PROCEEDINGS OF SCIENCE

The neutrino problem in string models

Christos Kokorelis[a,*]

[a] *College of Data Science and Engineering, American University of Malta, Triq Dom Mintoff, Bormla, BML 1013, Malta*

E-mail: christos.kokorelis@aum.edu.mt

At the standard model of electroweak interactions neutrinos are massless and mixing among the neutrinos in different families is not predicted. Also the standard model does not include gravity. I discuss the first appearance of sterile neutrinos in D-brane models from string theories. In particular, I focus on a 5-stack intersecting D6-brane string model from IIA orientifolds. The sterile neutrinos couple to the right handed neutrino and the left handed neutrino of a single family. The existence of sterile neutrinos is independent of string RR tadpole cancellation conditions satisfaction.

Corfu Summer Institute 2021 "School and Workshops on Elementary Particle Physics and Gravity"
29 August - 9 October 2021
Corfu, Greece

*Speaker

https://pos.sissa.it/

PoS(CORFU2021)126

1. Introduction

The Standard model (SM) admits the presence of three neutrino flavours, namely ν_e, ν_μ, ν_τ which however are massless, there is no gauge invariant mass term allowed that could give mass terms to the neutrinos. In this sence the SM is incomplete. On the other hand the SM does not describe gravity. Neutrinos could get masses, by adding to the SM Lagrangian Dirac terms like

$$\lambda_1^{ij} N_L^i \nu_R^j H_1, \tag{1}$$

where λ_1 a coupling coefficient, $N_L = (l, \nu)$ one of the three lepton doublets, l_R a right handed lepton singlet, i, j flavour indices and H a Higgs particle. No term violates baryon number B and lepton flavour numbers L_e, L_μ, L_τ and the lepton number $L = L_e + L_\mu + L_\tau$ that naturally appear as accidental symmetries.
Also possible it to add to (1) a Majorana mass term [1] in the form $\propto \nu_R \nu_R$, giving rise to the see-saw mechanism

$$\lambda_1^{ij} N_L^i \nu_R^j H_1 + \lambda_2^{ij} \frac{F_R^H F_R^H \nu_R^i \nu_R^i}{M_s} + h.c. \tag{2}$$

where F_R^H some Higgs-like fields, M_s some high scale acting as a natural cutoff (in string theory, it is the string scale). In its simplest form, involving one generation of neutrinos, it takes the form

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix},$$

where $m = \lambda_1 < H_1 >$. After diagonalization the neutrino mass matrix gives us two eigenvalues, the "light" eigenvalue giving a mass to ν_L

$$m_{light} \approx \frac{m^2}{M} = \frac{\lambda_1^2}{\lambda_2} \frac{< H_1 >^2 M_s}{< H >^2},$$

where $< F_R^H > = < H >$, and the "heavy" eigenvalue

$$M \approx M = \lambda_2 \frac{< H >^2}{M_s}$$

associated to the interacting right handed neutrino. For application of the see saw mechanism see [2], [3], [4]. The string scale can be high ($M_s \geq 10^{16}$ GeV) [5] or it can be low as 1 TeV as in string models [6, 7] with large extra dimensions [8]. Experiments regarding data from solar, atmospheric, reactor and accelerator experiments [9] (namely, SNO, Super-Kamiokande, Icecube, KamLand, DayaBay, RENO, Double Choz, T2K, Nova, Minos, Opera) describe with consistency the phenomenon of neutrino oscillations, where at the three flavour paradeigm of active neutrinos oscillations, the weak eigenstates mix with the mass eigenstates as described by PMNS unitary mixing matrix formalism [15]. The unitary matrix is described by three mixing angles θ_{12}, θ_{13}, θ_{23} and a CP violating phase δ_{CP}.

However, there are anomalies observed regarding : i) the non-canonical appearance of $\bar{\nu}_e$ in short baseline $\bar{\nu}_e$ beams of LSND [10] and MiniBooNE [11] experiments and also ii) decrement of ν_e predicted rates from radiaactive sources in gallium experiments. The new data are accommodated using a forth neutrino that does not couple through weak interactions, thus the name sterile.

Experimental results constrain the sterile neutrino mass m_s squared differences to be of order

$$10^{-4}\ \frac{eV^2}{c^4}\ < \triangle m^2_{s1} = n^2_s - m^2_1 < 3 \times 10^{-3}\ \frac{eV^2}{c^4}\ , \tag{3}$$

where the lower limit comes from Minos [12] (they have assumed in a 3+1 model, that $\triangle m^2_{32} \approx \triangle m^2_{31}$; and $\triangle m^2_{41} >> \triangle m^2_{31}$, such that $\triangle m^2_{41} \approx \triangle m^2_{42} \approx \triangle m^2_{43}$) and the upper limit from T2K Superkamiokande [13] experiments. The existence of sterile neutrino is also supported by various arguments in cosmology [14].

2. The five stack Standard Model

In intersecting brane constructions [17–20] chiral fermions appear as open strings stretching between brane intersecting at angles and gauge bosons living on D-branes. Each D-brane would give rise to a U(1) and the U(N) gauge group arises from N overlapping D-branes stacks. By considering N_a stacks of D-brane configurations with $N_a, a = 1, \cdots, N$, parallel branes one gets the gauge group $U(N_1) \times U(N_2) \times \cdots \times U(N_a)$. Each $U(N_i)$ factor will give rise to a $SU(N_i)$, charged under the associated $U(1_i)$ gauge group factor that appears in the decomposition $SU(N_a) \times U(1)_a$. The model we will be using to examine the presence of sterile neutrinos is a five stack D6-brane string model of [21]. For this class of models it has been shown [22], among other predictions, that it can accommodate $b \to sl + l-$ anomalies and furthermore its stringy Z′ boson considered has nonnegligible couplings to the first two quark generations and has a mass in the range [3.5, 5.5] TeV, so it is possible to be discovered directly during the next LHC runs via Drell-Yan production in the di-electron or di-muon decay channels.

The initial gauge group of the model is $U(3)_c \times U(2)_b \times U(1)_c \times U(1)_d \times U(1)_e$ or $SU(3)_c \times SU(2)_w \times U(1)_b \times U(1)_c \times U(1)_d \times U(1)_e$ at the string scale. The model accommodates the global symmetries of the Standard model (SM) , namely Baryon B and Lepton number L, to local gauge symmetries. The representation content of the Standard Model is seen at table (1) charged under the five U(1) symmetries Q_a, Q_b, Q_c, Q_d, Q_e.

There are various gauged low energy symmetries in the models. They are defined in terms of the U(1) symmetries Q$_a$, Q$_b$, Q$_c$, Q$_d$, Q$_e$, where the baryon number B and lepton number L, respectively are equal to

$$Q_a = 3B,\ L = Q_d + Q_e,\ Q_a - 3Q_d - 3Q_e = 3(B - L),\ Q_c = 2I_{3R} \tag{4}$$

and I_{3R} being the third component of weak isospin and $3(B - L)$ and Q_c are free of triangle anomalies. The $U(1)_b$ symmetry plays the role of a Peccei-Quinn symmetry, having mixed SU(3) anomalies.

3. The sterile neutrino appearance

Small neutrino masses ≈ 0.1-10 eV in consistency with LSND experiments, in the 5-stack classes of models, get generated from dimension 6 operators in the form,

$$\alpha'(LN_R) < Q_L U_R >,\ \ \alpha'(l\nu_R)(< q_L U_R >) \tag{5}$$

Matter Fields		Intersection	Q_a	Q_b	Q_c	Q_d	Q_e	Y
Q_L	$(3,2)$	$I_{ab}=1$	1	−1	0	0	0	1/6
q_L	$2(3,2)$	$I_{ab^*}=2$	1	1	0	0	0	1/6
U_R	$3(\bar{3},1)$	$I_{ac}=-3$	−1	0	1	0	0	−2/3
D_R	$3(\bar{3},1)$	$I_{ac^*}=-3$	−1	0	−1	0	0	1/3
L	$2(1,2)$	$I_{bd}=-2$	0	−1	0	1	0	−1/2
l_L	$(1,2)$	$I_{be}=-1$	0	−1	0	0	1	−1/2
N_R	$2(1,1)$	$I_{cd}=2$	0	0	1	−1	0	0
E_R	$2(1,1)$	$I_{cd^*}=-2$	0	0	−1	−1	0	1
ν_R	$(1,1)$	$I_{ce}=1$	0	0	1	0	−1	0
e_R	$(1,1)$	$I_{ce^*}=-1$	0	0	−1	0	−1	1

Table 1: Low energy *chiral* fermionic spectrum of the five stack string scale $SU(3)_C \otimes SU(2)_L \otimes U(1)_a \otimes U(1)_b \otimes U(1)_c \otimes U(1)_d \otimes U(1)_e$ intersectingg D6-brane model. At low energies only the SM gauge group $SU(3) \otimes SU(2)_L \otimes U(1)_Y$ survives.

breaking the $U(1)_b$ PQ like symmetry through chiral symmetry breaking related to the existence of the u-quark chiral condensate $< Q_L U_R > = < q_L U_R > \approx\ 240\ (MeV)^3$.

For the generation of sterile neutrino, we will use a different interation term than (5), namely the Dirac-type interactions, that mix left handed nutrino, right handed neutrino and the stetile neutrino

$$\mathcal{L} = \tilde{\lambda}_1\, l_L\, \nu_R\, \langle h_1 \rangle + \frac{\tilde{\lambda}_2}{M_s} \nu_R\, N_1\, \langle K \rangle\ +\ h.c, \tag{6}$$

or

$$\mathcal{L} =\ m_D \nu_L \nu_R\ + m_N \nu_R N_1\ \ , \tag{7}$$

where

$$m_D = \tilde{\lambda}_1 \langle h_1 \rangle\ , m_N\ = \frac{\tilde{\lambda}_2}{M_s} \langle K \rangle, \tag{8}$$

K a product of Higgs-like fields. The Yukawa couplings

$$\tilde{\lambda}_1, \tilde{\lambda}_2 \propto\ e^{-\frac{A_{ijk}}{2\pi\alpha'}}\ , \tag{9}$$

where A the is the area connecting the corresponding i, j and k intersections [23]. In the eigenstate basis (ν_L, ν_R, N_1) the sterile neutrino N_1 terms of (6) give rise to the 3 x 3 mass matrix

$$M_\nu\ \ =\ \left(\begin{array}{ccc} 0 & m_D & 0 \\ m_D & 0 & m_N \\ 0 & m_N & 0 \end{array} \right), \tag{10}$$

which gives a zero eigenvalue associated with the mass eigenstage of ν_L and two non-zero eigenvalues associated with ν_R and N_1, namely m_{ν_R} , m_{N_1} respectively. Given the limits (3) the values of sterile eigenvalue may be inside the limits

$$10^{-4}\ \frac{eV^2}{c^4}\ < \triangle m_{s1}^2 = m_{N_1}^2 < 3 \times 10^{-3}\ \frac{eV^2}{c^4} \tag{11}$$

Detailed studies of neutrino oscillations including also the accommodation of the rest of the left handed neutrino flavours will be performed elsewhere [24].

References

[1] P. Minkowski, Phys . Lett. B67 (1977) 421

[2] J. Pati and A. Salam, “Lepton number as a fourth colour”, Phys. Rev. D10 (1974) 275; J. C. Pati, "Advantages of Unity With SU(4)-Color: Reflections Through Neutrino Oscillations, Baryogenesis and Proton Decay", Int.J.Mod.Phys.A 32 (2017) 09, 1741013 , arXiv:1706.09531 [hep-ph]

[3] I. Antoniadis, G.K. Leontaris, "A supersymmetric SU(4) x O(4) Model", Phys. Lett.B 216 (1989) 333; G.K. Leontaris and J. Rizos, “A Pati-Salam model from branes”, Phys. Lett. B510 (2001) 295, arXiv:hep-ph/0012255[hep-ph];

[4] Alon E. Faraggi, Marco Guzzi, "Z′ and sterile neutrinos from heterotic string models: exploring Z′Z mass exclusion limits", arXiv: 2204.11974 [hep-ph]

[5] M. Cvetic, G. Shiu, A. M. Uranga, Chiral four-dimensional N=1 supersymmetric type 2A orientifolds from intersecting D6 branes Nucl. Phys. B 615 (2001) 3, arXiv: hep-th/0107166 [hep-th]; Tianjun Li, Adeel Mansha, Rui Sun, Lina Wu, Weikun He, N=1 supersymmetric $SU(12)_C \times SU(2)_L \times SU(2)_R$ models, $SU(4)_C \times SU(6)_L \times DU(2)_R$ models, and $SU(4)_C \times SU(2)_L \times SU(6)_R$ models from intersecting D6-branes, Phys. Rev. D 104 (2021) 4, 046018; Ching-Ming Chen, Tianjun Li, V.E. Mayes, Dimitri V. Nanopoulos, "A Realistic world from intersecting D6-branes", Phys. Lett. B 665 (2008) 267, arXiv: hep-th/0703280 [hep-th]

[6] Standard model at intersecting D5-branes: Lowering the string scale D. Cremades, L.E. Ibanez, F. Marchesano, Nucl. Phys. B 643 (2002) 93, arXiv: hep-th/0205074 [hep-th]

[7] Christos Kokorelis, Exact standard model structures from intersecting D5-branes, Nucl. Phys. B 677 (2004) 115, arXiv: hep-th/0207234 [hep-th]

[8] I. Antoniadis, N. Arkadi-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B436 (1998) 257, arXiv:hep-ph/9804398 [hep-ph]

[9]] B. Aharmim et al. (SNO Collaboration), Phys. Rev. C 88, 025501 (2013); K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D 94, 052010 (2016); K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D 97, 072001 (2018); M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. Lett. 120, 071801 (2018); A. Gando et al. (KamLAND Collaboration), Phys. Rev. D 88, 033001 (2013); D. Adey et al. (Daya Bay Collaboration), Phys. Rev. Lett. 121, 241805 (2018); G. Bak et al. (RENO Collaboration), Phys. Rev. Lett. 121, 201801 (2018); Y. Abe et al. (Double Chooz Collaboration), JHEP 01, 163 (2016); K. Abe et al. (T2K Collaboration), Phys. Rev. Lett. 121, 171802 (2018); M. A. Acero et al. (NOvA Collaboration), Phys. Rev. D 98, 032012 (2018); N. Agafonova et al. (OPERA Collaboration), Phys. Rev. Lett. 120, 211801 (2018)

[10] A. Aguilar et al. (LSND Collaboration), Phys. Rev. D 64, 112007 (2001)

[11] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. 121, 221801 (2018)

[12] P. Adamson et al. (MINOS Collaboration), Search for sterile neutrinos in MINOS and MINOS+ using a two-detector fit, Phys. Rev. Lett. 122, 091803 (2019), arXiv:1710.06488 [hep-ex]

[13] K. Abe et al., Search for light sterile neutrinos with the T2K far detector Super-Kamiokande at a baseline of 295 km, Phys. Rev. D 99, 071103 (2019), arXiv:1902.06529 [hep-ex]

[14] M.A. Acero, C.A. Argüelles, M. Hostert, D. Kalra, G. Karagiorgi, White Paper on Light Sterile Neutrino Searches and Related Phenomenology, Contribution to: 2022 Snowmass Summer Study, arXiv: 2203.07323 [hep-ex] ; E. Di Valentino, S. Gariazzo, C. Giunti, O. Mena, S. Pan, Minimal dark energy: key to sterile neutrino and Hubble constant tensions?, arXiv: 2110.03990 [astro-ph.CO]; E. Giusarma, M. Corsi, M. Archidiacono, R. de Putter, A. Melchiorri, O. Mena, S. Pandolfi, Constraints on massive sterile neutrino species from current and future cosmological data, Phys. Rev. D 83, 115023 (2011), arXiv:1102.4774 [astro-ph.CO] ; J. Hamann, S. Hannestad, G. G. Raffelt, I. Tamborra, Y. Y.Y. Wong, Cosmology seeking friendship with sterile neutrinos Phys. Rev. Lett. 105, 181301 (2010),arXiv:1006.5276 [hep-ph]; J. Hamann, S. Hannestad, G. G. Raffelt, Y. Y.Y. Wong Sterile neutrinos with eV masses in cosmology: How disfavoured exactly? , Cosmol. Astropart. Phys. 09 (2011) 034, e-Print: 1108.4136 [astro-ph.CO] ;

[15] B. Pontecorvo, Sov. Phys. JETP 6, 429 (1957); B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968);Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. 28, 870 (1962)

[16] K. L. De Holton, "Atmospheric Neutrino Oscillations with 8 years of data from IceCube DeepCore", PoS NuFact2021 (2022) 062,

[17] D. Lust, Intersecting Brane Worlds – A Path to the Standard Model ? Class. Quant. Grav. 21 (2004) S1399, arXiv:hep-th/0401156[hep-th]

[18] Carlo Angelantonj and A. Sagnotti, 'Open Strings", Phys. Rept. 371 (2002) 1; Phys.Rept. 376 (2003) 6, 407 (erratum) arXiv: hep-th/0204089 [hep-th]

[19] R. Blumenhagen, B. Kors, D. Lust, S. Stieberger, Four-dimensional String Compactifications with D-Branes, Orientifolds and Fluxes, Phys. Rept. 445 (2007) 1, arXiv: hep-th/0610327 [hep-th]

[20] R. Blumenhagen, M. Cvetic, P. Langacker, G. Shiu, Toward realistic intersecting D-brane models Ann. Rev. Nucl. Part. Sci. 55 (2005) 71, arXiv: hep-th/0502005 [hep-th]

[21] C. Kokorelis, "New standard model vacua from intersecting branes," JHEP 0209, 029 (2002), arXiv:hep-th/0205147 [hep-th/0205147]

[22] A. Celis, W. Z. Feng and D. Lust, "Stringy explanation of b $\to sl^{+}l^{-}$ anomalies," JHEP 1602, 007 (2016), arXiv:1512.02218 [hep-ph]

[23] S.A. Abel, A.W. Owen, Interactions in intersecting brane models Nucl. Phys. B 663 (2003) 197, arXiv: hep-th/0303124 [hep-th]

[24] I. Antoniadis and C. Kokorelis, to appear