Search for Lepton Number Violating Charged Current Processes with Neutrino Beams

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We propose a new idea to test a class of loop-induced neutrino mass mechanisms by searching for lepton number violating charged current processes with incident of a neutrino beam. The expected rates of these processes are estimated based on some theoretical assumptions. They turn out to be sizable so that detection of such processes could be possible at near detectors in future highly intense neutrino-beam facilities.

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It has been well established that neutrinos are massive, by various experimental observations of neutrino oscillations in the past decade. However, it remains unknown which type the neutrino mass is, either a Dirac or a Majorana type. Future experiments searching for neutrinoless double beta decays would give us a clue. However, even when the neutrinos turn out to be of the Majorana type, the mechanism for the neutrino mass generation should be further determined. There are two kinds of mechanisms to generate the Majorana neutrino mass. One of them is a tree-level mechanism, such as the seesaw models, and the other is a loop-level mechanism, such as the Zee model. Since the Majorana neutrino mass violates the lepton number, the Lepton Number Violating charged current processes are not extremely tight. According to the Particle Data Group, the LNV-CC processes have been searched for in neutrino oscillation experiments, which give the current direct upper limits to LNV-CC interaction with high precision. Therefore, in order to obtain a hint for the neutrino mass generation, the LNV interaction should be studied. For example, there have already been some studies on LNV processes associated with charged leptons at colliders in some specific models. Since the LNV processes caused by the seesaw mechanism highly suppressed by small neutrino masses, it is very difficult to detect them experimentally. On the other hand, it could be possible to detect the LNV interaction caused by a class of loop-induced neutrino mass models, since it is not necessarily related by the smallness of neutrino mass.

In this letter, we discuss a new possibility of experimental detection of the LNV Charged Current (LNV-CC) interaction for the loop-induced neutrino mass mechanism. In particular, we focus on the LNV interactions of the anti-symmetric combination of lepton doublets, $L$, given by

$$\mathcal{L} = 2\sqrt{2}G_F \left( C_{L/R} \beta \alpha \right) L S^+,$$

where $S$ is a charged singlet scalar field, which is often called as the Zee singlet. This contains a charged current interaction between a neutrino ($\nu$) and a charged lepton ($\ell$) given by $\bar{\nu} P_L \ell S^+$ and does not have a doubly-charged current interaction between pure charged lepton combination given by $F\ell$. Therefore, the interaction in Eq. (1) cannot be constrained by experimental bounds from the charged lepton processes. As a result, the studies of the LNV-CC processes would have large opportunity of discovery.

Experimentally, we propose the measurements of anti-lepton production by new charged current interaction of a neutrino beam, given by

$$\nu + N \rightarrow \ell^+ + X. \quad (2)$$

Such a measurement with high statistics can be made at a neutrino near detector with a magnetic field to identify an electric charge of the charged leptons. We also propose the measurements of LNV decays of hadrons, given by

$$\pi^+ \rightarrow \mu^+ + \nu \quad \text{and} \quad \frac{1}{2} X \rightarrow \frac{1}{2} Y + e^- + \nu. \quad (3)$$

These LNV decays produce anti-neutrinos (neutrinos) in a neutrino (an anti-neutrino) beam. The former in Eq. (3) corresponds to a source of conventional super neutrino beam and the latter affects that of a beta neutrino beam. Therefore, the measurement at a near detector can be used to identify these LNV decays of hadrons. The current direct upper limits to LNV-CC interaction are not extremely tight. According to the Particle Data Group, the LNV-CC processes have been searched for in neutrino oscillation experiments, which give the bound $\Gamma(\pi^+ \rightarrow \mu^+ \nu) < 1.5 \times 10^{-3}$. We can expect that future neutrino oscillation experiments with high neutrino intensity will improve significantly this type of direct bounds on the LNV-CC process with high precision.

The effective four-Fermi LNV Lagrangian for the charged current interaction with quarks can be parameterized by

$$\mathcal{L} = 2\sqrt{2}G_F \left( C_{L/R} \right)_i^\beta \alpha (O_{L/R})^i_\beta \alpha + H.c., \quad (4)$$

where $G_F$ is the Fermi constant, $C_{L/R}$ are mass dimension-two coefficients, and $O_{L/R}$ are the operators of mass dimension-six, defined as

$$(O_{L/R})^i_\beta \alpha \equiv [ \bar{P}_\beta \nu L \ell_\alpha ] [ \nu_L P_{L/R} u_i ], \quad (5)$$

where $\alpha, \beta$ and $i$ are indices for flavour. Here, for simplicity, we consider only the case where the quark flavour
is conserved. These effective interactions can be regarded as a remnant of physics at high energy scales. After integrating out the heavy particles from the high energy models, the effective interactions at the electroweak scale should be the Standard Model (SM) gauge invariant. Therefore, the operators in Eq. (5) can be considered as a remnant of physics at high energy scales. After focusing on the anti-symmetric combination of lepton doublets for the effective LNV-CC interaction, the lepton flavour in the operators must be off-diagonal, $\beta \neq \alpha$. Since the relevant effective operators must include the Higgs doublet to be kept invariant under the SM gauge transformation, the LNV effect depends on the detail of the scalar sector in the model. Later, we will specify the Yukawa sector to be one in the type II Two-Higgs Doublet Model (THDM).

We estimate the rates of LNV-CC signal events by a neutrino beam at a near detector, which can be generated by the interactions in Eq. (4). They are created in the following two different ways. They are (i) LNV-CC Deep Inelastic Scattering (DIS) process between neutrinos and nucleons in detectors and (ii) anti-neutrino production by LNV-CC interaction at a neutrino beam source. The amplitudes of the LNV source and detection processes interfere with each other, although we treat them individually in this letter. In the following, estimation of each process will be given.

Neutrinos are detected by charged leptons through the charged current interaction. The LNV-CC interaction of Eq. (4) would produce charged leptons of the opposite electric charge to the SM process, given in

$$\nu_\beta + N \rightarrow \ell_\alpha^+ + X,$$

where $N$ is a target nucleus and $X$ represents all particles in the final state. The cross-section of $\sigma_{LNV}$ of the LNV-CC DIS process in Eq. (4) is calculated to be

$$\frac{d\sigma_{LNV}}{dxdy} = \sum_i x \left[ f_{u_i}(x) + f_{\tau_i}(x) \right] \left[ (C_L)_{i}^{\beta\alpha} \right]^2 + \left[ (C_R)_{i}^{\beta\alpha} \right]^2 \right]$$

where $f_\alpha$ is the Parton Distribution Function (PDF) for quark $q_\alpha$, $x$ is a longitudinal momentum fraction of parton, $y$ is the fraction of incident neutrino energy, which is transferred to the hadron part, and $s$ is the Mandelstam $s$ parameter. Note that the LNV-CC cross-section takes the different kinematical structure from the SM charged current process owing to its Lorenz nature. Therefore, it is, in principle, possible to discriminate these signal processes from the SM processes by examining their kinematics.

To estimate the signal rate, let us evaluate the magnitudes of the LNV-CC couplings with a set of reference values of parameters in typical models for loop-induced neutrino masses. The models are categorized into two classes according to the source of the LNV: (i) Lepton number is violated by Majorana nature of the heavy mediation field, such as right-handed neutrino (e.g., Refs. [18–21]), and (ii) Lepton number is transmitted to the scalar sector and explicitly violated by an interaction in it (e.g., Refs. [7, 19, 21, 22]). The latter class of the models commonly contains the LNV-CC interaction shown in Eq. (1). We re-define it with the coupling $f_{\beta\alpha}$ as

$$\mathcal{L}_{LNV} = f_{\beta\alpha} \overline{L}_\beta \tau_\tau^2 L_\alpha S^+ + \text{H.c.}$$

Phenomenological consequences of this interaction have been studied in various context, see e.g. Refs. [27, 28]. As mentioned previously, the effective four-Fermi LNV-CC interactions are related with the scalar sector of the models. Here, we assume the type II THDM (e.g. Ref. [30]) for Yukawa interactions. The scalar sector of the models with the charged singlet field $S^\pm$, in general, includes the interaction between $S^\pm$ and Higgs doublets, and the

1 It is known that the original Zee model cannot reproduce the correct lepton mixing matrix. To solve this problem, some extensions are necessary, see e.g., Ref. [24].
relevant portion of Lagrangian is presented by
\[ \mathcal{L}_{\text{scalar}} = \left[ \mu S^- H_u^0 H_u + \text{H.c.} \right] + M_S^2 S^+ S^-, \tag{11} \]
where \( \mu \) is a parameter with a unit of mass dimension and \( M_S \) is the mass of \( S \). Two Higgs doubles coupled to the \( u \)-type and \( d \)-type quarks are given as \( H_u \) and \( H_d \), respectively. The charged scalars of \( S^\pm \) and \( H^\pm \) mediate the LNV-CC interaction of Eq. 4 through the tree-level diagram shown in Fig. 2, where \( H^\pm \) represents the physical charged Higgs state in the THDM in the limit of \( \mu = 0 \). Once a non-zero value of \( \mu \) is invoked, \( S^\pm \) and \( H^\pm \) are mixed (cf. e.g., Ref. [20]). Within the approximation of the mass insertion of \( \mu \) in the propagation of the charged scalars (which are the mixture states of \( S^\pm \) and \( H^\pm \)), the couplings of the effective interactions are described with the model parameters in Eqs. 10 and 11 as
\[ (C_{X=[L,R]})_i^{\beta \alpha} = \frac{f^{\beta \alpha} \mu [m_d, \tan \beta, m_u, \cot \beta]}{\sqrt{2} M_S^2 M_{H^\pm}^2 G_F}, \tag{12} \]
where \( \tan \beta \equiv v_u/v_d \) and \( v_u \) and \( v_d \) are the vacuum expectation values of \( H_u \) and \( H_d \), respectively. In this class of models, the magnitude of the LNV-CC coefficients is proportional to the mass of the interacting quarks. Therefore, the second generation quarks, \( s \) quarks, in nuclei play an important role. On the other hand, only the interactions with first generation quarks are relevant to the LNV-CC process at a beam source (cf. Eq. 3). Therefore, it is suppressed by small masses of the first generation quarks.

The magnitudes of the couplings of \( f^{\beta \alpha} \) and the mass of \( M_S \) depend on the details of the models. Here, we employ the values of
\[ f^{\beta \alpha} = 2 \cdot 10^{-2} \text{ and } M_S = 600 \text{ GeV}, \tag{13} \]
which are inspired by a model in which neutrino mass is induced at the two-loop level. For the parameters in the Higgs sector, we choose
\[ \mu = 200 \text{ GeV and } M_{H^\pm} = 300 \text{ GeV}. \tag{14} \]
By using these reference values, the effective LNV couplings are given as
\[ (C_L)_{i=[1,2]}^{\beta \alpha} = [1.9 \cdot 10^{-6}, 3.9 \cdot 10^{-5}] \left[ \tan \beta \right], \tag{15} \]
\[ (C_R)_{i=[1,2]}^{\beta \alpha} = [1.9 \cdot 10^{-8}, 9.7 \cdot 10^{-6}] \left[ \frac{1}{\tan \beta} \right]. \tag{16} \]
By substituting them into Eq. 4, the cross-section of the LNV-CC neutrino-proton scattering process can be estimated. The results with different values of \( \tan \beta \) are shown in Fig. 3. In the numerical calculations, we use MSTW NNLO as PDF. As shown in Fig. 3 the LNV-CC cross-section is dominated by the \( s \)-quark contribution. If we work on this theoretical framework, an extremely good charge-identification rate at near detectors is demanded to detect the LNV-CC neutrino-nucleon scattering process. Since the LNV-CC cross-section in Eq. 4 takes different kinematic structure from the SM one, the angular distribution of the signal lepton could be used to distinguish the signal events. The total cross-section of the process in Eq. 4 could be as large as \( 10^{-48} \text{ cm}^2 \) at neutrino energy of 50 GeV. For this case, using \( 10^{20} \) neutrinos which would be available in coming experiments, LNV-CC events of about \( \mathcal{O}(100) \) can be produced with \( \mathcal{O}(10) \) ton detector placed at 200 m away from the beam front. It is known that a neutrino beam based on pion decays (conventional beam) has contamination of \( \bar{\nu}_e \) and \( \bar{\nu}_\mu \) at a level of a few %. Therefore, to study LNV-CC interaction in a high precision, the measurement of \( \bar{\nu}_e \) should be attempted. In a neutrino beam

FIG. 3: Cross-sections of LNV-CC neutrino-proton scattering process (“LNV total” solid curve) with three different values of \( \tan \beta \in \{1, 10, 50\} \). The contributions from individual quarks are also shown (“quarks”). For comparison, we plot also the cross-section (times \( 10^{-10} \)) of the neutrino-proton scattering process through the standard model charged current (“\( \sigma_{CC} \times 10^{-10} \)” gray thick curve).
based on decay of radioactive ions (beta beam), any kind of anti-neutrinos can be studied.

Next, we estimate the case of anti-neutrino production by the LNV-CC interaction at a neutrino source. The signals are detected as events of charged leptons with opposite electric charge to the SM process at a near detector, which are finally the same signal as the LNV-CC process at detection. The conventional neutrino beam has an advantage to enhance the LNV-CC signal processes, because the pion decays in the SM $V - A$ interaction is suppressed by the factor of $\omega_\mu \equiv (m_\pi/m_\mu)(m_\pi/(m_\mu + m_\mu)) \sim 20$ (see e.g., Ref. [32]) in comparison with the LNV processes mediated by the charged scalar field. The branching ratio of the LNV pion decay process,

$$\pi^+ \rightarrow \mu^+ + \nu_\alpha,$$

induced by the effective interaction \( (O_{L/R})^{i=1}_{\alpha \beta} \) with a muon is calculated to be

$$\text{Br}(\pi^+ \rightarrow \mu^+ \nu_\alpha) = \omega_\mu^2 \left| \left( O_L^{\alpha \beta} \right)_{i=1} - \left( O_R^{\alpha \beta} \right)_{i=1} \right|^2.$$  

(18)

The anti-neutrino production in a beta beam is also affected by the interaction \( (O_{L/R})^{i=1}_{\alpha \beta} \) with an electron, given by

$$\frac{4}{2} X \rightarrow \frac{4}{2} + 1 Y + \epsilon + \nu_\beta.$$  

(19)

However, there is no enhancement mechanism in the case of beta decays of ions.

Although the LNV decay rate of pions is increased by the chiral enhancement factor $\omega_\mu$, it is suppressed in the type II THDM by the small Yukawa couplings of the first generation quarks. With the reference values Eqs. [15] and [16], the branching ratio is calculated to be

$$\text{Br}(\pi^+ \rightarrow \mu^+ \nu_\alpha) = 2.1 \times 10^{-9},$$

(20)

which is quite small but significantly larger than the LNV-CC process at the detection for the same reference values of model parameters. With the same setup as in the estimation of the LNV-CC event rate at the detector, the source LNV-CC of $O(10^3)$ events can be expected.

We have proposed new measurements of LNV-CC processes to discriminate the neutrino mass generation mechanisms. The proposed measurements are sensitive to the loop-induced neutrino mass models. We have calculated the rates of LNV-CC interaction, which are sizable to be detected. These measurements can be done in a new-generation neutrino beam facility.

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