Nonstandard neutrino interactions in $K^+ \to \pi^+ \nu\bar{\nu}$ and $D^+ \to \pi^+ \nu\bar{\nu}$ decays

Chuan-Hung Chen,[1,2,*] Chao-Qiang Geng,[3,4,†] and Tzu-Chiang Yuan[3,‡]

[1]*Department of Physics, National Cheng-Kung University, Tainan 701, Taiwan*
[2]*National Center for Theoretical Sciences, Taiwan*
[3]*Department of Physics, National Tsing-Hua University, Hsinchu 300, Taiwan*
[4]*Theory Group, TRIUMF, 4004 Wesbrook Mall Vancouver, British Columbia V6T 2A3, Canada*

(Received 21 March 2007; published 30 April 2007)

We study the contributions of the nonstandard neutrino interactions to the rare meson decays of $K^+ \to \pi^+ \nu\bar{\nu}$ and $D^+ \to \pi^+ \nu\bar{\nu}$. We show that both decays could provide strong constraints on the free parameters in the nonstandard neutrino interactions. We point out that the branching ratio of $D^+ \to \pi^+ \nu\bar{\nu}$ could be at the level of 10^{-8}.

DOI: 10.1103/PhysRevD.75.077301 PACS numbers: 14.60.Pq, 13.15.+g, 14.60.St

It has been widely anticipated to have new physics beyond the standard model (SM) in the neutrino sector due to the results of atmospheric and solar neutrino oscillations experiments [1]. In particular, it has been proposed to have new effective four-fermion interactions involving neutrinos, called nonstandard neutrino interactions (NSIs) [2–5], given by [6]

$$\mathcal{L}_{\rm eff}^{\rm NSI} = -2\sqrt{2}G_F \varepsilon^{fP}_{\ell\ell'}(\bar{\nu}_\ell \gamma_\mu L \nu_{\ell'})(\bar{f}\gamma^\mu P f), \qquad (1)$$

where the index of $\ell(\ell')$ corresponds to the light neutrino flavor, f denotes a charged lepton or quark in the first generation, and $P = L$ or R with $L(R) = (1 \mp \gamma_5)/2$. It has been shown that the NSIs would be compatible with the oscillation effects along with some new features in various neutrino searches [7–9]. The experimental constraints on NSIs have been studied in Refs. [6,10,11]. In particular, the authors in Ref. [6] also have pointed out that the lepton flavor violating decays of $\mu \to 3e$, $\tau \to (e, \mu)ee$, $\tau \to (e, \mu)M$ with $M = \rho$ or π, and the $\mu - e$ conversion on nuclei could be induced through one-loop effects and give some stringent constraints on the parameters of $\varepsilon^{fP}_{\ell\ell'}$ in Eq. (1). Explicitly, $\varepsilon^{fP}_{\mu e}$ and $\varepsilon^{fP}_{\tau\ell}(\ell = e, \mu)$ are limited to be less than 10^{-3} and order of 1, respectively. On the other hand, for the flavor diagonal NSIs in the first two generations, $\varepsilon^{fP}_{ee,\mu\mu}$ are constrained by the tree level processes in the low energy scattering experiments and could be limited at the level of $O(10^{-3})$ in future $\sin^2\theta_W$ experiments. For the third generation, $\varepsilon^{fP}_{\tau\tau}$ is presently bounded to be order of 1 by the LEP experiments, but its future limit can be improved slightly to be $O(0.3)$ [6] from KamLAND [12] and solar neutrino data [13,14]. Note that although the constraints on the parameters of $\varepsilon^{fP}_{\tau\ell}(\ell = e, \mu)$ can be given by the precision measurements on $\sin^2\theta_W$ at neutrino factories but the bounds can only be $O(10^{-2})$ [6,15].

In this brief report, we will study two new processes of $K^+ \to \pi^+ \nu\bar{\nu}$ and $D^+ \to \pi^+ \nu\bar{\nu}$ in the framework of the NSIs. We will show that the parameters involving τ neutrino in $\varepsilon^{uL}_{\ell\ell'}$ could be limited to be less than 10^{-2} by the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. We will also display the branching ratio of $D^+ \to \pi^+ \nu_\ell \bar{\nu}_{\ell'}$ could be at the level of 10^{-8} due to the NSI, which could be accessible to BESIII [16].

We start with the decay of $K^+ \to \pi^+ \nu\bar{\nu}$. Since we are not going to deal with CP violation, we will skip the discussion of the CP violating mode of $K_L \to \pi^0 \nu\bar{\nu}$, which is nevertheless interesting on its own [17]. It is well known that at the quark level, the effective Hamiltonian for $s \to d\nu\bar{\nu}$ in the SM is given by [18]

$$H = \frac{G_F}{\sqrt{2}} \frac{\alpha_{em}}{2\pi \sin^2\theta_W} \sum_{\ell=e,\mu,\tau} (V^*_{cs} V_{cd} X^\ell_{NL} + V^*_{ts} V_{td} X(x_t)) \times (\bar{s}d)_{V-A}(\bar{\nu}_\ell \nu_\ell)_{V-A}, \qquad (2)$$

where $(\bar{f}f')_{V-A} = \bar{f}\gamma_\mu(1-\gamma_5)f'$, X^ℓ_{NL} denotes the charm quark contributions, and $X(x_t)$ is the loop integral of the top-quark contribution given by

$$X(x_t) = \eta_X \frac{x_t}{8}\left[\frac{x_t + 2}{x_t - 1} + \frac{3x_t - 6}{(x_t - 1)^2} \ln x_t\right], \qquad (3)$$

with $x_t = m_t^2/m_W^2$ and $\eta_X = 0.985$ being the QCD short-distance correction. The SM prediction for $BR(K^+ \to \pi^+ \bar{\nu}\nu)_{SM}$ at the next-to-next-to-leading order is found to be $(8.0 \pm 1.1) \times 10^{-11}$ [19], which is smaller than the data of $BR(K^+ \to \pi^+ \nu\bar{\nu})_{\exp} = (1.5^{+1.3}_{-0.9}) \times 10^{-10}$ [20]. If future data still keep the tendency toward a larger central value, due to the small theoretical uncertainties [21], it should indicate the existence of new physics. Note that with $BR(K^+ \to \pi^+ \nu\bar{\nu}) \sim 10^{-10}$ it is possible to collect 40 signal events per year at the NA48/3 experiment of CERN-SPS [22,23].

The NSIs in Eq. (1) also can induce the process $s \to d\nu_\ell \bar{\nu}_{\ell'}$ through a one-loop diagram, as illustrated in Fig. 1. As a result, the following four-fermion interaction can be induced:

*Electronic address: physchen@mail.ncku.edu.tw
†Electronic address: geng@phys.nthu.edu.tw
‡Electronic address: tcyuan@phys.nthu.edu.tw

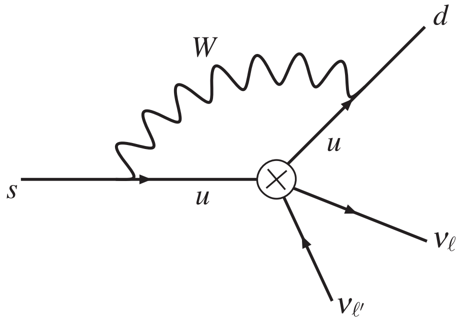

FIG. 1. Flavor diagram for the $s \to d\nu_\ell \bar{\nu}_{\ell'}$.

$$H^{\rm NSI}_{s\to d\nu_\ell\bar{\nu}_{\ell'}} = -\frac{G_F}{\sqrt{2}}\left(V^*_{us}V_{ud}\frac{\alpha_{em}}{4\pi\sin^2\theta_W}\varepsilon^{uL}_{\ell\ell'}\ln\frac{\Lambda}{m_W}\right) \times (\bar{\nu}_\ell\nu_{\ell'})_{V-A}(\bar{s}d)_{V-A}, \quad (4)$$

where Λ denotes the new physics energy scale above the weak scale with $\ln(\Lambda/m_W) > 1$. From Eq. (4), the branching ratio for $K^+ \to \pi^+\nu_\ell\bar{\nu}_{\ell'}$ from the NSIs is found to be

$$\mathrm{BR}(K^+ \to \pi^+\nu_\ell\bar{\nu}_{\ell'})_{\rm NSI} = \frac{\kappa_+}{3}\left|V^*_{us}V_{ud}\frac{1}{2}\varepsilon^{uL}_{\ell\ell'}\ln\frac{\Lambda}{m_W}\right|^2 \times \mathrm{BR}(K^+ \to \pi^0 e^+\nu_e), \quad (5)$$

with

$$\kappa_+ = r_{K^+}\frac{3\alpha^2_{em}}{|V_{us}|^2 2\pi^2\sin^4\theta_W}, \quad (6)$$

where the factor of 3 in κ_+ comes from the number of neutrino species and $r_{K^+} = 0.901$ denotes the isospin breaking effects [24]. Numerically, it is given by

$$\mathrm{BR}(K^+ \to \pi^+\nu_\ell\bar{\nu}_{\ell'})_{\rm NSI} \approx 6.5\times 10^{-7}\left|\varepsilon^{uL}_{\ell\ell'}\ln\frac{\Lambda}{m_W}\right|^2, \quad (7)$$

where we have used $\mathrm{BR}(K^+ \to \pi^0 e^+\nu_e) = (4.98 \pm 0.07)\%$ [1]. For simplicity, we will avoid the complicated interference effects to get the constraint on the free parameters directly by setting the upper bound for the contribution from the NSIs in Eq. (7) to be less than $\Delta\mathrm{BR} \equiv \mathrm{BR}_{\rm exp} - \mathrm{BR}_{SM} = \mathcal{C}\times 10^{-10}$ with $\mathcal{C}\sim 0.5$. Hence, we obtain the upper limit on $\varepsilon^{uL}_{\ell\ell'}$ to be

$$\varepsilon^{uL}_{\ell\ell'} \lesssim \frac{\mathcal{C}}{0.5}\frac{8.8\times 10^{-3}}{\ln\Lambda/m_W}. \quad (8)$$

Since ℓ or ℓ' can represent any charged lepton, the decay of $K^+ \to \pi^+\nu\bar{\nu}$ could give strong constraints on the parameters involving ν_τ.

Next, we discuss the NSIs on $D^+ \to \pi^+\nu\bar{\nu}$. It is well known that unlike the K and B systems, where the FCNC processes are enhanced by the internal heavy top-quark loop, the loop-induced rare decays of the charmed mesons are highly suppressed in the SM as they involve the light down-quark sector and the Glashow-Iliopoulos-Maiani cancellation. It has been estimated that $\mathrm{BR}(D^+ \to \pi^+\nu\bar{\nu})_{\rm SM} \sim 5.1\times 10^{-16}$ with long-distance QCD contributions included in the SM [25]. Obviously, it cannot be reached by future experiments such as BESIII, where the sensitivity on the rare charmed meson decays will be reached only at the level of 10^{-8} or so [16]. It is clear that if there is any evidence with $\mathrm{BR}(D^+ \to \pi^+\nu\bar{\nu}) \sim 10^{-8}$ in the future experiment, it will definitely indicate the existence of new physics.

The NSIs in Eq. (1) also can induce the transition $c \to u\nu_\ell\bar{\nu}_{\ell'}$ at one-loop level with a Feynman diagram displayed in Fig. 2. Similar to $s \to d\nu_\ell\bar{\nu}_{\ell'}$, the following effective interaction for $c \to u\nu_\ell\bar{\nu}_{\ell'}$ can be obtained:

$$H^{\rm NSI}_{c\to u\nu_\ell\bar{\nu}_{\ell'}} = \frac{G_F}{\sqrt{2}}\left(\frac{\alpha_{em}}{4\pi\sin^2\theta_W}V_{cd}V^*_{ud}\varepsilon^{dL}_{\ell\ell'}\ln\frac{\Lambda}{m_W}\right)(\bar{\nu}_\ell\nu_{\ell'})_{V-A} \times (\bar{c}u)_{V-A}, \quad (9)$$

which leads to

$$\mathrm{BR}(D^+ \to \pi^+\nu_\ell\bar{\nu}_{\ell'})_{\rm NSI} = \left|V^*_{ud}\frac{\alpha_{em}}{4\pi\sin^2\theta_W}\varepsilon^{dL}_{\ell\ell'}\ln\frac{\Lambda}{m_W}\right|^2 \times \mathrm{BR}(\bar{D}^0 \to \pi^+ e\bar{\nu}_e). \quad (10)$$

Numerically, we obtain

$$\mathrm{BR}(D^+ \to \pi^+\nu_\ell\bar{\nu}_{\ell'})_{\rm NSI} \approx 2\times 10^{-8}\left|\varepsilon^{dL}_{\ell\ell'}\ln\frac{\Lambda}{m_W}\right|^2, \quad (11)$$

where we have used $\mathrm{BR}(\bar{D}^0 \to \pi^+ e\bar{\nu}_e) = (2.81 \pm 0.19)\times 10^{-3}$ [1]. For $\ln(\Lambda/m_W) \sim 1$, $\varepsilon^{dL}_{\tau\tau} \sim 1$, and $\varepsilon^{dL}_{\ell\ell'} < 1$ (ℓ, $\ell' \neq \tau$), we get $\mathrm{BR}(D^+ \to \pi^+\nu\bar{\nu}) \sim 2\times 10^{-8}$, which could be reached at a future dedicated experiment [26] such as BESIII [16]. Turning this argument around, if future searches of these rare D decay modes at the level of 10^{-8} turn out to be nil at BESIII, useful constraints on the couplings $\varepsilon^{dL}_{\ell\ell'}$ can be deduced.

To recap, we have studied $K^+ \to \pi^+\nu\bar{\nu}$ and $D^+ \to \pi^+\nu\bar{\nu}$ in the framework of the NSIs. We have shown that both rare decays could provide strong constraints on the free parameters in the NSIs. Explicitly, we have found that $\varepsilon^{uL}_{\ell\ell'}$ and $\varepsilon^{dL}_{\ell\ell'}$ could be limited to be less than 10^{-2} and order of 1 by the current and future experiments for $K^+ \to \pi^+\nu\bar{\nu}$

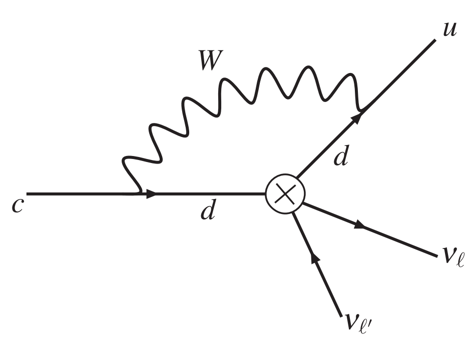

FIG. 2. Flavor diagram for the $c \to u\nu_\ell\bar{\nu}_{\ell'}$.

and $D^+ \to \pi^+ \nu \bar{\nu}$, respectively. Finally, we remark that $\mathrm{BR}(D^+ \to \pi^+ \nu \bar{\nu})$ could be at the level of 10^{-8} due to the NSIs, which could be accessible to BESIII [16].

We would like to thank Professor D. Bryman and Dr. Hiroaki Sugiyama for useful discussions. This work is supported in part by the National Science Council of Republic of China under Grants No. NSC-95-2112-M-006-013-MY2, No. NSC-95-2112-M-007-001, No. NSC-95-2112-M-007-059-MY3, and No. NSC-96-2918-I-007-010.

[1] W. M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
[2] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); S. P. Mikheev and A. Y. Smirnov, Yad. Fiz. **42**, 1441 (1985) [Sov. J. Nucl. Phys. **42**, 913 (1985)]; F. J. Botella, C. S. Lim, and W. J. Marciano, Phys. Rev. D **35**, 896 (1987); J. W. F. Valle, Phys. Lett. B **199**, 432 (1987); E. Roulet, Phys. Rev. D **44**, R935 (1991); M. M. Guzzo, A. Masiero, and S. T. Petcov, Phys. Lett. B **260**, 154 (1991).
[3] S. Bergmann, M. M. Guzzo, P. C. de Holanda, P. I. Krastev, and H. Nunokawa, Phys. Rev. D **62**, 073001 (2000); M. M. Guzzo, H. Nunokawa, P. C. de Holanda, and O. L. G. Peres, Phys. Rev. D **64**, 097301 (2001); M. Guzzo, P. C. de Holanda, M. Maltoni, H. Nunokawa, M. A. Tortola, and J. W. F. Valle, Nucl. Phys. **B629**, 479 (2002).
[4] Y. Grossman, Phys. Lett. B **359**, 141 (1995); S. Bergmann, Y. Grossman, and E. Nardi, Phys. Rev. D **60**, 093008 (1999).
[5] T. Hattori, T. Hasuike, and S. Wakaizumi, Prog. Theor. Phys. **114**, 439 (2005); M. Garbutt and B. H. J. McKellar, hep-ph/0308111; M. Blennow, T. Ohlsson, and W. Winter, Eur. Phys. J. C **49**, 1023 (2007).
[6] S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria, J. High Energy Phys. 03 (2003) 011.
[7] L. M. Johnson and D. W. McKay, Phys. Rev. D **61**, 113007 (2000); A. M. Gago *et al.*, Phys. Rev. D **64**, 073003 (2001); T. Ota and J. Sato, Phys. Lett. B **545**, 367 (2002); T. Ota, J. Sato, and N. Yamashita, Phys. Rev. D **65**, 093015 (2002); M. Campanelli and A. Romanino, Phys. Rev. D **66**, 113001 (2002).
[8] P. Huber, T. Schwetz, and J. W. F. Valle, Phys. Rev. Lett. **88**, 101804 (2002); Phys. Rev. D **66**, 013006 (2002).
[9] N. Kitazawa, H. Sugiyama, and O. Yasuda, hep-ph/0606013.
[10] V. D. Barger, R. J. N. Phillips, and K. Whisnant, Phys. Rev. D **44**, 1629 (1991); Z. Berezhiani and A. Rossi, Phys. Lett. B **535**, 207 (2002).
[11] J. Barranco, O. G. Miranda, C. A. Moura, and J. W. F. Valle, Phys. Rev. D **73**, 113001 (2006); G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, and P. D. Serpico, Nucl. Phys. **B756**, 100 (2006); M. Blennow, T. Ohlsson, and J. Skrotzki, hep-ph/0702059; J. Barranco, O. G. Miranda, and T. I. Rashba, hep-ph/0702175; J. Kopp, M. Lindner, and T. Ota, hep-ph/0702269.
[12] K. Eguchi *et al.* (KamLand Collaboration), Phys. Rev. Lett. **90**, 021802 (2003).
[13] J. Boger *et al.* (SNO Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **449**, 172 (2000).
[14] S. Fukuda *et al.* (Super-Kamiokande Collaboration), Phys. Lett. B **539**, 179 (2002).
[15] M. L. Mangano *et al.*, hep-ph/0105155.
[16] H. B. Li, Nucl. Phys. B, Proc. Suppl. **162**, 312 (2006).
[17] Y. Grossman, G. Isidori, and H. Murayama, Phys. Lett. B **588**, 74 (2004).
[18] G. Buchalla, A. J. Buras, and M. E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996).
[19] A. J. Buras, M. Gorbahn, U. Haisch, and U. Nierste, J. High Energy Phys. 11 (2006) 002.
[20] V. V. Anisimovsky *et al.* (E949 Collaboration), Phys. Rev. Lett. **93**, 031801 (2004).
[21] D. Rein and L. M. Sehgal, Phys. Rev. D **39**, 3325 (1989); J. S. Hagelin and L. S. Littenberg, Prog. Part. Nucl. Phys. **23**, 1 (1989); M. Lu and M. B. Wise, Phys. Lett. B **324**, 461 (1994); C. Q. Geng, I. J. Hsu, and Y. C. Lin, Phys. Lett. B **355**, 569 (1995).
[22] A. Ceccucci, *Proceedings of 4th Flavor Physics and CP Violation Conference (FPCP 2006), Vancouver, British Columbia, Canada, 2006*, hep-ex/0605120, p 033.
[23] G. Anelli *et al.*, CERN Report No. CERN-SPSC-2005-013.
[24] W. Marciano and Z. Parsa, Phys. Rev. D **53**, R1 (1996).
[25] G. Burdman, E. Golowich, J. Hewett, and S. Pakvasa, Phys. Rev. D **66**, 014009 (2002).
[26] A background study for $D^+ \to \pi^+ \nu \bar{\nu}$ is needed.