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Probing Neutrino Models in Extra Dimensions with Muon to Electron Conversion and Other Charged Lepton Flavor Violating Processes

We-Fu Chang

Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan

Abstract

Among the 27(+2) free parameters in Standard Model(SM) with massive neutrinos, 21(+2) out of them are related to the fermion masses. And most of them have been well measured in the past 50 years. Yet, we have no satisfactory understanding of the origin of flavor. However, models involve extra dimension(s) provide a new framework for understanding the hierarchical pattern of the SM Yukawa couplings. We are particularly interested in the neutrino models in higher dimension which alleviate some theoretical problems in their 4D versions. In this talk, some general features of the charged lepton flavor violating (LFV) processes in the higher dimensional neutrino models is illustrated by a simple 5D split fermion model.

Keywords: Neutrino Masses, Lepton Flavor Violation, Extra-Dimension

1. Introduction

It is well established that at least two of the SM active neutrinos are massive [1]. The nonzero neutrino masses inevitably result in nonvanishing LFV processes. On the other hand, the possibility that there exists extra spatial dimensions has opened up a new avenue to connect the fermion flavor problem with the fermion wave function profile in the extra dimension(s). The hierarchical Yukawa couplings in 4D theories can be resulted from different level of the wave function overlap between the left-handed(LH) and the right-handed(RH) chiral fermions in extra dimension (for recent studies along this line in the Randall-Sundrum model, see [2]). For simplicity, in this talk, the split fermion model [3] will be used to illustrate this idea. We stress that the same method can be applied to any extra dimension model with nontrivial bulk fermion profiles. In this talk, I review the work performed with I.T Chen and S.C. Liou [4] on a model which generates the neutrino mass via the Zee mechanism [5] in the 5D split fermion model. In the original 4D Zee model, in addition to the SM Higgs doublet Φ_1, a second Higgs doublet Φ_2 and an extra $SU(2)_L$ singlet charged Higgs h are included. A SM gauge symmetric but lepton number violating Yukawa term $\overline{\Psi}^c\Psi h$, where Ψ is the SM lepton doublet, is the key for generating the effective neutrino Majorana masses at 1-loop level. The Zee model provides a natural and economical explanation of the smallness of neutrino masses. However, it also suffers from the flavor changing neutral current(FCNC) problem as in models with two Higgs doublets. One way out was proposed by Wolfenstein [6] to further assume that only one of the two doublets couples to the leptons. This simplified version, or the so called Zee-Wolfenstein model, was later shown to be inconsistent with the accumulated neutrino experimental data. It does NOT mean the original version of the Zee model is ruled out [7], but rather fine tuning is then required to avoid the persistent FCNC.

2. Model Setup

We now proceed to detail the model setup. The spacetime of the model is described by an $M_4 \times S_1/Z_2$ orbifold

Email address: wfchang@phys.nthu.edu.tw (We-Fu Chang)

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and the fifth dimensional coordinate is denoted as y. The physical region is defined as $0 \leq y \leq \pi R$, where R is the radius of the compactified extra spatial dimension. In the model, all the SM fields are propagating in the bulk whereas the fermions are localized in the fifth dimension due to some unspecified potential(s). We also assume that the split fermions reside in a fat brane erected at the orbifold fixed point $y = 0$. For simplicity, we assume that all the SM chiral fermions are Gaussian distributed in y, and the width σ is universal. Assuming that $\sigma \ll R$ (we set $\sigma/R = 5 \times 10^{-4}$ for our numerical study). The Gaussian distribution, $\mathbf{g}(y, c_i^{L/R})$, can be normalized and each LH(RH)-chiral split fermion peaks at different location, $y = c_i^{L/R}$, in the fifth dimension. The hierarchical 4D Yukawa couplings is attributed to the Gaussian overlap between two chiral fermions. The further apart the two chiral fermions are the smaller their 4D Yukawa.

The Z_2 orbifolding transforms $y \leftrightarrow -y$, hence each bulk degree of freedom other than split fermions must be either even or odd under this Z_2. The first four (fifth) components of the SM gauge fields must be Z_2-even(odd) in order to reproduce the SM at low energy, and the bulk SM gauge fields can be spanned by either $\cos(ny/R)$ or $\sin(ny/R)$ with the proper normalization.

Since we are mainly interested in the neutrino masses, the quark sector will be left out of our discussion. To distinguish from the 4D field, the bulk field will be denoted with a hat. The 5D SM lepton doublet $\hat{\Psi}_{aL}$ and lepton singlet $\hat{e}_{aR}$ can be expressed as the product of the 4D wave function and the Gaussian profile in fifth dimension: $\hat{\Psi}_{aL}(x^\mu, y) = \Psi_{aL}(x^\mu)\mathbf{g}(y, c_a^L)$ and $\hat{e}_{aR}(x^\mu, y) = e_{aR}(x^\mu)\mathbf{g}(y, c_a^R)$, where a is the generation index. Since $\sigma \ll R$, their Kaluza-Klein(KK) modes are much heavier, $\sim 1/\sigma$, than those of the gauge and scalar bosons level by level and we shall not include them here. The bulk scalar fields $\{\hat{\Phi}_1, \hat{\Phi}_2, \hat{h}\}$ are assigned to be Z_2-(even, odd,odd). $\hat{\Phi}_1$ can be KK decomposed as

$$\hat{\Phi}_1(x, y) = \frac{\Phi_1^{(0)}(x)}{V} + \frac{\sqrt{2}}{V}\sum_{n=1} \cos\frac{ny}{R}\Phi_1^{(n)}(x), \qquad (1)$$

where the volume factor $V \equiv \sqrt{2\pi R}$ is of mass dimension $[-1/2]$. Similarly, $\hat{\Phi}_2$ and $\hat{h}$ can be decomposed as

$$\hat{\Phi}_2(x, y) = \frac{\sqrt{2}}{V}\sum_{n=1} \sin\frac{ny}{R}\Phi_2^{(n)}(x),$$
$$\hat{h}(x, y) = \frac{\sqrt{2}}{V}\sum_{n=1} \sin\frac{ny}{R}h^{(n)}(x). \qquad (2)$$

For the n-th KK mode of both parities, its mass is $m_n = \sqrt{\frac{n^2}{R^2} + m_0^2}$, where m_0 is the corresponding bulk mass parameter in the 5D Lagrangian. With this parity assignment, only $\Phi_1^{(0)}$ can develop a nonzero vacuum expectation value (VEV), $\langle\Phi_1^{(0)}\rangle = v/\sqrt{2}$, $v \simeq 250$ GeV. The $\Phi_1^{(0)}$ is identified as the SM Higgs. Its mass $m_{\Phi_1,0}$ is around 125 GeV. The remaining two bulk masses $m_{\Phi_2,0}$ and $m_{h,0}$ are also expected to be around or less than the electroweak scale. All other physical Higgs should be heavier than $1/R \sim O(\text{TeV})$. Since only $\Phi_1^{(0)}$ contributes to charged fermion masses, the fermion Yukawa couplings to $\Phi_1^{(0)}$ is automatically diagonal after the mass diagonalization. Then the dangerous FCNC will be only mediated by the KK excitations hence being suppressed compared to the usual two Higgs doublets model in 4D. This parity assignment also ensures that the profiles of Φ_2 and h differ from the profile of Φ_1. So the resulting 4D Yukawa couplings matrix of Φ_2 is not diagonal in the mass basis of the charged leptons. This is the key to have non-zero diagonal elements in the 4D effective neutrino mass matrix and the passport to successfully accommodate the observed neutrino data. Moreover, the profiles of Φ_2 and h, $\sin(ny/R)$, fall off near $y = 0$, which naturally results in a smaller 4D Yukawa f^2 and f^h. With an order one 5D Yukawa couplings, this miraculously makes neutrino masses roughly the desired order of magnitude without fine turning.

The relevant Lagrangian for 5D Zee model is given by

$$\mathcal{L}_{5DZee} = -V\hat{f}^1_{ab}\overline{\hat{\Psi}}_{aL}\hat{\Phi}_1\hat{e}_{bR} - V\hat{f}^2_{ab}\overline{\hat{\Psi}}_{aL}\hat{\Phi}_2\hat{e}_{bR}$$
$$-V\hat{f}^h_{ab}\overline{\hat{\Psi}}^c_{aL}i\tau_2\hat{\Psi}_{bL}\hat{h} - \frac{\kappa}{V}\hat{\Phi}_1 i\tau_2\hat{\Phi}_2\hat{h}^* + H.c., \qquad (3)$$

where the volume factor V have been factored out to make the coupling constants $\hat{f}$'s and κ dimensionless. After integrating over y and approximating $\mathbf{g}^2(y, c)$ by $\delta(y - c)$ for $\sigma \ll R$, we obtain the effective 4D Yukawa:

$$f^{1(n)}_{ab} \simeq (\sqrt{2})^{1-\delta_{n,0}}\hat{f}^1_{ab}\exp\left[\frac{-(\triangle^{LR}_{ab})^2}{2\sigma^2}\right]\cos\frac{n\bar{c}^{LR}_{ab}}{R},$$
$$f^{2(n)}_{ab} \simeq \sqrt{2}\hat{f}^2_{ab}\exp\left[\frac{-(\triangle^{LR}_{ab})^2}{2\sigma^2}\right]\sin\frac{n\bar{c}^{LR}_{ab}}{R},$$
$$f^{h(n)}_{ab} \simeq \sqrt{2}\hat{f}^h_{ab}\exp\left[\frac{-(\triangle^{LL}_{ab})^2}{2\sigma^2}\right]\sin\frac{n\bar{c}^{LL}_{ab}}{R}, \qquad (4)$$

where the KK level is labeled by "(n)", $\bar{c}^{\alpha\beta}_{ab} \equiv (c^\alpha_a + c^\beta_b)/2$ and $\triangle^{\alpha\beta}_{ab} \equiv (c^\alpha_a - c^\beta_b)$ are the mean position and the relative distance between split fermion-a and b respectively. Furthermore, a tower of KK Higgs cubic terms appears