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A variety of lepton number violating processes related to Majorana neutrino masses

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The origin of neutrino masses, strongly suggested by neutrino oscillation experiments, is an issue to be settled. We argue how the Majorana nature of neutrino masses is revealed by the study of lepton-number violating processes. The details of the analysis are seen in our recent paper [1].

1. Introduction

It is a great experimental achievement that SuperKamiokande [2], SNO [3], and KamLAND [4] experiments have confirmed the neutrino oscillations. Theoretically it is quite important that these experiments have clearly indicated non-vanishing neutrino mass-squared differences, i.e. non-vanishing neutrino masses, and therefore opened a new window beyond physics of the standard model.

The origin of small neutrino masses, however, is still an issue to be settled. Since neutrinos are electrically neutral and allowed to possess Majorana masses, there is a good reason to expect that the Majorana nature plays a crucial role in the study of the origin. The most popular and plausible mechanism to generate the Majorana masses is "See-Saw" [5] mechanism, where the smallness of neutrino masses is attributed to the largeness of ν_R Majorana masses compared with the Dirac masses (or to the large Parity violation).

Unfortunately, the neutrino oscillation experiments cannot prove the Majorana nature of neutrinos. This is essentially because the rates of neutrino oscillation with chirality flip, $\nu_L \to \nu_R$, are strongly suppressed by $(\frac{m_\nu}{E})^2 \ll 1$ with E being the neutrino energy, and such oscillations practically cannot be seen. In principle, the neutrino masses causes chirality flip $\nu_L \to \bar{\nu}_R$ or $\nu_L \to \nu_R$ for Majorana- or Dirac-type masses, with or without lepton number violation, which could be clearly discriminated if the oscillations with chirality flip were observable. But since the rates are strongly suppressed what we are observing in the oscillation experiments are oscillations without chirality flip, $\nu_L \to \bar{\nu}_R \to \nu_L$ or $\nu_L \to \nu_R \to \nu_L$, thus making the discrimination of the intermediate states impossible. More precisely the neutrino oscillation experiments are measuring

$$P(\nu_\alpha \to \nu_\beta) = |(e^{i\frac{MM^\dagger}{2E}t})_{\alpha\beta}|^2, \tag{1}$$

where M is the neutrino mass matrix. The appearance of the combination $MM^\dagger$ rather than M itself is the clear indication that oscillation without chirality flip is relevant. In this combination the genuine feature of Majorana masses is seen to be lost. To see this, consider a simplified 2 generation case of Majorana mass matrix,

$$M = U \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} U^T,$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix}, \quad (2)$$

where ϕ is a CP violating "Majorana phase", which is the genuine feature of the Majorana neutrinos. It, however, is easy to see that the Majorana phase disappears in the combination of $MM^\dagger$.

This lesson tells us that to test the Majorana nature, we need to see the Majorana mass matrix M itself. which inevitably leads to lepton number, L, violating processes. Neutrino-less double beta decay $N \to N' + 2e^-$ is the typical example. We wish to study systematically a variety of L-violating processes due to an effective (low-energy) operator

$$ll\bar{q}q\bar{q}q \quad (\Delta L = 2), \quad (3)$$

with l and q being lepton and quark doublets, which is induced by a tree level Feynman diagram, Fig.1, where the cross is the Majorana neutrino mass matrix and the exchanged particle is a weak boson, either $W^\pm$ or Z. Existence of this class of operators requires a new physics beyond the standard theory, but we do not need to specify the new physics.

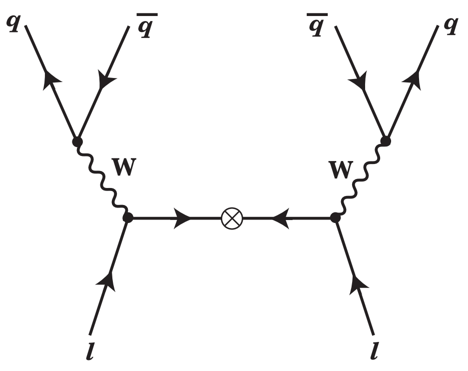

Figure 1. The Feynman diagram that generates effective lepton number violating operators

A few remarks are in order. First, this operator is universal: it exists as long as neutrinos have Majorana masses, irrespectively of the scenario of the mass generation. Secondly, when flavor mixing is taken into account, by studying various combination of $l_\alpha l_\beta$, we basically can determine whole $M_{\alpha\beta}$, not only M_{ee} exploited by the neutrino-less double beta decay. Thirdly, the rate of neutrino-less double beta decay handled by $M_{ee} = \sum_i U_{ei}^2 m_i$ may be suppressed by small neutrino masses or destructive interference in the amplitude due to the Majorana phases, even in the inverted hierarchy of neutrino masses. Thus the search for various (not only $(\alpha, \beta) = (e, e)$) L-violating processes is quite important.

2. L-violating processes

With the lepton flavor mixing, the effective operators above give a variety of lepton number violating processes. Here we discuss the following typical processes;

$$(e\mu); \qquad e^- + A^Z \to \mu^+ + A^{Z-2}, \quad (4)$$
$$(\mu e); \qquad \mu^- + A^Z \to e^+ + A^{Z-2}, \quad (5)$$
$$(ee); \qquad e^- + e^-(atomic) \to \pi^- + \pi^-, \quad (6)$$
$$(e\mu); \qquad \nu_\mu + e^-(atomic) \to \pi^- + \pi^0. \quad (7)$$

Here $(\alpha\beta)$ means that the process may explore the matrix element $m_{\alpha\beta}$. We successively discuss these processes very briefly below. For the details of the analysis see [1].

• $e^- + A^Z \to \mu^+ + A^{Z-2}$

The background of this process is μ^+ from π^+ decay. To exclude the possibility to search for the energy range $m_\mu \le E_e \le m_\pi$ is desirable. The cross section at low energies is given by

$$\sigma = \frac{G_F^4 m_{e\mu}^2 < p_+ >< E_+ >}{32\pi^3 R_n^2} \sum_{f,s} |t^{\mu\nu}\Omega_{\mu\nu}|^2, \quad (8)$$

where $t^{\mu\nu}$ is the lepton wave function, $\Omega_{\mu\nu}$ is the nuclear matrix element and R_n is an "effective nuclear radius". Let us note that the factor $\sum_{f,s} |t^{\mu\nu}\Omega_{\mu\nu}|^2 \propto Z(Z-1)$ gets an enhancement due to the $Z(Z-1)$ factor. Numerically,

$$\sigma \sim 5 \times 10^{-65}\, cm^2 \left(\frac{|m_{e\mu}|}{100eV}\right)^2, \quad (9)$$

for the average μ momentum of $30MeV$.

• $\mu^- + A^Z \to e^+ + A^{Z-2}$ [6]

This "μ-capture" process is cute in the following sense:
(1) Self-focusing of the incident μ^- into the area of nuclear size is realized.
(2) The same μ^- can be used repeatedly as in the case of high luminosity accumulator ring.

We thus may be able to expect rather high event rate. But, unfortunately the rate of the main process $\mu^- \to \nu_\mu$ is huge, and the resultant branching ratio $Br(\mu^- \to e^+) \sim 3 \times 10^{-29} |m_{\mu e}/100\text{eV}|^2$ is quite small.

• $e^- + e^-(atomic) \to \pi^- + \pi^-,\ \nu_\mu + e^-(atomic) \to \pi^- + \pi^0$

For the latter process, ν_μ may be available in proposed ν factory. These processes are unique in the sense that lepton number completely disappear in the final states.

As these processes are similar, we discuss only $e^- + e^-(atomic) \to \pi^- + \pi^-$. This process is possible only for high energy electron beam $E_e > (2m_\pi^2)/m_e \simeq 80(GeV)$. The cross-section can be obtained without uncertainty of hadronic matrix element:

$$\sigma = \frac{G_F^4 f_\pi^4 |m_{ee}|^2}{2\pi} \sqrt{\frac{s - 4m_\pi^2}{s}}\ , \tag{10}$$

where f_π is the π decay constant of order $90MeV$, and $s \approx 2m_e E_e$ is the CMS energy squared. The event rate is $10(\frac{|m_{ee}|}{100eV})^2\ (1/year)$ for a flux $10^{34}(1/cm^2 \cdot s)$ and target mass of $500g$. A non-trivial background of the usual electromagnetic origin is $e^- + n \to e^- + p + \pi^- + \pi^- + \pi^+$ with a missing p. This may be rejected by imposing a kinematical condition: invariant mass of $\pi^- + \pi^-$ should be $(2E_e m_e)^{1/2}$.

3. Summary

(i) The Majorana nature of neutrino mass matrix, which cannot be proved via neutrino oscillation experiments, can be fully verified by the study of L-violating processes, whose typical examples have been discussed above.
(ii) Though the rates are generally very small, the prediction in terms of the mass matrix is definite, and if one of these processes is discovered with a larger rate than given above, it means the existence of a new class of diagrams not involving the neutrino mass matrix and may provide a new feature to the lepton sector such as R-parity violating interactions in SUSY models. In that sense lepton number violating processes may provide the unique window to determine the mechanism of how the lepton number violation occurs.
(iii) It has been known that one CP violating phase of MNS matrix, which plays roles in neutrino oscillation experiments, does not participate in the leptogenesis scenario for the baryogenesis in the universe by Fukugita-Yanagida [7]. The "Majorana phases", exploited via the L-violating processes discussed here are expected to be responsible, even though indirectly, for the leptogenesis.
(iv) If 7 observables, from both of neutrino oscillation and L-violating process, are measured, and if their rates deviate from what we expect assuming real symmetric neutrino mass matrix (with 6 degrees of freedom), it will clearly indicate the presence of CP violating phases, including the Majorana phases.

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