperscript{2}División de Ciencias e Ingenierías, Universidad de Guanajuato, Campus León, C.P. 37150, León, Guanajuato, México

A. Bolaños\textsuperscript{3}

\textsuperscript{3}Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Apartado Postal 1152, Puebla, Puebla, México.

E. A. Garcés\textsuperscript{4}

\textsuperscript{4}Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740 07000 México, D F, México

O. G. Miranda\textsuperscript{4}

\textsuperscript{4}Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740 07000 México, D F, México

T. I. Rashba\textsuperscript{5}

\textsuperscript{5}IZMIRAN, Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences, 142190, Troitsk, Moscow region, Russia

We have analyzed the electron anti-neutrino scattering off electrons and the electron anti-neutrino-nuclei coherent scattering in order to obtain constraints on tensorial couplings. We have studied the formalism of non-standard interactions (NSI), as well as the case of Unparticle physics. For our analysis we have focused on the recent TEXONO collaboration results and we have obtained current constraints to possible electron anti-neutrino-electron tensorial couplings in both new physics formalisms. The possibility of measuring for the first time electron anti-neutrino-nucleus coherent scattering and its potential to further constrain electron anti-neutrino–quark tensorial couplings is also discussed.

PACS numbers:13.15.+g,12.90.+b,14.60.St

\textsuperscript{*}jbarranc@fisica.ugto.mx

\textsuperscript{†}azucena@fcfm.buap.mx

\textsuperscript{‡}egarces@fis.cinvestav.mx

\textsuperscript{§}omr@fis.cinvestav.mx

\textsuperscript{¶}timur@mppmu.mpg.de
1. Introduction

Searching for new physics has been highly motivated by neutrino oscillation physics which implies non-zero neutrino mass. Neutrino oscillations are the first clue of physics beyond the standard model and this fact has motivated a new generation of neutrino experiments as well as the development of phenomenological and theoretical research on models beyond the Standard Model. The future generation of neutrino experiments put the field as very promising in the search for new physics.

A very useful tool for the phenomenological study of these types of new physics is the formalism of non standard interactions (NSI). This formalism can parametrize a wide range of well motivated models of neutrino mass and, at the same time, gives model independent constraints.

In the NSI formalism, operators with $(V±A)$ Lorentz structure have been widely studied in the literature, giving stringent limits in both neutrino-electron and anti-neutrino-electron interactions when solar and reactor data are analyzed. However, a similar analysis based on an effective approach of tensorial NSI has not been done in the neutrino sector. To the best of our knowledge, constraints on tensorial NSI based on this phenomenological approach have been only derived using accelerator neutrinos at LAMPF and stellar energy loss arguments. In the present work we use the most recent measurement on the $\bar{\nu}_e$-electron scattering to constrain the tensorial NSI coupling constant.

The study of neutrino-electron scattering has been of interest for elementary particle physics since its first measurement at the GARGAMELLE bubble chamber. Recently, neutrino detectors using reactor anti-neutrinos in a short baseline have taken profit of the intense and pure source of $\bar{\nu}_e$ as a probe of physics beyond the Standard Model.

Moreover, $\bar{\nu}_e$-electron scattering has been recently measured with improved accuracy by using reactor anti-neutrinos. In particular the TEXONO collaboration has reported recent results using 187 kg of crystal scintillator detector ($CSI(Tl)$). In their results they showed, contrary to previous experiments, a binned sample for low energy antineutrino electron scattering. It is natural to expect a better accuracy in searching for new physics by using this data sample. In the present work we have used these results to study tensorial interactions in the framework of NSI.

On the other hand, a very different type of new physics that also can give rise to tensorial interactions is the recently proposed unparticle physics. In this extension, particles couple to a hidden conformal sector, which could be probed in future experiments.

Unparticle physics signatures could be directly produced in accelerator experiments and therefore tested by searching for signatures of missing energy in the detectors. There is another way to study their effects, which is through low energy processes mediated by the unparticle stuff. The latter could, for example, modify neutrino elastic scattering phenomenology due to effects of virtual unparticle
exchange between fermionic currents.

Previous analysis of $\bar{\nu}_e$-electron elastic scattering have been performed for scalar and vectorial unparticle propagators \cite{27,28,29} in order to obtain constraints on relevant unparticle parameters. Here we introduce the analysis of tensorial unparticle propagators in $\bar{\nu}_e$ elastic scattering off electrons and in $\bar{\nu}_e$-nuclei coherent scattering.

We will see in this work that it is possible to obtain strong constraints to both NSI and unparticle parameters using $\bar{\nu}_e$-electron scattering results. These constraints are valid for a non conformal invariant unparticle theory where the dimension of the operator is not bounded from unitarity constraints \cite{30,31}. Furthermore, the unparticle tensor propagator used in our analysis is antisymmetric as the one reported in Ref. \cite{32}.

Our paper is organized as follows: In Section 2 we introduce the NSI formalism and present the corresponding $\bar{\nu}_e$-electron and the $\bar{\nu}_e$-nucleus coherent scattering cross sections, while in Section 3 we present the analog discussion for the unparticle case. The description of our analysis for the TEXONO case is shown in Section 4 and for the $\bar{\nu}_e$-nucleus coherent scattering is shown in Section 5. Finally, our conclusions are given in Section 6.

2. Tensorial NSI in neutrino scattering

It is a common characteristic of many extensions of the Standard Model (SM) to introduce new interactions that can be parametrized with the help of an effective Lagrangian. The most studied case regards with $(V - A)$ extensions of the SM. It is well known that in this case the effective four fermion Lagrangian takes the form: \cite{4,5,6,7,8}

$$-\mathcal{L}_{V-A}^{eff} = \varepsilon_{\alpha\beta}^{P} \sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f} \gamma^\rho P f),$$

(1)

where $f$ is a first generation SM fermion: $e, u$ or $d$, and $P = L$ or $R$, are the chiral projectors and $\varepsilon_{\alpha\beta}^{P}$ parametrize the strength of the NSI with $\alpha$ and $\beta$ the initial and final flavor states. There is plenty of literature studying either current constraints on the neutrino NSI with electrons \cite{9,10,11,12} and quarks \cite{13,14} as well as future perspectives for long baseline neutrino experiments \cite{15,16} as well as in reactor low energy neutrino experiments \cite{17}.

In particular for the $\nu_e$-electron scattering, which has the advantage of being a purely leptonic process and therefore is free from QCD uncertainties, the $\nu_e$-electron cross section for the NSI case is given by

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi} \left[ (\tilde{g}_L^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^L|^2) + (\tilde{g}_R^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^R|^2) \left( 1 - \frac{T}{E_{\nu}} \right)^2 \right. - \left. (\tilde{g}_L \tilde{g}_R + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^L||\varepsilon_{\alpha e}^R|) m_e \frac{T}{E_{\nu}} \right],$$

(2)
Here, $E_\nu$ is the incident neutrino energy, $T$ is the electron recoil energy, $m_e$ is the electron mass, $\tilde{g}_L = g_L + \epsilon_{ee}^L$, $\tilde{g}_R = g_R + \epsilon_{ee}^R$ and $G_F$ the Fermi constant. The SM coupling constants are given by $g_L = \frac{1}{2} + \sin^2 \theta_W$, $g_R = \sin^2 \theta_W$. For $\bar{\nu}_e$-electron the cross section is obtained by interchanging $\tilde{g}_L(R) \rightarrow \tilde{g}_R(L)$ in Eq. (2). It can be noticed that, in the absence of NSI, this expression takes the form of the SM cross section.

On the other hand, limited attention has been given to possible tensor interactions. This may be motivated by the $(V-A)$ structure of the SM, however, with neutrino physics entering into a precision era, it could be a good moment to study this kind of interactions with more detail. In previous studies, the tensorial fermion currents of the form $\bar{f}\sigma^{\mu\nu}f$ have been studied \(^{34,35}\). In particular, $\bar{\nu}_e$-electron scattering received some attention \(^{36}\) and there have been constraints reported in the literature \(^{17}\).

In the case of $\bar{\nu}_e$ scattering off electrons, the tensorial contribution to the amplitude is given by \(^{36}\)

$$|M|^2 = \sum_{\beta=e,\mu,\tau} \epsilon^{eT\beta} \frac{G_F^2}{2} 128 m_e^2 (4E_\nu^2 + T^2 - (4E_\nu + m_e)T)$$

(3)

and therefore the differential NSI $\bar{\nu}_e$-electron cross section takes the form:

$$\frac{d\sigma_{NSI}}{dT} = \frac{|M|^2}{64\pi m_e E_\nu^2} = \sum_{\beta=e,\mu,\tau} \epsilon^{eT\beta} 4G_F^2 m_e \left[ \left( 1 - \frac{T}{2E_\nu} \right)^2 - \frac{m_e T}{4E_\nu^2} \right].$$

(4)

In this case, $\epsilon^{eT\beta}$ parametrizes the strength of the tensorial NSI coupling on electrons. Note that there is no interference term between the tensorial non-standard amplitude and the SM amplitude. Neutrino flavor changing processes have the same contribution to the total cross section as the conserving neutrino flavor process. Hence, the limits that are derived for $\epsilon^{eT\beta}$ are the same as the ones obtained for flavor changing coupling constants $\epsilon^{e\beta\beta}$ $\beta \neq e$ when only one parameter is allowed to vary at a time. For this reason, from now on we will denote the tensorial coupling $\epsilon^{eT\beta}$ as $g^{T\epsilon}$. It is also worth to be noticed that the tensor interaction could imply a change in chirality for the incoming neutrino. Given the fact that neutrinos are massive it is natural to consider such a possibility.

In order to have an idea about the effect of the tensorial NSI interaction, we plot the differential cross section versus the energy and compare it with the SM prediction, figure 1, for some values of $g^{T\epsilon}$.

2.1. Neutrino-nucleus coherent scattering

The coherent neutrino-nucleus \(^{37}\) and neutrino-atom \(^{38,39}\) scattering have been recognized for many years as interesting processes to probe the SM. The coherent scattering takes place when momentum transfer, $q$, is small compared with $R^{-1}$, the inverse nucleus (or atom) size, i.e. $qR < 1$. For most nuclei, this condition is fulfilled for neutrino energies below 150 MeV. Therefore, the condition for full coherence in
the neutrino-nucleus scattering is well satisfied for reactor anti-neutrinos and also for solar, supernovae, and artificial neutrino sources.

The TEXONO collaboration has a program towards the detection of the coherent $\bar{\nu}_e$-nucleus scattering $^{40}$. Such a detection will be helpful to improve the limits on the neutrino magnetic moment and other types of new physics such as NSI and unparticle tensorial interactions and might even set better constraints than those coming from future neutrino factory experiments $^{33}$.

Within the SM, neglecting radiative corrections, the cross section for $\bar{\nu}_e$-nucleus coherent scattering is

$$\frac{d\sigma}{dT} = \frac{G^2_F M^2}{2\pi} \left\{ \left( G_V - G_A \right)^2 + \left( G_V + G_A \right)^2 \left( 1 - \frac{T}{E_\nu} \right)^2 - \left( G_V^2 - G_A^2 \right) \frac{M}{E_\nu^2} \right\}, \quad (5)$$

where $M$ is the mass of the nucleus, $T$ is the recoil nucleus energy, $E_\nu$ is the incident anti-neutrino energy and the axial and vector couplings are

$$G_V = \left[ g^p_V Z + g^n_V N \right] F^V_{\text{nuc}}(q^2), \quad (6)$$

$$G_A = \left[ g^p_A (Z_+ - Z_-) + g^n_A (N_+ - N_-) \right] F^A_{\text{nuc}}(q^2). \quad (7)$$

$Z$ and $N$ represent the number of protons and neutrons in the nucleus, while $Z_\pm$ ($N_\pm$) stands for the number of protons (neutrons) with spin up and spin down respectively. The vector and axial nuclear form factors, $F^V_{\text{nuc}}(q^2)$ and $F^A_{\text{nuc}}(q^2)$, are usually assumed to be equal and of order of unity in the limit of small energies, $q^2 \ll M^2$. The SM neutral current vector couplings of neutrinos with protons, $g^p_V$, and with neutrons, $g^n_V$, are

$$g^p_V = \rho^{NC}_{\nu N} \left( \frac{1}{2} - 2\kappa_{\nu N} s^2_Z \right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR},$$

$$g^n_V = -\frac{1}{2}\rho^{NC}_{\nu N} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}. \quad (8)$$

Here $s^2_Z = \sin^2\theta_W = 0.23120$, $\rho^{NC}_{\nu N} = 1.0086$, $\kappa_{\nu N} = 0.9978$, $\lambda^{uL} = -0.0031$, $\lambda^{dL} = -0.0025$ and $\lambda^{dR} = 2\lambda^{uR} = 7.5 \times 10^{-5}$ are the radiative corrections given by
the PDG \(^{11}\). The axial contribution can be neglected as can be seen from Eq. \(^{5}\) since the ratio of axial to vector contribution is expected to be of the order \(1/A\), where \(A\) is the atomic number. The spin-zero cross section of \(\bar{\nu}_e\) scattering off nuclei in the low energy limit, \(T \ll E_\nu\) is

\[
\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E_\nu^2} \right) \left[ Z (g_\nu^p + N(g_\nu^n)) \right]^2.
\]

Now we can compute the \(\bar{\nu}_e\)-nucleus coherent dispersion with a tensorial NSI coupling. Analogously to the previous lines, and incorporating the tensorial NSI term, we calculate the tensor NSI coherent neutrino-nucleus cross section as:

\[
\frac{d\sigma^{NSI}}{dT} = \frac{4G_F^2 M}{\pi} \left[ g_T^u (2Z + N) + g_T^d (Z + 2N) \right]^2 \left[ \left( 1 - \frac{T}{2E_\nu} \right)^2 - \frac{MT}{4E_\nu^2} \right],
\]

where \(m_A\) is the mass of the nucleus and \(g_T^u, g_T^d\) the tensor couplings for u-type or d-type quark, respectively.

3. Neutrino-electron scattering mediated by tensorial unparticle interactions

At energies above certain \(\Lambda\), a hidden sector operator \(O_{UV}\) of dimension \(d_{UV}\) could couple to the SM operators \(O_{SM}\) of dimension \(d_{SM}\) via the exchange of heavy particles of mass \(M\)

\[
L_{UV} = \frac{O_{UV}O_{SM}}{M^{d_{UV}+d_{SM}−d}}.
\]  

The hidden sector becomes scale invariant at \(\Lambda\) and then the interactions become of the form

\[
L_U = C_{O_U} \frac{\Lambda^{d_{UV}−d}}{M^{d_{UV}+d_{SM}−d}} O_U O_{SM},
\]

where \(O_U\) is the unparticle operator of scaling dimension \(d\) in the low energy limit and \(C_{O_U}\) is a dimensionless coupling constant. Therefore the unparticle sector can appear at low energies in the form of new massless fields coupled very weakly to the SM particles.

Scalar and vectorial unparticle interactions have been studied previously in the context of \(\bar{\nu}_e\)-electron scattering \(^{24,28,29}\). In what follows we will concentrate on the case of tensorial interactions.

Effective interactions for the tensor unparticle interactions in the low energy regime have been studied in the past \(^{32,42}\).

In this work we will use the antisymmetric tensor operator of the form \(^{32}\)

\[
[A_T(P^2)]_{\mu\nu,\rho\sigma} = \frac{A_d}{2 \sin (d\pi)} (-P^2)^{d−2} T_{\mu\nu,\rho\sigma}(P),
\]

where

\[
A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d}} \frac{\Gamma(d + 1/2)}{\Gamma(d - 1)\Gamma(2d)}.
\]
The tensor $T_{\mu\nu\rho\sigma}$ is split into a 'magnetic' and an 'electric part'. The 'magnetic part' (m) is defined as:

$$T^{(m)}_{\mu\nu\rho\sigma} = \frac{1}{2} \left\{ \pi_{\mu\rho} \pi_{\nu\sigma} - \pi_{\mu\sigma} \pi_{\nu\rho} \right\},$$

(15)

and the 'electric part' is given by:

$$T^{(e)}_{\mu\nu\rho\sigma} = \frac{1}{2} \left\{ \pi_{\mu\rho} w_{\nu\sigma} - \pi_{\mu\sigma} w_{\nu\rho} - \pi_{\nu\rho} w_{\mu\sigma} + \pi_{\nu\sigma} w_{\mu\rho} \right\},$$

(16)

where

$$w_{\mu\nu} = \frac{(k - k')_\mu (k - k')_\nu}{(k - k')^2}.$$  

(17)

The neutrino matrix for the neutrino (of any flavor)-fermion interaction, mediated by a tensor unparticle is

$$\mathcal{M} = \frac{\lambda^\alpha_\nu \lambda^\beta_f}{2 \sin(d\pi) \Lambda^d_{2d-2}} A_d [\vec{\nu}_\beta (k') \sigma^\alpha \nu_\alpha (k)] \left[ (k - k')^2 \right]^{d-2} T_{\mu\nu\rho\sigma} (\vec{f}(p')) \sigma_{\rho\sigma} f(p),$$

(18)

and $T_{\mu\nu\rho\sigma}$ is either the 'magnetic' $T^{(m)}$ or the 'electric' part $T^{(e)}$. In what follows we will use the definition for the neutrino and fermion couplings as $\lambda_f = \sqrt{\lambda^\alpha_\nu \lambda^\beta_f}$, with

$$\lambda^\alpha_\nu = C^\alpha_\nu \frac{\Lambda^{d_{UV} - d}}{M^{d_{UV} + d_{SM} - d}}; \quad \lambda^\beta_f = C^\beta_f \frac{\Lambda^{d_{UV} - d}}{M^{d_{UV} + d_{SM} - d}},$$

(19)

and we will fix the scale $\Lambda = 1$ TeV. With this information, it is possible to obtain the differential cross section for $\bar{\nu}_e$-electron scattering for the tensorial unparticle interactions. We concentrate in the flavor conserving case of the $\bar{\nu}_e$-electron interaction, i.e. $\lambda_e = \sqrt{\lambda^e_\nu \lambda^e_f}$.

The 'electric part' contributes with the differential cross section

$$\frac{d\sigma_T}{dT} = \frac{f(d)^2}{\pi \Lambda^d_{d_{UV} - d} 2^{2d-3} m_e^{2d-3} T^{2d-4}} \left[ \left( 1 - \frac{T}{2E_{\nu_e}} \right)^2 - \frac{m_e T}{2E_{\nu_e}^2} \right],$$

(20)

and the 'magnetic part' contribution is given by

$$\frac{d\sigma_T}{dT} = \frac{f(d)^2}{\pi \Lambda_{d_{UV} - d}^{2d-4} 2^{2d-2} m_e^{2d-3} T^{2d-4}} \left( 1 - \frac{T}{2E_{\nu_e}} \right)^2,$$

(21)

where we have defined

$$f(d) = \frac{\lambda_e}{2 \sin(d\pi) A_d}.$$  

(22)

Notice that in this case an integer dimension for $d$ leads to a singularity in the value of $f(d)$.

In order to obtain the total cross section, both expressions, the 'magnetic' and 'electric' contributions should be added to the SM prediction.
8

Fig. 2. Comparison between Standard Model and tensor unparticle differential cross section for \( \Lambda = 1 \text{ TeV} \).

\[
\frac{d\sigma(\bar{\nu}_e)}{dT} = \frac{2G_F^2m_e}{\pi}\left[\frac{g_R^2}{2} + \frac{g_L^2}{2}(1 - \frac{T}{E_{\nu}})^2 - g_R g_L \frac{m_e T}{E_{\nu}^2}\right].
\] (23)

We show in figure 2 the comparison between the SM prediction for the differential cross section and the unparticle case, we can see that the expectations to obtain a good constraint from this process at low energies are encouraging.

If the theory is not only scale invariant but also conformal invariant then unitarity constraints apply to the the dimension \( d \) of the unparticle operator. We will relax this constraint in our phenomenological analysis as has been done in other phenomenological and theoretical works.

3.1. \( \bar{\nu}_e \)-nucleus coherent scattering for tensorial unparticle

Now we can write the tensor unparticle part of the \( \bar{\nu}_e \)-nucleus coherent scattering cross section. We get the following expressions for the 'magnetic part'

\[
\frac{d\sigma^{(m)}_{U_e}}{dT} = \frac{1}{\pi \Lambda^{d-4}} \left| g_u(d)(2Z + N) + g_d(d)(Z + 2N)\right|^2 \times 2^{2d-2}m_A^{2d-3}T^{2d-4} \left(1 - \frac{T}{2E_{\nu}}\right)^2,
\] (24)

while for the 'electric part' we get

\[
\frac{d\sigma^{(e)}_{U_e}}{dT} = \frac{1}{\pi \Lambda^{d-4}} \left| g_u(d)(2Z + N) + g_d(d)(Z + 2N)\right|^2 \times 2^{2d-3}m_A^{2d-3}T^{2d-4} \left(1 - \frac{T}{2E_{\nu}}\right)^2 \left(1 - \frac{m_A T}{2E_{\nu}^2}\right).
\] (25)

In the last expressions we have defined the new coupling constants

\[
g_{u,d}(d) = \frac{\lambda_{u,d}^2}{2 \sin(d\pi)} A_d = \frac{\lambda_{u,d}^2}{2 \sin(d\pi)} A_d,
\] (26)
where we have used the same definition of $A_d$ as defined for the $\bar{\nu}_e$-electron scattering.

4. Limits on tensor interactions from the TEXONO experiment

Among the most recent reactor neutrino experiments, the TEXONO collaboration has published results on the cross section for the $\bar{\nu}_e$-electron scattering\cite{44,24} using the Kuo Sheng 2.9 GW reactor as an anti-neutrino source that provides an average flux of $6.4 \times 10^{12}$ cm$^{-2}$ s$^{-1}$. Even though the collaboration has made use of three different detectors, we will focus on the CsI(Tl) detector data in order to obtain constraints for the tensor interactions both for the NSI and unparticle cases.

In order to obtain a constraint on the tensorial parameters we have computed the expected number of events for the TEXONO detector in the case of a NSI or unparticle interaction given by (4) and (21,23) respectively and compute the integral

$$N_i = K \int_{T_i}^{T_{i+1}} \int_{E_{\nu}}^{E_{\nu}} \frac{d\sigma}{dT} d\phi(\bar{\nu}_e) dE_{\nu} dT, \quad (27)$$

where the factor $K$ accounts for the time exposure and the number of electron targets, $d\sigma/dT$ is the cross section for the NSI or the unparticle interaction and $d\phi(\bar{\nu}_e)/dE_{\nu}$ is the neutrino spectrum which we have parametrized as the exponential of a polynomial order five as has been recently discussed in the literature\cite{45}. We have also considered the relative abundances of each radioactive isotope in the nuclear reactor, $^{235}$U(98%), $^{238}$U(1.5%), and $^{239}$Pu(0.4%). The electron recoil energy is divided into ten bins, $T_i$, running from 3 to 8 MeV. The detector is located at a distance of 28 m from the reactor. For $\bar{\nu}_e$ energies around 1 MeV, the estimated oscillation length into an active neutrino is of the order of 10 km, hence in the calculation of the expected number of events we do not take into account neutrino oscillation effects.

Once we have computed the theoretical expected events per bin we can compute the $\chi^2$ function

$$\chi^2 = \sum_{i=1}^{N_{expt}(i)} \left[ \frac{N_{NSI,U}(i) - [N_{NSI,U}(i)]}{\Delta_{stat}(i)} \right]^2, \quad (28)$$

where $N_{NSI,U}(i)$ is the calculated event rate in the $i$th energy data bin for the Tensorial NSI or the unparticle cases, $N_{expt}(i)$ is the observed event rate for the corresponding energy bin, and $\Delta_{stat}(i)$ is the statistical uncertainty of the associated measurement.

The results of our analysis are shown in figures\cite{3} and\cite{4}. We can see that for the NSI case the constraint on the tensorial coupling gives the bound $g^{T_e} \leq 0.20$ at 90 % C. L., which is much better than the previously reported constraint by the LAMPF collaboration\cite{17}. We obtained the value of $\chi^2_{min} = 5.43$ for 9 d.o.f. We have verified explicitly that previous reactor experiments give weaker constraints than
those obtained here using the TEXONO data (see Table 1). Recently, a recalculation of the reactor anti-neutrino fluxes has been done \cite{46}, leading to a deficit in the observed rates of reactor neutrino experiments; we have also performed an analysis taken into account this revaluation. The result is shown in figure (3). We can see that there is some impact in the constraints, although we prefer to be conservative and quote the more relaxed bounds that are still better than previous reported constraints.

For the unparticle case we have shown the 90 % CL region for the parameter $\lambda_e$ and $d$. In this case we obtained $\chi^2_{\text{min}} = 5.16$ for 8 d.o.f. We have also extracted the constraints from the solar neutrino analysis reported in Ref. \cite{30} (following analogous assumptions to those discussed in Ref. \cite{29}) and also plotted the result in figure (4) in order to show the interplay between different analysis; as can be seen, the results from our analysis are more restrictive for values of $d > 2.03$. We also can note, as expected from Eq. (22), that there is a singularity for integer values of $d$, for example, in the case of $d = 2$. 

Fig. 3. $\Delta \chi^2$ for the tensorial NSI coupling $g^{Te}$ in the TEXONO experiment.

Fig. 4. limits at 90 % CL for the tensorial unparticle parameters $d$ and $\lambda_e$ from our analysis of the recent TEXONO data.
5. Tensorial neutrino-quark constraints with $\bar{\nu}_e$-nucleus coherent scattering

In this section we study the sensitivity to tensorial NSI and unparticle couplings coming from the coherent $\bar{\nu}_e$-nucleus scattering. In order to apply our analysis to a concrete case, we will concentrate our discussion on the germanium TEXONO proposal\textsuperscript{40}. The detector would be located at the Kuo-Sheng Nuclear Power Station at a distance of 28 m from the reactor core. We assume a typical neutrino flux of $10^{13}$ s$^{-1}$ cm$^{-2}$. Since the experiment is not running yet and therefore we don’t know the precise fuel composition, we use for this case the main component of the spectrum\textsuperscript{17} coming from $^{235}$U. For energies below 2 MeV there are only theoretical calculations for the anti-neutrino spectrum that we take from Ref.\textsuperscript{48}. We can estimate the expected total number of events in the detector in an analogous way as for the previous section

$$N_{\text{events}} = K \int_{E_{\text{min}}}^{E_{\text{max}}(E_{\nu})} dE_{\nu} \int_{T_{\text{th}}}^{T_{\text{max}}(E_{\nu})} dT \lambda(E_{\nu}) \frac{d\sigma}{dT}(E_{\nu}, T), \quad (29)$$

where in this case $K = t\phi_0 N_n$, with $t$ the data taking time period, $\phi_0$ the total neutrino flux, and $N_n$ the number of targets in the detector, $\lambda(E_{\nu})$ the normalized neutrino spectrum, $E_{\text{max}}$ the maximum neutrino energy, $T_{\text{th}}$ the detector energy threshold and the differential cross section refers to the coherent $\bar{\nu}_e$-nucleon interaction. Notice that in this case we are considering the total number of events without binning the sample and we are neglecting neutrino oscillation effects because the distance to the source is small compared with the typical oscillation length.

For the particular case of a minimum detector energy threshold of $T_{\text{th}} = 400$ eV, a 1 kg mass detector made of $^{76}$Ge and 1 yr of data taking we found that the number of events is $N_{\text{events}}^{\text{SM}} = 4346$, in good agreement with TEXONO proposal\textsuperscript{49}.

We have estimated the sensitivity for the TEXONO proposal to constrain unparticle parameters by means of a $\chi^2$ analysis

$$\chi^2 = \left( \frac{N_{\text{events}}^{\text{SM}} - N_{\text{events}}^{\text{NSI}}}{\delta N_{\text{events}}} \right)^2, \quad (30)$$

where we have calculated $N_{\text{events}}^{\text{NSI}}$ by exchanging the SM differential cross section in Eq.\textsuperscript{(29)} with the cross section given in Eqs.\textsuperscript{(24)} and \textsuperscript{(25)}, for the tensorial unparticle case and with Eqs.\textsuperscript{(10)} for the tensorial NSI case respectively. In the left panel of figure\textsuperscript{(5)} we show the $\Delta \chi^2$ function for the case when only one parameter $g^{T_u}$ is varied at a time. Furthermore, in right panel of the same figure\textsuperscript{(5)} we show in solid (dashed) black lines the sensitivity for the tensorial non standard coupling at 90\% (68\%) CL for the case of 1 yr of data taking and a 1 kg mass $^{76}$Ge detector and varying both parameters $g^{T_u}, g^{T_d}$.

As already discussed in Ref.\textsuperscript{33} there is a degeneracy in the parameters $g^{T_u}, g^{T_d}$ as long as we use only one material for the detector. In order to break the degeneracy, another material should be used. We have proposed to use, in addition to the $^{76}$Ge...
Fig. 5. Left panel: $\Delta \chi^2$ at 90% CL for different total errors expected for TEXONO proposal. We take a threshold energy $T_{th} = 400$ eV and vary only the $g_{Tu}$ parameter. Right panel: The allowed regions of tensorial NSI parameters $g_{Td}$ and $g_{Tu}$ are shown at 68% and 90% CL for combined data from two detectors of $^{28}$Si and $^{76}$Ge (colored regions) and only for $^{76}$Ge (solid and dashed lines). A 1 kg mass and 1 yr of data taking is assumed for both detectors. Only statistical errors are taken into account.

Fig. 6. Limits at 90% CL for the unparticle case sensitivity on the parameters $d$ and $\lambda_u$ for the neutrino-nucleus coherent scattering.

detector, a $^{28}$Si detector to break such degeneracy. The expected sensitivity is shown in colored lines in the same figure 5.

For the tensorial unparticle case, we have performed a similar analysis as done in Ref. 29 and we vary one parameter at a time. In figure 6, we show the sensitivity of the coherent $\bar{\nu}_e$–nucleus scattering for the tensorial unparticle propagator for the case $\lambda_d = 0$.

6. Discussion and summary

Neutrino physics is entering into a precision era that could give important guidance about new physics beyond the Standard Model.

In this article we have concentrated in the case of tensorial couplings that could
give a signal in reactor anti-neutrino experiments. We have studied in particular the recent TEXONO results on $\bar{\nu}_e$-electron scattering. The tensorial interactions have been studied both in the framework of NSI and for the unparticle case. We have found new constraints that are stronger than previous laboratory constraints. These results can be summarized in Table 1 for the NSI case where we show the previous laboratory result from the LAMPF experiment [17]. Besides, we also show the astrophysical estimates that come from stellar energy loss [18,19]. For completeness, we report the limits obtained by doing a $\chi^2$ analysis by using the measurements of the cross section reported for the Irvine experiment [50] and MUNU [51].

Table 1. Limits on the tensorial coupling $g^{T_e}$, obtained by using the data from previous experiments and from the TEXONO experiment analyzed in this work.

| experiment         | Energy Range (MeV) | Events | $g^{T_e}$          |
|--------------------|--------------------|--------|-------------------|
| Stellar energy loss| − − −              |        | 0.06 − 3.6        |
| Irvine             | 1.5 − 3.0          | 381    | 0.297 90% CL      |
| Irvine             | 3.0 − 4.5          | 77     | 0.360 90% CL      |
| LAMPF              | 10 − 50            | 191    | 0.379 90% CL      |
| MUNU               | 0.7 − 2.0          | 68     | 0.250 90% CL      |
| TEXONO             | 3.0 − 8.0          | 414    | 0.20 90% CL       |

Table 2. Limits on the tensorial couplings $g^{T_d}$ and $g^{T_u}$, obtained from a futuristic analysis of coherent neutrino-nucleus scattering taking possible results from TEXONO as a case study.

| experiment | $|g^{T_d}|$ 90% C.L. | $|g^{T_u}|$ 90% C.L. |
|------------|--------------------|--------------------|
| $^{28}$Si   | 0.0065             | 0.0065             |
| $^{76}$Ge   | 0.0060             | 0.0060             |

For the case of an unparticle tensor interaction, we have found that our constraints are more restrictive than previous analysis for values of $d > 2.03$.

As can be seen the results are encouraging and future $\bar{\nu}_e$-electron scattering experiments could give even stronger constraints. Another possible place to search for this type of interaction in the future could be the coherent $\bar{\nu}_e$-nucleus scattering that is also part of the TEXONO low energy neutrino physics program [52] and other proposals [53,54,55,56]. We have shown that in this case the future perspectives are quite encouraging since constraints to the tensorial parameters studied in this work could be improved in more than one order of magnitude.
Acknowledgments

We would like to thank M. Deniz and C. Moura for useful discussions. This work has been supported by CONACyT grant 166639 and SNI-Mexico. J.B. is partially supported by UNAM-DGAPA PAPIIT IN113211. A. B. acknowledges RED-FAE CONACYT for Postdoctoral Grant.

References

1. T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. 13, 063004 (2011) [arXiv:1103.0754 [hep-ph]].
2. H. Nunokawa, S. J. Parke and J. W. F. Valle, Prog. Part. Nucl. Phys. 60, 338 (2008) [arXiv:0710.0554 [hep-ph]].
3. R. N. Mohapatra and A. Y. Smirnov, Ann. Rev. Nucl. Part. Sci. 56, 569 (2006) [arXiv:hep-ph/0603118].
4. V. D. Barger, R. J. N. Phillips and K. Whisnant, Phys. Rev. D 44, 1629 (1991).
5. S. Bergmann, M. M. Guzzo, P. C. de Holanda, P. I. Krastev and H. Nunokawa, Phys. Rev. D 62, 073001 (2000) [arXiv:hep-ph/0004049].
6. F. Huber and J. W. F. Valle, Phys. Lett. B 523, 151 (2001) [arXiv:hep-ph/0108193].
7. Z. Berezhiani and A. Rossi, Phys. Lett. B 535, 207 (2002); Z. Berezhiani, R.S. Raghavan and A. Rossi, Nucl. Phys. B 638, 62 (2002).
8. S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, J. of High Ener. Phys. 303, 11 (2003);
9. J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle, Phys. Rev. D 73, 113001 (2006) [arXiv:hep-ph/0512195].
10. J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle, Phys. Rev. D 77, 093014 (2008) [arXiv:0711.0695 [hep-ph]].
11. A. Bolanos, O. G. Miranda, A. Palazzo, M. A. Tortola and J. W. F. Valle, Phys. Rev. D 79, 113012 (2009) [arXiv:0812.3417 [hep-ph]].
12. D. V. Forero, M. M. Guzzo, Phys. Rev. D 84, 013002 (2011).
13. F. J. Escrihuela, M. Tortola, J. W. F. Valle and O. G. Miranda, Phys. Rev. D 83, 093002 (2011) [arXiv:1103.1366 [hep-ph]].
14. J. Kopp, P. A. N. Machado and S. J. Parke, Phys. Rev. D 82, 113002 (2010) [arXiv:1009.0014 [hep-ph]].
15. N. C. Ribeiro, H. Nunokawa, T. Kajita, S. Nakayama, P. Ko and H. Minakata, Phys. Rev. D 77, 073007 (2008) [arXiv:0712.3314 [hep-ph]].
16. P. Huber, M. Lindner, M. Rolinec and W. Winter, Phys. Rev. D 74, 073003 (2006) [arXiv:hep-ph/0606119].
17. R. C. Allen et al., Phys. Rev. D 47, 11 (1993).
18. D. A. Dicus and E. W. Kolb, Phys. Rev. D 15, 977 (1977).
19. P. Sutherland, J. N. Ng, E. Flowers, M. Ruderman and C. Inman, Phys. Rev. D 13, 2700 (1976).
20. F. J. Hasert et al. [ Gargamelle Neutrino Collaboration ], Nucl. Phys. B73, 1-22 (1974). F. J. Hasert et al. [ Gargamelle Neutrino Collaboration ], Phys. Lett. B46, 138-140 (1973).
21. Z. Daraktchieva et al. [MUNU Collaboration], Phys. Lett. B 615, 153 (2005) [arXiv:hep-ex/0502037].
22. H. T. Wong et al. [TEXONO Collaboration], Phys. Rev. D 75, 012001 (2007) [arXiv:hep-ex/0605006].
23. M. Deniz et al. [TEXONO Collaboration], Phys. Rev. D 81, 072001 (2010).
24. M. Deniz et al. [TEXONO Collaboration], *Phys. Rev. D* **82**, 033004 (2010) [arXiv:1006.1947 [hep-ph]].
25. H. Georgi, *Phys. Rev. Lett.* **98**, 221601 (2007) [arXiv:hep-ph/0703260].
26. H. Georgi, *Phys. Rev. D* **82**, 033004 (2010) [arXiv:0704.2457 [hep-ph]].
27. S. Zhou, *Phys. Lett. B* **659**, 336 (2008) [arXiv:0706.0302 [hep-ph]].
28. A. B. Balantekin and K. O. Ozansoy, *Phys. Rev. D* **76**, 095014 (2007) [arXiv:0710.0028 [hep-ph]].
29. J. Barranco, A. Bolanos, O. G. Miranda, C. A. Moura and T. I. Rashba, *Phys. Rev. D* **79**, 073011 (2009) [arXiv:0901.2099 [hep-ph]].
30. M. C. Gonzalez-Garcia, P. C. de Holanda and R. Zukanovich Funchal, *JCAP* **0806**, 019 (2007) [arXiv:0704.2457 [hep-ph]].
31. J. Barranco, O. G. Miranda and T. I. Rashba, *JHEP* **0512**, 021 (2005) [arXiv:hep-ph/0508299].
32. R. L. Kingsley, F. Wilczek and A. Zee, *Phys. Rev. D* **10**, 2216 (1974).
33. C. F. Cho and M. Gourdin, *Nucl. Phys. B* **112**, 387 (1976).
34. B. Kayser, E. Fischbach, S. P. Rosen and H. Spivack, *Phys. Rev. D* **20**, 87 (1979).
35. D. Z. Freedman, *Phys. Rev. D* **9** (1974) 1389.
36. Y. V. Gaponov and V. N. Tikhonov, *Yad. Fiz.* **26** (1977) 594.
37. L. M. Sehgal and M. Wanninger, *Phys. Lett. B* **171** (1986) 107.
38. [http://hepmail.phys.sinica.edu.tw/~texono/TEXT/TEXONO/texono0402.pdf](http://hepmail.phys.sinica.edu.tw/~texono/TEXT/TEXONO/texono0402.pdf)
39. W. M. Yao et al. [Particle Data Group], *J. Phys. G* **33** (2006) 1.
40. K. Cheung, W. Y. Keung and T. C. Yuan, *Phys. Rev. D* **76**, 055003 (2007) [arXiv:0706.3155 [hep-ph]].
41. G. Mention, M. Fechner, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau et al., *Phys. Rev. D* **83**, 073006 (2011) [arXiv:1101.2555 [hep-ex]].
42. H. M. Chang et al. [TEXONO Collaboration], *Phys. Rev. D* **75**, 052004 (2007) [arXiv:hep-ex/0609001].
43. T. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot and T. Lasserre et al., *Phys. Rev. C* **83**, 054615 (2011) [arXiv:1101.2663 [hep-ex]].
44. G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau, *Phys. Rev. D* **83**, 073006 (2011) [arXiv:1101.2755 [hep-ex]].
45. K. Schreckenbach, G. Colvin, W. Gelletly and F. Von Feilitzsch, *Phys. Lett. B* **160**, 325 (1985).