F-theory and Neutrinos: Kaluza-Klein Dilution of Flavor Hierarchy

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Abstract. We present a Majorana neutrino scenario in a F-theory SU(5) GUT model, which is recently proposed in [1]. The mass scale of the neutrinos arises from integrating out heavy Kaluza-Klein modes on the right-handed neutrinos. The participation of non-holomorphic Kaluza-Klein mode wave functions dilutes the mass hierarchy in comparison to the quark and charged lepton sectors, in agreement with experimentally measured mass splittings. The neutrinos are predicted to exhibit a "normal" mass hierarchy, with masses $(m_3, m_2, m_1) \sim .05 \times (1, \alpha_{GUT}^{1/2}, \alpha_{GUT})$ eV. The neutrino mixing matrix exhibits a mild hierarchical structure with $\theta_{13} \sim \alpha_{GUT}^{1/2} \sim 0.2$. We also predict mass measurements in single and double beta decay experiments.

Keywords: F-theory GUT models, neutrino, Kaluza-Klein modes, normal hierarchy, neutrino oscillation, PMNS matrix, large reactor angle, GUT coupling constant
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INTRODUCTION

The aim of this proceeding is to deliver the main idea of our recent work [1] on minimal implementations of neutrino scenarios in F-theory GUT models. In order to make the presentation more accessible to wider audience, we will focus on sketching one particular case and discussing its experimental prediction.

Let us begin by motivating why neutrino physics is interesting, particularly to model builders. Then we will explain why F-theory is a promising set-up for building a GUT model. In the next section, we will introduce our neutrino model in F-theory GUT. Then, we will state what experimental results this model predicts.

Neutrino oscillations [2, 3] tell us that neutrinos have small nonzero masses, which defies Standard Model and challenges us to look into physics beyond the Standard Model. It is particularly challenging to put neutrinos into a GUT, because they behave very differently from charged lepton and quark sectors, in their mass and mixing structure. The mass hierarchy is much milder and mixing is much wilder for neutrinos. Also, we are still waiting to obtain more experimental result about neutrinos. We still need to test whether neutrinos have Majorana nature. We also want to know more precise values of masses and mixing angles. Particularly, we do not know what kind of mass hierarchy the neutrinos have. This scarcity of information makes the model building harder, but potentially more rewarding, because this gives us an opportunity for prediction instead of postdiction.

String theory can help putting neutrinos into a GUT by providing higher-dimensional operator for neutrino seesaw mechanism. Among many string theory based model building schemes, F-theory model building has some advantages over heterotic string theory in breaking GUT group and over Type IIB string in allowing up-type interaction terms [4].

F-THEORY SU(5) GUT MODEL WITH MAJORANA NEUTRINO

Now we turn to discuss our Majorana neutrino scenario in minimal F-theory GUT model setting. The most essential knowledge of the F-theory GUT model necessary for understanding this proceeding is this. In the F-theory GUT model, the fields charged under GUT lives in a 4 real dimensional surface. Various matters charged under certain representations of GUT group live on this 4d surface, and their distribution is given by a wave function, which is peaked along 2d matter curve. When the matter curves intersect at a point, we have a Yukawa interaction, whose strength is given as the overlap of the corresponding wavefunctions. In [5], Yukawa couplings of charged lepton and quark sectors and their hierarchy structure are studied in detail.

Now we are ready to discuss Yukawa interactions involving neutrinos. We will restrict the discussion to a Majorana neutrino scenario with seesaw mechanism involving heavy right-handed neutrinos N_R. The right-handed neutrinos is singlet under SU(5) GUT group, therefore it does not live on the same 4d manifold as other matter fields. Instead, the right-handed neutrinos matter curve intersect 4d manifold at a point, and there are no zero modes on this curve. This is to be contrasted against other MSSM matter curves which have zero-modes living on them. Right-handed neutrinos fields are Kaluza Klein modes, in other words, heavy excited state in internal compactified geometry, on this curve. They are much heavier than other fields, and this provides the heavy mass for the seesaw mechanism to give the appropriate mass scale.

There is an extra prize we get for considering KK modes. They also explain why mass hierarchy and mixing structure is qualitatively different for neutrinos from other sectors. Wavefunction for KK modes behaves differently than that of 0-modes, in that the former is non-holomorphic and the latter is holomorphic. Therefore the wavefunction overlap breaks U(1) symmetry of holomorphicity, and wavefunction overlap or Yukawa coupling strength behaves very differently. In short, the Yukawa couplings involving right-handed neutrinos are very different from others, due to non-holomorphicity of Kaluza-Klein mode wavefunction of right-handed neutrinos matter curve.

Let us sketch the result. Superpotential terms for neutrino interactions are given as

$$\widetilde{W} \supset \widetilde{y}_{i,I}\widetilde{H}_u\widetilde{L}^i\widetilde{N}_I + \widetilde{y}'_{j,J}\widetilde{H}_u\widetilde{L}^j\widetilde{N}^c_J + \widetilde{M}_{IJ}\widetilde{N}^c_I\widetilde{N}_J$$

with Yukawa strength $\widetilde{y}_{i,I} = \int \widetilde{\Psi}_{H_u}\widetilde{\Psi}^i_L\widetilde{\Psi}^{(I)}_N$ which is amount of wave function overlap. After integrating out the heavy N_Rs, we get

$$W_{\text{eff}} \supset \lambda^{(\nu)}_{ij}\frac{\left(H_uL^i\right)\left(H_uL^j\right)}{\Lambda_{\text{UV}}}$$

from which we can read off neutrino mass matrix

$$\frac{\lambda^{(\nu)}}{\Lambda_{\text{UV}}} = \widetilde{y}\cdot\frac{1}{M}\cdot\widetilde{y}^T \sim \frac{1}{M_*}\begin{pmatrix} \varepsilon^2 & \varepsilon^{3/2} & \varepsilon \\ \varepsilon^{3/2} & \varepsilon & \varepsilon^{1/2} \\ \varepsilon & \varepsilon^{1/2} & 1 \end{pmatrix} \qquad (1)$$

with $\varepsilon \sim \sqrt{\alpha_{GUT}}$. From diagonalizing this, we obtain mass eigenvalues and mixing matrix. Let us compare them with the experiments in next section.

COMPARISON WITH EXPERIMENTS

Let us first study the neutrino mixing matrix, or so-called PMNS matrix after [6, 7].

$$U_{\rm PMNS} = U_L^{(l)} \left(U_L^{(\nu)}\right)^\dagger = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot D_\alpha$$

where $D_\alpha = {\rm diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$, $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. δ, α_1 and α_2 are CP violating phases.

In our model, we get

$$U_{\rm PMNS}^{\rm F-th} \sim \begin{pmatrix} U_{e1} & \varepsilon^{1/2} & \varepsilon \\ \varepsilon^{1/2} & U_{\mu 2} & \varepsilon^{1/2} \\ \varepsilon & \varepsilon^{1/2} & U_{\tau 3} \end{pmatrix}$$

with $\varepsilon \sim \sqrt{\alpha_{GUT}} \sim .2$.

Our model gives

$$\left|U_{\rm PMNS}^{\rm F-th}\right| \sim \begin{pmatrix} 0.87 & 0.45 & 0.2 \\ 0.45 & 0.77 & 0.45 \\ 0.2 & 0.45 & 0.87 \end{pmatrix},$$

whereas the global fit [8, 9]of experimental result tells

$$\left|U_{\rm PMNS}^{3\sigma}\right| \sim \begin{pmatrix} 0.77-0.86 & 0.50-0.63 & 0.00-0.22 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix},$$

displaying a remarkable agreement. Note that we predict a rather large value of upper right corner, $\sin\theta_{13} \sim 0.2$, and we are delighted that there is new experimental result confirming the largeness of θ_{13} angle [10].

Next, let us look at the ratio of neutrino mass eigenvalues. Our model predicts mild "normal hierarchy" $m_1 : m_2 : m_3 \sim \varepsilon^2 : \varepsilon : 1$ with $\varepsilon \sim \sqrt{\alpha_{GUT}} \sim .2$. If one assumes normal hierarchy, the experimental data automatically gives $m_3^{\rm observe} \sim \sqrt{\Delta m_{31}^2} \sim 50 \pm 4$ meV, $m_2^{\rm observe} \sim \sqrt{\Delta m_{21}^2} \sim 8.7 \pm 0.4$ meV, and our F theory model predicts the smallest mass eigenvalue to be $m_1^{\rm F-th} \sim 1-3$ meV.

Our prediction for double beta decay mass $\left|m_{\beta\beta}\right|^2 = \left|\sum_{i=1}^{3} m_i \left(U_{ei}^{\rm PMNS}\right)^2\right|^2$ is $m_{\beta\beta}^{\rm max} \sim$ 6 meV, and this may be observed within ten years. The EXO experiment is expected to be sensitive down to 4-40 meV [11].

For single beta decay $\left|m_\beta\right|^2 = \sum_{i=1}^{3} m_i^2 \left|U_{ei}^{\mathrm{PMNS}}\right|^2$, we predict $\left|m_\beta^{\mathrm{F-th}}\right| \sim 5 - 10$ meV, which is too small to be observed soon. The KATRIN experiment is expected to be sensitive down to 0.2 eV [12].

CONCLUSION

F-theory GUT model offers a neutrino model which explains or accommodates neutrino mass's normal hierarchy and mixing matrix. KK modes living on N_R curve provide heavy mass for seesaw mechanism to work. They also dilute the hierarchy of neutrino physics. We predict θ_{13} to be near current experimental bound, and we also predict m_1 and other mass values to be measured in beta decay experiments.

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