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Unparticle physics and neutrino phenomenology

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We have constrained unparticle interactions with neutrinos and electrons using available data on neutrino-electron elastic scattering and the four CERN LEP experiments data on mono photon production. We have found that, for neutrino-electron elastic scattering, the MUNU experiment gives better constraints than previous reported limits in the region $d > 1.5$. The results are compared with the current astrophysical limits, pointing out the cases where these limits may or may not apply. We also discuss the sensitivity of future experiments to unparticle physics. In particular, we show that the measurement of coherent reactor neutrino scattering off nuclei could provide a good sensitivity to the couplings of unparticle interaction with neutrinos and quarks. We also discuss the case of future neutrino-electron experiments as well as the International Linear Collider.

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I. INTRODUCTION

Motivated by the idea that a scale invariant sector could exist above TeV energies and could be probed at present or future colliders, a scenario has been proposed [1,2] where it is possible to calculate the interaction of such a sector with the standard model (SM) sector in the low-energy limit. In this case, with the help of effective field theory, in particular with Banks-Zaks fields [3], it is possible to obtain quantitative results. In this limit, the scale invariant sector with scale dimension d looks like a nonintegral number d of invisible particles, named unparticles [1].

From the phenomenological point of view, it is interesting that the low-energy processes involving unparticles can have a particular energy spectrum, that is not predicted by other types of new physics. There is a rich phenomenology that can be extracted from the unparticle idea and currently there are several constraints on the relevant parameters of unparticle physics using a wide variety of processes: collider phenomenology, flavor physics, top quark physics, Higgs physics, supersymmetry, dark matter, etc. (for a recent review see, e.g., [4] and also, for more recent works, Ref. [5]).

On the other hand, measurements of neutrino elastic scattering off leptons and quarks are becoming more and more precise and provide a sensitive tool to probe neutrino nonstandard interactions (NSI) and various kinds of new physics beyond the SM. For example, new limits on the nonstandard neutrino-electron couplings [6,7] and on the neutrino charge radius [8] from all neutrino-electron scattering experiments have been recently derived. As for nuclei the sensitivity of future low-energy coherent neutrino-nucleus scattering experiments to NSI neutrino-quark interactions has also been studied in detail [9–11].

Neutrino data can offer the possibility of studying unparticle phenomenology in two ways: first by effects of virtual unparticles exchanged between fermionic currents, second by the direct production of unparticles. The neutrino-electron and neutrino-nuclei scattering are examples where unparticle effects of the first type are measurable, while single-photon production ($e^-e^+ \to \gamma X$) at CERN LEP is an example of the direct production of unparticles. Notice that, beside neutrinos ($\nu\bar{\nu}$), X can be any new hypothetical particle, in particular, unparticle stuff. In this case, neutrino production is the background

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reaction, because the signatures for detection of unparticles are also the missing energy and momentum.

The recent progress of neutrino physics experiments offers an interesting scenario for studying unparticle physics. In this article we derive bounds on unparticle physics using both neutrino-electron scattering data coming from reactors, including the interference term between SM amplitude. We have derived limits from single-photon production in electron-positron collisions. We have also estimated the sensitivity of upcoming neutrino-nuclei coherent scattering measurements to unparticle physics. Moreover, we have also compared our results with previous works that either used the same processes that we considered or astrophysical phenomena and discuss the different hypothesis that should be fulfilled for each limit; in some cases our constraints are better than the previously reported values, and in general they are obtained from a more detailed analysis of the experiments under consideration and, therefore, more robust. We also have corrected some factors derived in previous works.

Our paper is organized as follows: In Sec. II we review the unparticle phenomenology and derive all relevant cross sections. The numerical results are obtained in Sec. III. Finally the discussion of the results and our conclusions are given in Sec. IV.

II. UNPARTICLE PHENOMENOLOGY

At energies above Λ, a hidden sector operator $\mathcal{O}_{UV}$ of dimension d_{UV} could couple to the SM operators $\mathcal{O}_{\rm SM}$ of dimension $d_{\rm SM}$ via the exchange of heavy particles of mass M

$$\mathcal{L}_{UV} = \frac{\mathcal{O}_{UV}\mathcal{O}_{\rm SM}}{M^{d_{UV}+d_{\rm SM}-4}}. \tag{1}$$

The hidden sector becomes scale invariant at Λ and then the interactions become of the form

$$\mathcal{L}_{\mathcal{U}} = C_{\mathcal{O}_{\mathcal{U}}}\frac{\Lambda^{d_{UV}-d}}{M^{d_{UV}+d_{\rm SM}-4}}\mathcal{O}_{\mathcal{U}}\mathcal{O}_{\rm SM}, \tag{2}$$

where $\mathcal{O}_{\mathcal{U}}$ is the unparticle operator of scaling dimension d in the low-energy limit and $C_{\mathcal{O}_{\mathcal{U}}}$ 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.

In the low-energy regime, the effective interactions for the scalar and vector unparticle operators with the SM fermion fields are

$$\lambda_{0f}\frac{1}{\Lambda^{d-1}}\bar{f}f\mathcal{O}_{\mathcal{U}} + \lambda_{0\nu}^{\alpha\beta}\frac{1}{\Lambda^{d-1}}\bar{\nu}_\alpha\nu_\beta\mathcal{O}_{\mathcal{U}} \tag{3}$$

and

$$\lambda_{1f}\frac{1}{\Lambda^{d-1}}\bar{f}\gamma_\mu f\mathcal{O}^\mu_{\mathcal{U}} + \lambda_{1\nu}^{\alpha\beta}\frac{1}{\Lambda^{d-1}}\bar{\nu}_\alpha\gamma_\mu\nu_\beta\mathcal{O}^\mu_{\mathcal{U}}, \tag{4}$$

where

$$\lambda_{if} = C_{\mathcal{O}_{\mathcal{U}}{}^i f}\frac{\Lambda^{d_{UV}}}{M^{d_{UV}+d_{\rm SM}-4}}, \tag{5}$$

$$\lambda_{i\nu}^{\alpha\beta} = C^{\alpha\beta}_{\mathcal{O}_{\mathcal{U}}{}^i \nu}\frac{\Lambda^{d_{UV}}}{M^{d_{UV}+d_{\rm SM}-4}}, \tag{6}$$

with $i = 0$ indicating the unparticle scalar field and $i = 1$ the vector field. We use α and β to denote neutrino flavors (including flavor changing processes) and $f = e, u, d$ for electrons, up, and down quarks, respectively.

In the following subsections we introduce the cross sections that are relevant for our calculations. It is useful for this purpose to use the definitions:

$$g_{if}^{\alpha\beta}(d) = \frac{\lambda_{i\nu}^{\alpha\beta}\lambda_{if}}{2\sin(d\pi)}A_d \tag{7}$$

and

$$A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d}}\frac{\Gamma(d+1/2)}{\Gamma(d-1)\Gamma(2d)}. \tag{8}$$

A. Neutrino-electron scattering mediated by unparticles

Neutrino-electron scattering in the context of unparticles has already been discussed in the literature [12–14]. In this subsection we summarize the main cross sections and we also show some differences in our computations with the results already reported in the literature.

The neutrino-electron cross section mediated by the scalar unparticle is given by the expression

$$\frac{d\sigma_{\mathcal{U}_s}}{dT} = \frac{[g_{0e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}\frac{2^{(2d-6)}}{\pi E_\nu^2}(m_eT)^{(2d-3)}(T+2m_e), \tag{9}$$

where T is the electron recoil energy. Note that this cross section is twice larger than the one derived in Ref. [14]. We have neglected terms containing a neutrino mass, since it is much smaller than both the electron mass and the typical energies for the process.

An additional interference term between the SM and the unparticle amplitude should be considered for the case of a flavor conserving scattering ($\nu_e e^- \to \nu_e e^-$) [13]. However, for the scalar unparticle case, this term is proportional to the neutrino mass and, therefore, it is negligible [14].

For the case of a neutrino-electron scattering mediated by vector unparticles, the differential cross section has the form

$$\frac{d\sigma_{\mathcal{U}_v}}{dT} = \frac{1}{\pi}\frac{[g_{1e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}2^{(2d-5)}(m_e)^{(2d-3)}(T)^{(2d-4)} \times\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_eT}{E_\nu^2}\right], \tag{10}$$

which is eight times larger than the cross section obtained for the same process in Ref. [14].

We would like to comment on the differences between the scalar and the vector unparticle cross sections derived here and in Ref. [14]. There is a factor 4 in the vector case due to a typo in Eq. (12) of Ref. [14]: the factor $2^{(2d-8)}$ appearing there should be $2^{(2d-6)}$ [15]. Another factor 2 difference in both cross sections comes from the averaging over initial spins of massive neutrinos [15] performed in Ref. [14]. Here we do not average over the spins of initial neutrinos, because the deviations from the left (right) polarizations of initial neutrinos (antineutrinos) are highly suppressed by the smallness of neutrino masses.

In the neutrino-electron scattering mediated by the vector unparticles an additional interference term should be considered for the flavor conserving case, which is given by

$$\frac{d\sigma_{\mathcal{U}_V-\mathrm{SM}}}{dT} = \frac{\sqrt{2}G_F}{\pi}\frac{g_{1e}(d)}{\Lambda^{(2d-2)}}(2m_eT)^{(d-2)}m_e \times \left\{g_L + g_R\left(1-\frac{T}{E_\nu}\right)^2 - \frac{(g_L+g_R)}{2}\frac{m_eT}{E_\nu^2}\right\}. \tag{11}$$

This interference term for vector unparticles is linearly proportional to the SM couplings and to the unparticle couplings, therefore it can be bigger than the pure unparticle contribution shown in Eq. (10) for some values of the couplings. Note, however, that this term would not appear in the case of flavor changing interactions, $\nu_e e \to \nu_{\mu,\tau} e$. In other words, neutrino flavor conserving and neutrino flavor changing scatterings are equivalent to the cases with and without the interference term (11), respectively.

B. Single-photon production in electron-positron collisions

Direct production of an unparticle with a single-photon in electron-positron collisions were studied in Refs. [16–18]. In Ref. [18] there is also a prediction for unparticle detection at ILC. The differential cross section for the interaction $e^+e^- \to \gamma\mathcal{U}_V$ is given by

$$\frac{d\sigma_{\gamma\mathcal{U}}}{d\Omega} = \frac{1}{2s}\overline{|\mathcal{M}|^2}\frac{A_d}{16\pi^3\Lambda^2}\left(\frac{P_{\mathcal{U}}^2}{\Lambda^2}\right)^{(d-2)}E_\gamma dE_\gamma, \tag{12}$$

with

$$\overline{|\mathcal{M}|^2} = 2\lambda_{1e}^2 e^2\frac{u^2+t^2+2sP_{\mathcal{U}}^2}{ut}, \tag{13}$$

u, t, and s being the Mandelstam variables.

Then the total cross section can be written as

$$\frac{d\sigma_{\gamma\mathcal{U}}}{dx} = \int_{y_{\min}}^{y_{\max}}\frac{A_d}{(4\pi)^2}\left(\frac{\lambda_{1e}e}{\Lambda}\right)^2\left[\frac{s(1-x)}{\Lambda^2}\right]^{(d-2)} \times \frac{x^2+x^2y^2+4(1-x)}{x(1-y^2)}dy, \tag{14}$$

with $x = E_\gamma/E_{\mathrm{beam}}$ and $y = \cos\theta_\gamma$, θ_γ being the angle between the incident beam and the outgoing photon.

C. Coherent neutrino-nuclei scattering mediated by unparticles

When momentum transfer Q is small comparing with inverse nucleus size, $QR \leq 1$, a coherent neutrino-nucleus scattering can take place [19]. Since for most nuclei the typical inverse sizes are in the range from 25 to 150 MeV, the condition for full coherence in the neutrino-nuclei scattering is well satisfied for reactor neutrinos and other artificial neutrino sources.

There are currently several experimental proposals that intend to observe for the very first time this process [20–22], while other experimental setups have also been studied [23,24]. The potential of some of these experimental proposals for constraining new physics, such as nonstandard neutrino interactions [9,21] or a nonzero neutrino magnetic moment [21,25–27] has already been discussed.

Here we derive the coherent neutrino-nucleus scattering cross section with intermediate scalar unparticles, in analogy with the neutrino-electron scalar unparticle scattering cross section, and we find

$$\frac{d\sigma_{\mathcal{U}_S}^{\nu N}}{dT} = \frac{1}{\Lambda^{(4d-4)}}\frac{2^{(2d-6)}}{\pi E_\nu^2}[g_{0u}(d)(2Z+N) + g_{0d}(d)(Z+2N)]^2(m_AT)^{(2d-3)}(T+2m_A), \tag{15}$$

where T is the recoil energy of the entire nucleus target, Z and N are the number of protons and neutrons, respectively, of the detector nucleus target, and A is the mass number ($A = Z + N$). As in the neutrino-electron scattering case, the interference term is proportional to the neutrino mass and can be safely neglected.

The neutrino-nucleus coherent scattering cross section mediated by a vector unparticle has the form

$$\frac{d\sigma_{\mathcal{U}_V}^{\nu N}}{dT} = \frac{2^{(2d-5)}}{\pi\Lambda^{(4d-4)}}m_A(m_AT)^{(2d-4)}[g_{1u}(d)(2Z+N) + g_{1d}(d)(Z+2N)]^2\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_AT}{E_\nu^2}\right]. \tag{16}$$

In case of the flavor conserving process the interference between SM and vector unparticle fields is linearly proportional to the neutrino-unparticle couplings, as we show in the following expression:

$$\frac{d\sigma^{\nu N}_{\mathcal{U}_V-\mathrm{SM}}}{dT} = \frac{\sqrt{2}G_F}{\pi}\frac{[g_{1u}(d)(2Z+N)+g_{1d}(d)(Z+2N)]}{\Lambda^{(2d-2)}} \times 2^{d-1}m_A(m_AT)^{(d-2)}(g_V^pZ+g_V^nN) \times\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_AT}{E_\nu^2}\right], \quad (17)$$

where $g_V^{p,n}$ are the SM neutral current vector couplings of neutrinos with protons p and with neutrons n, defined as

$$g_V^p = \rho^{NC}_{\nu N}(\tfrac{1}{2}-2\hat{\kappa}_{\nu N}\hat{s}_Z^2)+2\lambda^{uL}+2\lambda^{uR}+\lambda^{dL}+\lambda^{dR},$$
$$g_V^n = -\tfrac{1}{2}\rho^{NC}_{\nu N}+\lambda^{uL}+\lambda^{uR}+2\lambda^{dL}+2\lambda^{dR}. \quad (18)$$

Here $\hat{s}_Z^2=\sin^2\theta_W=0.231\,20$, $\rho^{NC}_{\nu N}=1.0086$, $\hat{\kappa}_{\nu N}=0.9978$, $\lambda^{uL}=-0.0031$, $\lambda^{dL}=-0.0025$, and $\lambda^{dR}=2\lambda^{uR}=7.5\times10^{-5}$ are the radiative corrections given by the PDG [28]. In order to obtain both the SM as well as the interference term, Eq. (17), we have neglected the axial contribution since the ratio of the axial to the vector contributions is expected to be of the order $1/A$, A being the atomic number. We have also considered the axial and vector form factors equal to unity, which is a good approximation for $Q^2 \ll m_A^2$, where Q is the transferred momentum.

III. ANALYSIS AND RESULTS

With the cross sections obtained in the previous section, it is possible to obtain constraints on different unparticle parameters from the experimental data presented in the literature. In this section we report the constraints that we have derived from a χ^2 analysis applied to the relevant experiments.

A. Neutrino-electron scattering

We performed an analysis of the $\bar{\nu}_e e \to \bar{\nu} e$ considering the MUNU data. In order to estimate the constraints on the parameters d and $\lambda_0(\lambda_1)=\sqrt{\lambda^{e\beta}_{0\nu}\lambda_{0e}}(\sqrt{\lambda^{e\beta}_{1\nu}\lambda_{1e}})$ we compute the integral

$$\sigma=\int dT'\int dT\int dE_\nu \frac{d\sigma_{\mathcal{U}_{S,V}}}{dT}\lambda(E_\nu)R(T,T') \quad (19)$$

with $R(T,T')$ the energy resolution function for the MUNU detector. The relative energy resolution in this detector was found to be 8% and it scales with the power 0.7 of the energy [29].

We use an antineutrino energy spectrum $\lambda(E_\nu)$ given by

$$\lambda(E_\nu)=\sum_{k=1}^{4}a_k\lambda_k(E_\nu), \quad (20)$$

where a_k are the abundances of ^{235}U ($k=1$), ^{239}Pu ($k=2$), ^{241}Pu ($k=3$), and ^{238}U ($k=4$) in the reactor; $\lambda_k(E_\nu)$ is the corresponding neutrino energy spectrum which we take from the parametrization given in [30], with the appropriate fuel composition. For energies below 2 MeV there are only theoretical calculations for the antineutrino spectrum which we take from Ref. [31].

With this formula we can compute the number of events expected in MUNU in the case of a SM cross section, as well as in the case of an extra contribution due to unparticle physics, for the parameters d and λ_0. We are considering $\Lambda = 1$ TeV.

The expected number of events in the case of an unparticle contribution to the neutrino-electron scattering $N_i^{\mathrm{theo}}=N_i^{\mathrm{SM}}+N_i^{\mathcal{U}_{S,V}}$, can be compared with measured number of events per day, $N^{\mathrm{exp}}=(1.07\pm0.34)$ events/day, reported by the MUNU collaboration [29]. We show the results of our analysis in Fig. 1, where the maximum allowed values of the unparticle parameters are shown at 90% C.L. We also show in the same plot the results obtained in previous analysis [14].

The same analysis was done for the vectorial case and the result is shown in the same Fig. 1. We show both the result that considers the interference term ($\nu_e e \to \nu_e e$) as well as the case where such an interference term is absent ($\nu_e e \to \nu_{\mu,\tau} e$). Finally, we also show previous reported results from Ref. [14] for comparison.

In order to illustrate the sensitivity of future neutrino-electron scattering experiments and to show the behavior of the different unparticle interactions, we show in Fig. 2 the differential cross section antineutrino scattering off electrons. Several experimental proposals plan to perform an accurate measurement of this process [24,32,33]. It is

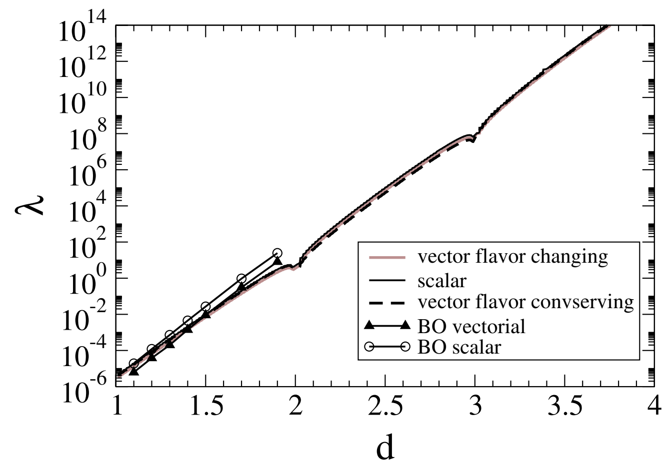

FIG. 1 (color online). Limits on the parameters d and $\lambda_{0,1}=\sqrt{\lambda^{e\beta}_{0,1\nu}\lambda_{0,1e}}$ (90% C.L.) from the MUNU experiment for the scalar unparticle case (black solid line) and for the vector unparticle cases, both for flavor changing currents (gray solid line) and for the flavor conserving case (dashed line). Previous bounds obtained by Balantekin and Ozansoy (BO) [14] (dots and triangles) are shown for comparison. The present analysis based on the MUNU data gives stronger constraints on $\lambda_{0,1}$ for values of $d > 1.5$.

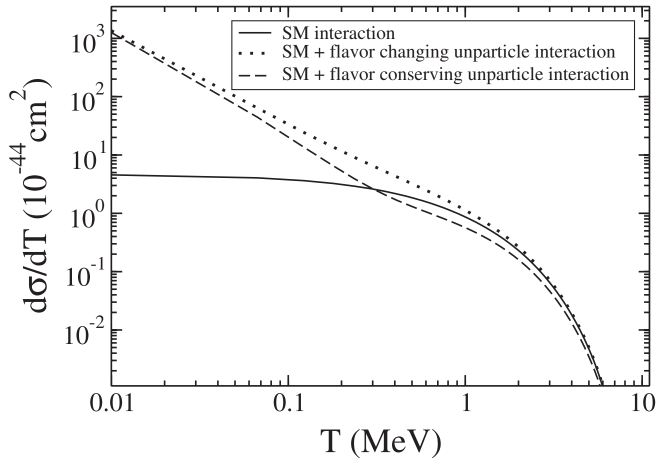

FIG. 2. Differential cross section for $\nu - e$ scattering for the SM case and for the vector unparticle case. We show both the flavor conserving as well as the flavor changing case. In the flavor conserving interaction mediated by unparticles, the negative interference term gives a different spectral shape. The effective coupling $\lambda_1 = \sqrt{\lambda_{1\nu}^{\alpha\beta}\lambda_{1e}}$ was fixed to $\lambda_1 = 5.5 \times 10^{-5}$ and $d = 1.2$.

clear from this figure that besides the increase in the expected number of events, the shape of the spectrum will also change in different energy regions.

B. Limits from single-photon production with unparticles

The real emission of an unparticle plus a single photon in electron-positron collisions at CERN LEP has the same signature of missing energy carried by neutrino pairs plus single-photon production.

The best data on single-photon production plus missing energy has been collected by the four CERN LEP experiments: ALEPH, DELPHI, L3, and OPAL [34–36]. We analyze this data considering the sum of the cross sections for single-photon production with neutrino pairs and an unparticle.

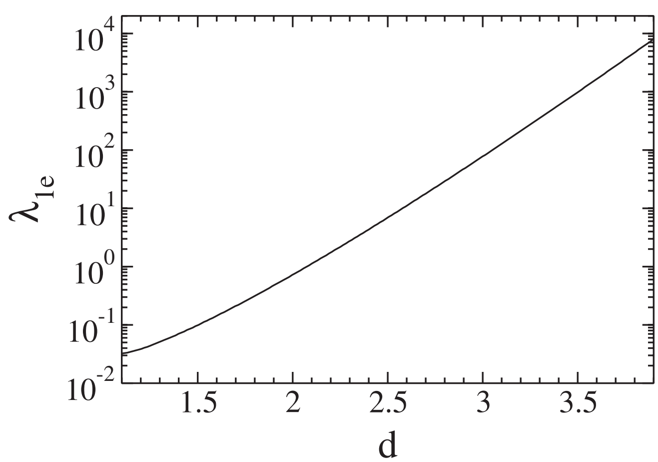

FIG. 3. Limits on the parameters d and λ_{1e} for the unparticle analysis of the four CERN LEP experiments at 90% C.L. considering $\Lambda = 1$ TeV.

TABLE I. Limits on Λ from single-photon production data of $\sigma(e^+e^- \to \gamma \mathcal{U}_V)$ from CERN LEP data, $\lambda_{1e} = 1$, 95% C.L. In the last column we show possible future bounds for a center of mass energy of $\sqrt{s} = 500$ GeV.

d	Λ (TeV) from [37]	Λ (TeV) Our analysis	Λ (TeV) future ILC
2.0	1.35	1.1	1.69
1.8	4	3.1	4.25
1.6	23	22.1	17.9
1.4	660	612	257

Disagreements between our calculations and the Monte Carlo results quoted by the CERN LEP collaborations are included as an additional theoretical uncertainty which we have added in quadrature in the calculation of our errors [7]. Because of the small systematic error they have, we can assume that all of them are independent, with no correlation between them. In the case of the more recent DELPHI data analysis [34], we perform our analysis considering the cross section reported instead of the number of events.

The results of our analysis are presented in Fig. 3 and in Table I. In Table I we show the comparison of our results with the previous results obtained in Ref. [37] and we also compare these results with a possible future limit that can be obtained with ILC for a center of mass energy, $\sqrt{s} = 500$ GeV.

The analysis made in Ref. [37] considered the cross section limit of $\sigma \sim 0.2$ pb at 95% C.L. for the process $e^+e^- \to \gamma X$ obtained by L3 [36] under the cuts $E_\gamma > 5$ GeV, $|\cos\theta_\gamma| < 0.97$, and $\sqrt{s} = 207$ GeV. By fixing the coupling $\lambda_{1e} = 1$, bounds on the energy scale Λ are obtained for different values of d. Our limits are looser but more robust in the sense that we have used all CERN LEP experiments data and obtained the constraints from a χ^2 statistical analysis. ILC limits would be stronger for large d's, i.e., for $d > 1.8$.

C. Sensitivity of coherent neutrino-nucleus scattering

The coherent neutrino-nuclei scattering can be a great complementary tool in order to constrain physics beyond the standard model such as unparticle physics. As already mentioned, there are several experimental proposals that intend to observe this process [20–22]. To show the sensitivity of such experiments to unparticle parameters we consider for definiteness the TEXONO collaboration proposal which has started a program towards the measurement of the coherent $\nu - N$ scattering by using reactor neutrinos and 1 kg of an ''ultra-low-energy'' germanium detector (ULEGe) [20]. The number of expected events, neglecting for the moment the detector efficiency and

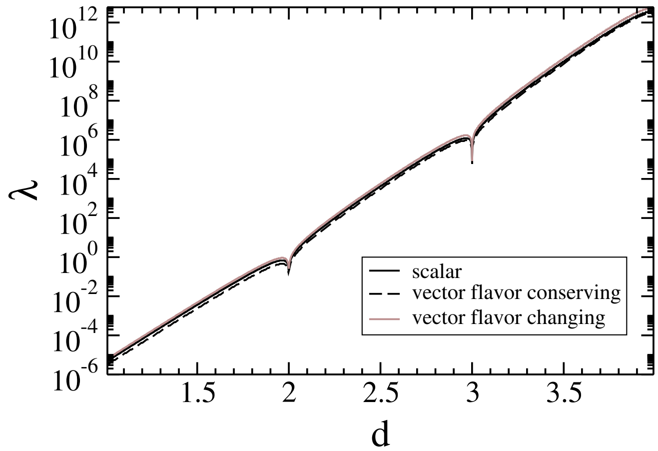

FIG. 4 (color online). Future sensitivity of the TEXONO proposal (90% C.L.) on the unparticle dimension d and the effective coupling λ. Scalar case corresponds to $\lambda = \sqrt{\lambda_{0\nu}^{e\beta}\lambda_{0d}}$ (black solid line). Vector flavor conserving for $\lambda = \sqrt{\lambda_{1\nu}^{ee}\lambda_{1d}}$ (dashed line) and vector flavor changing $\lambda = \sqrt{\lambda_{1\nu}^{e\beta}\lambda_{1d}}$, $\beta = \mu, \tau$ (gray solid line). Limits were done assuming $\lambda_{0,1u} = 0$. The flavor conserving case, which includes the interference term, is the most sensitive.

resolution, can be calculated by

$$N_{\text{events}}^{\text{SM}} = t\phi_0 \frac{M_{\text{detector}}}{m_A} \int_{E_{\min}}^{E_{\max}} dE_\nu \int_{T_{th}}^{T_{\max}(E_\nu)} dT \lambda(E_\nu) \frac{d\sigma_{\text{SM}}^{\nu N}}{dT} \times (E_\nu, T), \tag{21}$$

with t being the period of data acquisition, ϕ_0 the total neutrino flux, M_{detector} the total mass of the detector, $\lambda(E_\nu)$ the normalized neutrino spectrum, $E_{\max}$ the maximum neutrino energy, and T_{th} the detector energy threshold. The maximum nucleus' recoil energy depends on the nucleus mass m_A through the relation

$$T^{\max} = 2(E_\nu^{\max})^2/(m_A + 2E_\nu^{\max}).$$

For the TEXONO proposal we take a minimum threshold energy of $T_{\text{th}} = 400$ eV. We have estimated the sensitivity for the TEXONO proposal to constrain unparticle parameters by means of a χ^2 analysis

$$\chi^2 = \frac{(N_{\text{events}}^{\text{SM}} - N_{\text{events}}^{\mathcal{U}_{S,V}})^2}{\delta N_{\text{events}}^2}, \tag{22}$$

where we have calculated $N_{\text{events}}^{\mathcal{U}_{S,V}}$ exchanging the SM differential cross section in Eq. (21) by the cross section given in Eqs. (9) and (10), for the scalar and vectorial unparticles, respectively. In Fig. 4 we show the sensitivity of the coherent $\nu - N$ scattering for the scalar unparticle propagator. We have shown also the sensitivity for the case when the propagator has a vectorial structure. As we have discussed, in this case there is an interference between the scattering mediated by the vectorial unparticle propagator and the usual SM scattering mediated by the Z boson. We can see that the sensitivity becomes more stringent when this interference is included. In all the previous cases we have fixed the scale $\Lambda = 1$ TeV.

IV. DISCUSSION AND SUMMARY

So far, in Sec. III, we have derived the current bounds on the relevant unparticle's parameter by using the current available neutrino data from reactor and from CERN LEP experiments. We have also shown the future sensitivity for coherent neutrino-nucleus scattering. There are, however, other limits obtained from astrophysical observations. We would like to discuss three of them, namely, from the observation of supernova SN1987A neutrinos [38,39], from the tests of gravitational inverse square law (Eötvös-type or fifth force experiments) [40,41], and the limits obtained by the possible existence of new electronic long-range forces. We will emphasize that, despite these limits being much stronger than those coming from reactor and accelerator experiments, they are valid under certain assumptions and therefore the terrestrial limits shown here give an important complementarity.

The limits obtained from neutrinos coming from SN1987A in Refs. [38,39] were derived under the assumption that unparticles could freely escape supernova core, thus releasing a large amount of energy and therefore leading to a decrease of the duration of the neutrino burst during supernovae explosion. However, if the couplings are large enough this could cause trapping of unparticles in the supernova due to their interaction with the dense medium in the core, which therefore would relax the present constraints [38,39].

Other very strong constraints on unparticle interactions with the SM particles were obtained from experiments testing the Newtonian law of gravity [40,41] and positronium decays [42]. However, if the theory is not exactly scale invariant, or if scale invariance is broken at some scale smaller than a millimeter, thereby screening the long-range forces, then these limits will not apply [40,41,43]. Therefore, although we will consider in what follows values that are bigger than these constraints, they may well be allowed under the appropriate assumptions.

Finally, let us comment on the possibility that long-range forces could be originated by unparticles. In [44] it was found that solar neutrino data can constrain the vector and scalar unparticle interactions. The constraints obtained in [44] can be rewritten as

$$(\lambda_{0\nu}^{ee} - \lambda_{0\nu}^{\nu a})\left(\lambda_{0e} + \lambda_{0p} + \lambda_{0n}\left\langle\frac{Y_n}{Y_e}\right\rangle\right) \times \frac{\Gamma(d+1/2)\Gamma(d-1/2)}{2\pi^{2d}\Gamma(2d)(R_\odot\Lambda)^{2(d-1)}} < 6.8 \times 10^{-45}, \tag{23}$$

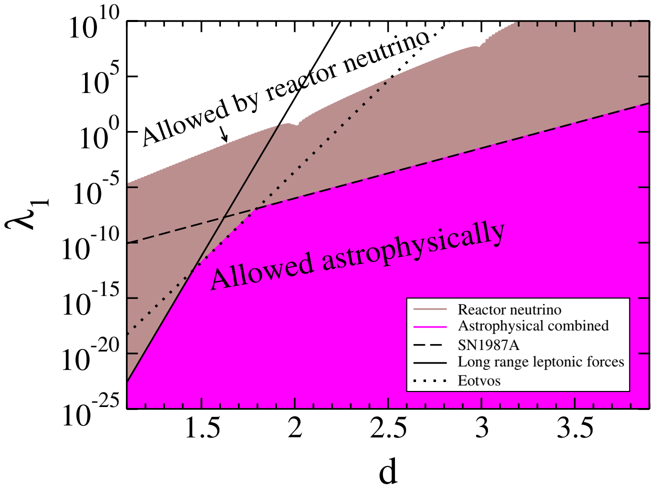

FIG. 5 (color online). Current constraints on vectorial unparticle couplings λ_1 and d from reactor neutrino $\nu - e$ elastic scattering (MUNU experiment). The current astrophysical limits are shown for comparison, although both for the SN1987A and the Eötvös case a different initial hypothesis should be considered (see text for details.)

$$(\lambda_{1\nu}^{ee} - \lambda_{1\nu}^{\nu a})\left(\lambda_{1e} + \lambda_{1p} + \lambda_{1n}\left\langle\frac{Y_n}{Y_e}\right\rangle\right) \times \frac{\Gamma(d+1/2)\Gamma(d-1/2)}{2\pi^{2d}\Gamma(2d)(R_\odot\Lambda)^{2(d-1)})} < 4.5 \times 10^{-53}, \qquad (24)$$

where $\lambda_{0,1\nu}^{\nu a} = \cos^2\theta_{23}\lambda_{0,1\nu}^{\mu\mu} + \sin^2\theta_{23}\lambda_{0,1\nu}^{\tau\tau}$, θ_{23} is the solar mixing angle. $Y_{n,e}$ are the relative number densities of neutrons and electrons, respectively, and $\langle\ldots\rangle$ means average along the neutrino trajectory. Bounds (23) and (24) are given at 3σ C.L.

Let us assume for the moment, and just as an illustrative example, that $\lambda_{0,1\nu}^{\nu a} = \lambda_{0p} = \lambda_{0n} = 0$. In this particular case we can see that the constraints (23) and (24) involve the same parameters that our parameter λ has shown in Fig. 1. We have also plotted this constraint (24) in Fig. 5 and we can see that, for this special case, indeed long-range forces are very restrictive for values of d close to one, while for $d > 2$ reactor neutrinos are more restrictive.

In Fig. 5 and Table II we report our limits on λ_1 for the vectorial unparticle case obtained by using the MUNU neutrino data (Sec. III A). For the Eötvös-type limit we have closely followed Ref. [40] with a different interpolation on β_k. Instead of a linear interpolation, we interpolated β_k as a function of $1/k$ and $1/k^2$ for the values reported in [45]. k is related with the unparticle parameter dimension d through the relation $k - 1 = 2d - 2$ [40]. The long-range force limits where obtained from Eq. (24) and for the limits from supernova cooling (SN1987A) we have used the limit obtained in Ref. [38]. Finally, we also show in the same table, the limits reported in [12] that were obtained by considering the recent Borexino data; please note that in this case the reported limits apply to the scalar coupling, but we show them for the sake of completeness.

We can summarize now the results shown in this work as follows:

(i) we have corrected the neutrino-electron cross sections and calculated the coherent neutrino-nucleus scattering cross sections for the unparticle case.

(ii) we have obtained the constraints on unparticle couplings with neutrinos and electrons coming from available reactor and accelerator experiments, specifically MUNU and CERN LEP data.

(iii) we have included into the analysis the interference term for the vector unparticle case of flavor conserving scattering and we have shown its relevance.

(iv) we have compared our results with astrophysical limits and have discussed that, although the astro-

TABLE II. Constraints on the vector coupling λ_1 from the neutrino-electron scattering experiment and from astrophysical limits. The confidence level considered in different reported results is different and therefore the comparison is qualitative. Besides, for the SN1987A and for the Eötvös case a different initial hypothesis should be considered (see text for details). For the sake of completeness, we show in the last column limits coming from solar data for the case of the λ_0 scalar coupling.

d	$\nu - e$ scattering	Eötvös	Long range	SN1987A	Solar ν's
1.1	2.0×10^{-5}	6.3×10^{-19}	2.8×10^{-23}	9.1×10^{-11}	1.1×10^{-5}
1.25	1.9×10^{-4}	1.6×10^{-16}	5.2×10^{-19}	4.0×10^{-10}	1.2×10^{-4}
1.5	9.7×10^{-3}	1.7×10^{-12}	5.7×10^{-12}	5.7×10^{-9}	7.3×10^{-3}
1.75	3.7×10^{-1}	2.6×10^{-8}	6.1×10^{-5}	7.4×10^{-8}	3.4×10^{-1}
2.1	40	1.1×10^{-2}	6.0×10^{5}	2.9×10^{-6}	100
2.25	713	4.2	1.0×10^{10}	1.3×10^{-5}	1127
2.5	5.5×10^{4}	4.8×10^{4}	1.1×10^{17}	1.8×10^{-4}	6.6×10^{4}
2.75	2.9×10^{6}	5.5×10^{8}	1.8×10^{24}	2.3×10^{-3}	3.5×10^{6}
3.1	1.2×10^{9}	3.3×10^{14}	1.1×10^{34}	9.9×10^{-2}	1.0×10^{9}
3.25	2.3×10^{10}	9.6×10^{16}	3.1×10^{38}	4.7×10^{-1}	1.1×10^{10}
3.5	2.1×10^{12}	1.5×10^{21}	3.2×10^{45}	6.1	6.7×10^{11}
3.75	1.1×10^{14}	1.9×10^{25}	3.3×10^{52}	87.2	3.5×10^{13}
3.9	1.1×10^{15}	6.2×10^{27}	5.8×10^{56}	414.3	4.0×10^{14}

physical constraints are stronger than the direct experimental bounds, they are based on some assumptions which may be violated and, therefore, both types of limits are relevant and complementary.

(i) we have found that reactor limits are stronger than Eötvös-type (fifth force) limits for values of $d > 2.55$ and stronger than the long-range leptonic force limits for values of $d > 1.95$. SN1987A limits are always stronger than the reactor limits.

(v) we have obtained CERN LEP limits derived from accounting for all four CERN LEP experiments and the sensitivity of ILC is also given.

(vi) we have estimated future sensitivity of coherent neutrino scattering experiments to the neutrino-quark unparticle interaction.

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