Neutrino-electron scattering in noncommutative space

\[^a\text{M. M. Ettefaghi} \, ^1\text{ and } ^b\text{T. Shakouri}\]

\(^a\) Department of Physics, The University of Qom, Qom 371614-6611, Iran.
\(^b\) Department of physics, Tafresh University, Tafresh, Iran.

Abstract

Neutral particles can couple with the \(U(1)\) gauge field in the adjoint representation at the tree level if the space-time coordinates are noncommutative (NC). Considering neutrino-photon coupling in the NC QED framework, we obtain the differential cross section of neutrino-electron scattering. Similar to the magnetic moment effect, one of the NC terms is proportional to \(\frac{1}{T}\), where \(T\) is the electron recoil energy. Therefore, this scattering provides a chance to achieve a stringent bound on the NC scale in low energy by improving the sensitivity to the smaller electron recoil energy.

PACS: 11.10.Nx, 12.60.Cn

\(^1\text{mettefaghi@qom.ac.ir} \)
1 Introduction

There exist strong evidences such as solar and atmospheric as well as long baseline accelerator and reactor neutrino measurements which imply finite neutrino masses and mixings [1]. The finite neutrino masses leads to the couplings of neutrinos with photons through loop corrections in the usual space-time. These properties of neutrinos can be explored using a number of possible physical processes involving a neutrino with a magnetic moment. Among these are the neutrino-electron scattering, spin-flavor precession in an external magnetic field, plasmon decay and the neutrino decay. For the first process, the magnetic moment contribution of neutrinos in the differential cross section of the neutrino-electron scattering is [2]

$$\frac{d\sigma_{MM}}{dT} = \frac{\pi\alpha^2}{m_e^2} \left[ \frac{1}{T} - \frac{1}{E_{\nu}} \right].$$

(1)

where $T$ is electron recoil energy and $\mu_\nu$ is neutrino magnetic moment which is expressed in unit of $\mu_B$. Clearly this contribution is dominant at the small recoil energies, i.e., the lower the smallest measurable recoil energy is, the smaller values of the magnetic moment can be probed. To perform such an experiment either solar or reactor neutrinos have been used. The MUNU [3] experiment at the Bugey reactor in France and TEXONO [4] at the Kuo-Sheng reactor in Taiwan have analyzed the recoil electron energy spectrum $dN/dT$ for very small recoil kinetic energies, $T \lesssim 1 MeV$. The limit on the neutrino magnetic moments of $\mu_{\bar{\nu}_e} < 7.4 \times 10^{-11} \mu_B$ at 90% confidence level was derived [5]. Moreover, using neutrino-electron scattering the experimental constraints on non-standard neutrino interactions and unparticle physics were explored recently by TEXONO collaboration [6]. In this paper we show that this experiment is appropriate to obtain stringent bound on the noncommutative scale in low energy.

Noncommutative (NC) quantum field theories have been considered in the recent decade extensively because of some motivations coming from string theory [7] and quantum gravity [8]. In the NC field theory one encounters new properties such as UV/IR mixing [9], Lorentz violation [10] and CP-violation [11]. The phenomenological aspects of the NC field theory at testable energy scales have been studied extensively:

- At the atomic scale, for instance, the Lamb shift in the hydrogen atom [12], the positronium hyperfine splitting [13] and the transitions in the Helium atom [14] were studied in the NC space-time. The best bound on the NC scale obtained at this scale is about 30GeV from the transitions in the Helium atom.

- At the electroweak scale, for instance, $Z \rightarrow \gamma\gamma$ [15], $Z \rightarrow l^+l^-$ and $W \rightarrow \nu l$
[16], quarkonia decay [17], top quark decay [18] and so on were studied in the NC standard model framework. In this scale an experimental bound on the NC scale about $141\text{GeV}$ was found by the OPAL collaboration using $e^+e^- \rightarrow \gamma\gamma$ at LEP [19].

- At the above the electroweak scale accessible in future experiment, the NC effects were explored for various processes such as $e^+e^-$ scattering [20], hadrons colliders [21] and photon-photon colliders [22].

Also the NC signatures were followed in the astrophysics and cosmology, for example see [23]. The usual bounds on the NC scale obtained from the mentioned considerations are about $1\text{TeV}$. However, there exist various candidates of new physics such as supersymmetry at this scale and searching for NC signals at the energies near this scale seems ambiguous. Therefore, the study of the NC signals which are dominant below the electroweak scale will be important. The NC field theories are constructed on the space-time coordinates which are operators and do not obey commutative algebra. In the case of canonical version of the NC space-time, the coordinates satisfy the following algebra:

$$\theta^{\mu\nu} = -i[\hat{x}^\mu, \hat{x}^\nu],$$

(2)

where a hat indicates a NC coordinate and $\theta^{\mu\nu}$ is a real, constant and antisymmetric matrix. To construct the NC field theory, according to the Weyl-Moyal correspondence, an ordinary function can be used instead of the corresponding NC one by replacing the ordinary product with the star product as follows:

$$f \star g(x, \theta) = f(x, \theta) \exp(i\frac{\partial}{2} \theta^{\mu\nu} \overrightarrow{\partial}_\mu \overrightarrow{\partial}_\nu)g(x, \theta).$$

(3)

Due to the above correspondence a neutral particle (as well as a charged particle) can couple with the $U(1)$ gauge field in the adjoint representation. Some effects of this new coupling were studied in the literature [24, 25, 26, 27]. In particular, in [25] the coupling between photons and left-(right-)handed neutrinos was considered. The usual requirement that any new energy-loss mechanism in globular stellar clusters should not excessively exceed the standard neutrino losses implies a scale of NC gauge theory above the scale of week interactions. In this paper, we study the effects of this new coupling of neutrinos on the neutrino-electron scattering. As we will see, the behavior of the NC corrections in terms of $T$ (electron recoil energy) is similar to the correction due to the neutrino magnetic moment which is dominant for the small electron recoil energy. Therefore, we compare the NC contribution in the neutrino-electron scattering.
with the standard model one for reactor neutrino whose energies are about 1MeV and for neutrinos whose energies are about 1GeV such as beta beam [28]. This paper is organized as follows: In Section two we review briefly the NC QED for neutral particles. In Section three the neutrino-electron scattering is discussed. Finally, we summarize our results in the last section.

2 Neutral particles in the NC QED

According to the Weyl-Moyal correspondence, Eq. (2), the usual products in $eA_\mu \psi$ where $e$, $A_\mu$, and $\psi$ are the coupling, the gauge field, and the matter field, respectively, are replaced by star products. This leads to an ambiguity in the ordering of fields: $eA_\mu \ast \psi$, $e\psi \ast A_\mu$, and $e(A_\mu \ast \psi - \psi \ast A_\mu)$. In the action, however, it has been shown that the two first couplings are the charge conjugations of each other, but the third one is the charge conjugation of itself [11]. Therefore, a neutral particle can have the third coupling and its covariant derivative is defined as follows:

$$\hat{D}_\mu \hat{\psi} = \partial_\mu \hat{\psi} - ie(\hat{A}_\mu \ast \hat{\psi} - \hat{\psi} \ast \hat{A}_\mu),$$

(4)

where hats on the fields are used to emphasize that these fields are defined in the NC space-time. We can write these NC fields in terms of the usual fields using corresponding Seiberg-Witten maps. The corresponding Seiberg-Witten maps up to the first order of $\theta$ are [29]

$$\hat{\psi} = \psi + \theta^{\mu\nu} A_\nu \partial_\mu \psi,$$

$$\hat{A}_\mu = A_\mu + e\theta^{\nu\rho} A_\rho [\partial_\nu A_\mu - \frac{1}{2} \partial_\mu A_\rho].$$

(5)

Hence, the action describing a neutral fermion field in the NC QED framework is

$$S = \int d^4x (\bar{\hat{\psi}} i\gamma^\mu \hat{D}_\mu \hat{\psi} - m\bar{\hat{\psi}} \ast \hat{\psi}).$$

(6)

After using above Seiberg-Witten maps and expanding the star product up to the first order of $\theta$, this action can be written as follows [25]:

$$S = \int d^4x (\bar{\psi} i\gamma^\mu \partial_\mu - m) - \frac{e}{2} \theta^{\nu\rho} (i\gamma^\mu (F_{\nu\rho} \partial_\mu + F_{\rho\mu} \partial_\nu + F_{\mu\nu} \partial_\rho) - mF_{\nu\rho}) \psi,$$

(7)

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The NC induced photon-neutrino vertex in the case of massless left-handed neutrino is

$$\Gamma^\mu (\nu \bar{\nu} \gamma) = -e\theta^{\mu\nu\rho} k_\nu q_\rho \left(\frac{1 - \gamma^5}{2}\right),$$

(8)
where $\theta^{\mu\nu\rho} = \theta^{\mu\nu}\gamma^\rho + \theta^{\mu\rho}\gamma^\nu + \theta^{\nu\rho}\gamma^\mu$. Since the expansion of the action in terms of $\theta$ is truncated up the first order of $\theta$, it is permissible to apply this theory for the energies below NC scale.

The Weyl-Moyal correspondence leads to some restrictions on NC gauge theories termed as NC gauge theory no-go theorem. These restrictions cause one to have some problems for constructing the NC standard model [30]. Until now, two approaches have been suggested to solve these problems. In one of them, the gauge group is restricted to $U(n)$ and the symmetry group of the standard model is achieved by the reduction of $U(3) \times U(2) \times U(1)$ to $SU(3) \times SU(2) \times U(1)$ by an appropriate symmetry breaking [31]. In the other approach, the $SU(n)$ gauge group in the NC space-time can be achieved via Seiberg-Witten map [29]. Hence, the NC standard model is constructed through replacing the usual products and fields, respectively, by star products and NC fields which can be written in terms of the usual fields using the corresponding Seiberg-Witten maps [32]. The NC standard model based on the $U(3) \times U(2) \times U(1)$ gauge group incorporates directly a coupling between photon and left-handed neutrinos. But the coupling between the left-handed neutrinos and photon cannot be accommodated in the NC standard model based on the $SU(3) \times SU(2) \times U(1)$ gauge group since the left-handed neutrinos are involved in the $SU(2)$ gauge theory [26]. The right-handed neutrinos which are singlet under the standard model gauge transformation can be added and couple directly with photon in both version of the NC standard model.

### 3 Neutrino-electron scattering

We are interested in the first order of NC corrections on the cross section of the neutrino-electron scattering. In the usual space-time, $\nu_\mu + e \rightarrow \nu_\mu + e$, where $\nu_\mu$ stands for either muon neutrino or antimuon neutrino, proceeds solely via neutral current channel (via $Z_0$ exchange) while $\nu_e + e \rightarrow \nu_e + e$ proceeds via both neutral and charged current channels (via both $Z_0$ and $W^\pm$ exchange). Hence, the corresponding cross sections are proportional to $G_F^2$. In the NC standard model, the interference of a standard model diagram with a diagram where one electroweak vertex is replaced by the first order in $\theta$ is zero. That is why there is $\frac{\pi}{2}$ phase difference between the usual terms and the first order of $\theta$ NC terms [32] and it causes $M_1^* M_2 + M_1 M_2^*$ to be zero in the case of massless neutrinos. Therefore, the leading order term of the NC standard model corrections on the neutrino-electron scattering is proportional to $G_F^2 \theta^2$. However, when we include the NC induced photon-neutrino coupling, there exists a new channel at the tree level which proceeds via photon exchange. The interference between this new
Table 1: Standard model $a$ and $b$ parameter values for the differential cross-section, given by Eq. (9). Here $s = \sin \theta_W$ where $\theta_W$ is the electroweak mixing angle.

channel and electroweak channels is also zero and the first order of the NC corrections due to the photon exchange channel is proportional to $\theta^2$. In fact the leading order term of the NC correction for neutrino-electron scattering is proportional to $\theta^2$ in both NC QED and NC standard model framework. However, the latter is suppressed by a factor $G_F^2$ in comparison with the former.

In the standard model, the differential cross sections for all neutrinos-electron scattering are given by [34]

$$
\frac{d\sigma_l}{dT} = \frac{2G_F^2m_e}{\pi E_\nu^2}(a^2E_\nu^2 + b^2(E_\nu - T)^2 - abm_eT),
$$

where subscript $l$ refers to neutrino flavors and $E_\nu$ and $T$ stand for the energy of the incident neutrino and the kinetic energy of the recoil electron, respectively. $a$ and $b$ are process-dependent parameters and are given by table (1) as functions of the weak mixing angel, $\theta_W$.

Using Eq. (8), we can write the Feynman amplitude of the NC QED contribution to the neutrino-electron scattering as follows:

$$
-iM_{NC} = \frac{e^2}{2q^2} [\bar{u}(p')\gamma^\mu u(p)][\bar{u}(k')\gamma^\nu k'q'^\mu(1 - \gamma^5)u(k)].
$$

Unitarity is satisfied for $\theta_{0i} = 0$ and $\theta_{ij} \neq 0$ [33]. Hence, let us assume $\theta_{0i} = 0$ and define $\vec{\theta} = (\theta_{23}, \theta_{31}, \theta_{12})$. Also we ignore neutrino mass. Summing over initial and averaging over final spin stats, one can obtain

$$
|M_{NC}|^2 = \frac{32e^4}{q^4} \left(\vec{\theta} \cdot (\vec{k} \times \vec{k}')\right)^2 \{(p.k)(p'.k') + (p.k')(p'.k) - m_e^2(k.k')\},
$$

in which $\theta_{\mu\nu}k^\mu k'^\nu = \vec{\theta} \cdot (\vec{k} \times \vec{k}')$ and Dirac equation for neutrinos, $\not{k}u(k) = 0$ and $\bar{u}(k')\not{k}' =
0, are used. We choose the following orientations for the lab frame:

\[
P = (m_e, 0, 0, 0),
\]

\[
k = (E_\nu, 0, 0, E_\nu),
\]

\[
p' = (T + m_e, |\vec{p}'| \sin \alpha \cos \phi, |\vec{p}'| \sin \alpha \sin \phi, |\vec{p}'| \cos \alpha),
\]

\[
k' = (E_\nu - T, -|\vec{p}'| \sin \alpha \cos \phi, -|\vec{p}'| \sin \alpha \sin \phi, E_\nu - |\vec{p}'| \cos \alpha),
\]

\[
\vec{\theta} = (\theta \sin \lambda, 0, \theta \cos \lambda).
\] (12)

After averaging over \( \lambda \), the contribution of the NC QED to the differential cross section of the neutrino-electron scattering is obtained as follows:

\[
\frac{d\sigma_{NC}}{dT} = \frac{e^4 E_\nu^2 \theta^2}{16\pi} \left[ \frac{1}{T} - \frac{2}{E_\nu} + \frac{3T - 2m_e}{2E_\nu^2} - \frac{T^2 - 2m_e T}{2E_\nu^4} - \frac{m_e T^2}{4E_\nu^4} (1 - \frac{m_e}{E_\nu}) \right].
\] (13)

The first term of this equation is dominant at low recoil energy of electron, similar to the contribution of the neutrino magnetic moment, see Eq. (1). Explicitly, the NC QED contribution will exceed the standard model one for recoil energies

\[
\frac{T}{m_e} < \frac{\pi^2 \alpha^2 E_\nu^2 \theta^2}{G_F^2 m_e^2} = \frac{\pi^2 \alpha^2 E_\nu^2}{G_F^2 m_e \Lambda_{NC}^2},
\] (14)

where \( \Lambda_{NC} = \frac{1}{\sqrt{\theta}} \). For example, let us consider electron antineutrinos with energies up to about 10 MeV which are emitted by nuclear reactors. The exact energy spectrum depends on the specific fuel composition of the reactor. For instance, the energy spectrum of neutrinos coming from the fissioning of \(^{235}\text{U} \) is approximately given by [35]

\[
\frac{dN_\nu}{dE_\nu} \sim \exp(0.870 - 0.160 E_\nu - 0.0910 E_\nu^2),
\] (15)

where the antineutrino energy, \( E_\nu \), is given in MeV. Now, the relevant quantity for the number of neutrino-electron elastic scattering events within the interval \([T, T + dT]\) is the cross section folded with the above energy spectrum and is given by

\[
\langle \frac{d\sigma}{dT} \rangle = \int_{E_\nu^{min}}^{\infty} \frac{dN_\nu}{dE_\nu} \frac{d\sigma}{dE_\nu} dE_\nu,
\] (16)

where \( E_\nu^{min} = 0.5(T + \sqrt{T^2 + 2Tm_e}) \). The behavior of \( \langle \frac{d\sigma}{dT} \rangle \) and \( \langle \frac{d\sigma_{NC}}{dT} \rangle \) for \( \Lambda_{NC} \) equals 500 GeV and 1 TeV versus \( T \) in the range 0.01 MeV \( \leq T \leq 10 \) MeV is depicted in Figure 1. For the NC scale about 500 GeV, the NC contribution is more than the commutative one for \( T < 0.1 \) MeV. Therefore, using an analysis similar to TEXONO [5], one can obtain a bound of a few hundred of GeV on the NC scale. It is noticeable
Figure 1: The differential neutrino-electron cross section versus the electron recoil energy in $E_\nu$ of the order of a few $MeV$ (reactor neutrino). Black (solid), blue (dot), and red (dashed) curves represent the contributions of the standard model, the NC QED with $\Lambda_{NC} = 500 GeV$, and the NC QED with $\Lambda_{NC} = 1 TeV$, respectively.

that this bound on the NC scale is obtained by an experiment at energy of a few of $MeV$. However one can obtain more stringent bounds if the sensitivity to the smaller electron recoil energy is improved.

Moreover, there is a difference between the contribution of the NC QED and the contribution of the magnetic moment to the cross section of the neutrino-electron scattering; $\frac{d\sigma_{NC}}{dT}$ is proportional to $E_\nu^2$ and grows rapidly with energy. Hence, the NC contribution can be more significant in higher energies. For instance, we contrast $\frac{d\sigma_{\bar{\nu}e}}{dT}$ and $\frac{d\sigma_{NC}}{dT}$ at $E_\nu = 2 GeV$ and $\Lambda_{NC} = 1 TeV$ in Figure 2. Therefore, using neutrino beams with energy about 1$GeV$ such as beta beam neutrinos [28], one can obtain a bound on $\Lambda_{NC}$ more stringent than 1$TeV$ which is achievable by future linear accelerators such as LHC.

4 conclusion

Neutrino-electron scattering is one of the various processes which can be used to study the neutrino electromagnetic properties. In the NC field theory neutrinos, as well as

\[ \frac{d\sigma_{\nu e}}{dT} \] is proportional to $E_\nu^2$ and grows rapidly with energy. Hence, the NC contribution can be more significant in higher energies. For instance, we contrast $\frac{d\sigma_{\bar{\nu}e}}{dT}$ and $\frac{d\sigma_{NC}}{dT}$ at $E_\nu = 2 GeV$ and $\Lambda_{NC} = 1 TeV$ in Figure 2. Therefore, using neutrino beams with energy about 1$GeV$ such as beta beam neutrinos [28], one can obtain a bound on $\Lambda_{NC}$ more stringent than 1$TeV$ which is achievable by future linear accelerators such as LHC.

It seems to conflict with unitarity theorem. However, we should remind that the corresponding Lagrangian has been expanded in terms of NC parameter, $\theta$. Actually, the region where the $\theta$-expansion is well defined is restricted to $\theta^{\mu\nu}p^\mu q^\nu < 1$ or $\frac{E_{\nu}}{\Lambda_{NC}} < 1$ where $E = \sqrt{s}$ is the energy of the system.
Figure 2: The differential neutrino-electron cross section versus the electron recoil energy in $E_\nu$ of the order of a few GeV. Black (solid), and red (dot) curves represent the contributions of the standard model, and the NC QED with $\Lambda_{NC} = 1 TeV$, respectively.

the others neutral and charged particles, can have new electromagnetic interactions. Namely, neutrinos can couple with photon through adjoint representation in the NC QED. In this paper we have calculated the NC QED corrections on the neutrino-electron scattering. This scattering is exceptional from the others NC phenomenologies in the sense that the behavior of the NC QED contributions in terms of electron recoil energy is similar to that of the neutrino magnetic moments in the commutative space-time, i.e., one of NC correction terms is proportional to the inverse of the electron recoil energy. In contrast to the linear accelerators in which we need higher energy to find more stringent bound on the NC scale, for neutrino-electron scattering the crucial quantity is the minimum electron recoil energy accessible to the experiment. With current Experiments such as TEXONO [4], in which reactor neutrinos with energy about 1MeV are used, one can obtain a bound about a few hundred of GeV.

Acknowledgement: Authors would like to thank M. Hghaighat and R. Moazemi for reading the manuscript and their useful suggestions. The financial support of the University of Qom research council is acknowledged.

References

[1] Y. Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998); 81, 1158 (1998); S. Fukuda et al., Phys. Lett. B 539, 179 (2002); M. B. Smy et al., Phys. Rev. D 69, 011104
(2004); Y. Ashie et al., Phys. Rev. Lett. 93, 101801 (2004). For a recent review, see C.W. Walter, [arXiv:0802.1041], and references therein.

[2] A. B. Balantekin, AIP Conf. Proc. 847, 128 (2006) [arXiv:hep-ph/0601113].

[3] Z. Daraktchieva et al. [MUNU Collaboration], Phys. Lett. B 615, 153 (2005).

[4] H. B. Li et al. [TEXONO Collaboration], Phys. Rev. Lett. 90, 131802 (2003).

[5] H. T. Wong et al. [TEXONO Collaboration], Phys. Rev. D 75, 012001 (2007).

[6] M. Deniz et al. [TEXONO Collaboration], Phys. Rev D 82, 033004 (2010).

[7] M.R. Douglas and N.A. Nekrasov, Rev. Mod. Phys. 73, 9772002.

[8] X. Calmet, M. Graesser, and S.D.H. Hsu, Phys. Rev. Lett. 93, 211101 (2004).

[9] S. Minwalla, M. van Raamsdonk and N. Seiberg, JHEP 0002, 020 (2000); A. Matusis, L. Susskind and N. Toumbas, JHEP 0012, 002 (2000).

[10] S. M. Carroll, J. A. Harvey, V. A. Kostelecky, C. D. Lane, and T. Okamoto, Phys. Rev. Lett. 87, 141601 (2001).

[11] M.M. Sheikh-Jabbari, Phys. Rev. Lett. 84, 5265 (2000); P. Aschieri, B. Jurco, P. Schupp, and J. Wess, Nucl. Phys. B651, 45 (2003).

[12] M. Chaichian, M. M. Sheikh- Jabbari, and A. Tureanu, Phys. Rev. Lett. 86, 2716 (2001); A. Stern, Phys. Rev. Lett. 100, 061601 (2008).

[13] M. Haghighat, S. M. Zebarjad and F. Loran, Phys. Rev. D. 66, 016005 (2002).

[14] M. Haghighat and F. Loran, Phys. Rev. D. 67, 096003 (2003).

[15] M. Buric, D. Latas, V. Radovanovic and J. Trampetic, Phys. Rev. D75, 097701 (2007).

[16] E. O. Iltan, Phys. Rev. D 66, 034011 (2002).

[17] B. Melic, K. Passek-Kumericki and J. Trampetic, Phys. Rev. D72, 054004 (2005); Phys. Rev. D72, 057502 (2005); C. Tamarit, and J. Trampetic, Phys. Rev. D 79, 025020 (2009).
[18] N. Mahajan, Phys. Rev. D 68, 095001 (2003); M. Mohammadi Najafabadi, Phys. Rev. D74, 025021 (2006); M. Mohammadi Najafabadi, Phys. Rev. D77, 116011 (2008).

[19] G. Abbiendi et al. [OPAL collaboration], Phys. Lett. B 568, 181 (2003).

[20] J. L. Hewett, F. J. Petriello and T. G. Rizzo, Signals for non-commutative interactions at linear colliders, Phys. Rev. D 64, 075012 (2001); P. K. Das, N. G. Deshpande, and G. Rajasekaran, Phys. Rev. D77, 035010 (2008); J. i. Kamoshita, Probing noncommutative space-time in the laboratory frame, Eur. Phys. J. C 52, 451 (2007); Y. Liao and C. Dehne, Some phenomenological consequences of the time-ordered perturbation theory of QED on noncommutative spacetime, Eur. Phys. J. C 29, 125 (2003); M. Haghighat, N. Okada, and A. Stern, Phys. Rev. D 82, 016007 (2010).

[21] A. Alboteanu, T. Ohl and R. Ruckl, Phys. Rev. D74, 096004 (2006).

[22] T. Ohl, and J. Reuter, Phys. Rev. D 70, 076007 (2004).

[23] M. M. Ettefaghi, Phys. Rev. D79, 065022 (2009); M. Haghighat, Phys. Rev. D79, 025011 (2009); R. Horvat and J. Trampetic, Phys. Rev. D79, 087701 (2009); E. Bavarsad, M. Haghighat, Z. Rezaei, R. Mohammadi, I. Motie, and M. Zarei, Phys. Rev. D 81, 084035 (2010).

[24] H. Grosse, and Y. Liao, Phys. Lett. B520, 63 (2001); H. Grosse, and Y. Liao, Phys. Rev. D64, 115007 (2001).

[25] P. Schupp, J. Trampetic, J. Wess and G. Raffelt, Eur. Phys. J. C36, 405 (2004).

[26] M. Haghighat, M. M. Ettefaghi and M. Zeinali, Phys. Rev. D73, 013007 (2006).

[27] M. M. Ettefaghi, and M. Haghighat, Phys. Rev. D77, 056009 (2008).

[28] C. Albright et al. [Neutrino Factory/Muon Collider Collaboration], physics/0411123.

[29] J. Madore, S. Schraml, P. Schupp, and J. Wess, Eur. Phys. J. C 16, 161 (2000); B. Jurco, S. Schraml, P. Schupp, and J. Wess, Eur. Phys. J. C 17, 521 (2000); B. Jurco, L. Moller, S. Schraml, P. Schupp, and J. Wess, Eur. Phys. J. C 21, 383 (2001); L. Moller, J. High Energy Phys. 10, 063 (2004); M. M. Ettefaghi and M. Haghighat, Phys. Rev. D75, 125002 (2007).
[30] M. Chaichian, P. Presnajder, M. M. Sheikh-Jabbari, and A. Tureanu, Phys. Lett. B 526, 132 (2002).

[31] M. Chaichian, P. Presnajder, M. M. Sheikh-Jabbari, and A. Tureanu, Eur. Phys. J. C29, 413(2003).

[32] X. Calmet, B. Jurčo, P. Schupp, J. Wess and M. Wohlgenannt, Eur. Phys. J. C23, 363 (2002); B. Melić, K. Passek-Kumerički, J. Trampetić, P. Schupp and M. Wohlgenannt, Eur. Phys. J. C42, 483(2005).

[33] J. Gomis and T. Mehen, Nucl. Phys. B 591, 265 (2000).

[34] A. D. Gouvea, and J. Jenkins, Phys. Rev. D74, 033004 (2006); W. J. Marciano, and Z. Parsa, J. Phys. G29, 2629 (2003); A. B. Balantekin, and K. O. Ozansoy, Phys. Rev. D76, 095014 (2007).

[35] P. Vogel and J. Engel, Phys. Rev. D 39, 3378 (1989).