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SU(5) unified theories from intersecting branes

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Abstract: We discuss the first string theory examples of three generation non-supersymmetric SU(5) and *flipped* SU(5) GUTS, which break to the Standard model at low energy, without extra matter and/or gauge group factors. Our GUT examples are based on IIA $\mathbb{Z}_3$ orientifolds with D6-branes intersecting at non-trivial angles. These theories necessarily satisfy RR tadpoles and are free of NSNS tadpoles as the complex structure moduli are frozen (even though a dilaton tadpole remains) to discrete values. We identify appropriately the bifundamental Higgses responsible for electroweak symmetry breaking. In this way, the neutrino see-saw mechanism gets nicely realized in these constructions. Moreover, as baryon number is not a gauged symmetry gauge mediated dimension six operators do contribute to proton decay; however proton lifetime may be safely enhanced by appropriately choosing a high GUT scale. An accompanying natural doublet-triplet splitting guarantees the suppression of scalar mediated proton decay modes and the stability of triplet scalar masses against higher dimensional non-renormalizable operators.

Keywords: D-branes, Beyond Standard Model, GUT, Compactification and String Models.

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1. Introduction

Grand Unified Theories (GUTS) were historically formulated in order to derive the Standard Model (SM), $SU(3) \times SU(2) \times U(1)_Y$, from a single unified gauge group [1, 2] interaction.[1] For more recent reviews see [3, 4]. Novel phenomena such as rapid proton decay as well as the gauge hierarchy problem motivated the development of $N = 1$ supersymmetric (SUSY) unification [5]. See also [6] for reviews in the development of supergravity GUTS that follow the early global SUSY GUT era. The subsequent advent of superstring unification [7] motivated much work on embedding (SUSY) GUTS in the framework of four dimensional compactifications of the heterotic string [8]. Important challenges that these model building constructions still have to face are: abundance of extra matter and a large number of undetermined scalar moduli, the sypersymmetry breaking mechanisms etc. However, apart from providing a consistent framework for perturbative quantum gravity, a standing goal of string theory has been to demonstrate, that vacua with only the SM at low energy exist. Steps towards bypassing this obstacle have been taken recently through the use of D-brane machinery [9] , in model building constructions based on intersecting brane worlds (IBW's) [14]–[29]. There, in a top-bottom approach, it became possible to localize, at four dimensions, the Standard Model with right handed neutrinos [10]–[12]. We

[1]Embedding the SM into a larger albeit semi-simple gauge group was the original idea of [2].

note that models with only the SM at low energy were also derived from a rather more arbitrary non-string bottom-up approach [13]. In the context of IBW's, the first string theory examples of four dimensional (4D) three generation (3G) non-SUSY string GUT models which break to exactly the Standard model at low energies without extra matter and/or gauge group factors were constructed in [14]. The most important phenomenological features of these classes of models,[2], which have D6-branes intersecting at angles on a toroidal orientifold [15], may be briefly described as follows :

- The models are built on an orientifolded toroidal background [15], with the a; b branes (supporting a $U(4)_C$; $U(2)_L$ gauge group resp.) accommodating the quarks, leptons; antiquarks respectively. Also some 'basic' branes $c, d, \dots$ are needed to be added, whose fermionic content is enforced by the RR tadpole[3] cancellation conditions. Their solution, in turn, enforces the introduction of extra e^i branes.

- Baryon number is a gauged symmetry and thus proton is stable. The theory has overall $N = 0$ supersymmetry (SUSY) in its open sectors, but it allows the existence of $N = 1$ SUSY in some open string sectors. The latter sectors may respect $N = 1$ SUSY in order, e.g. to allow for the existence of a Majorana mass for the right handed neutrino. Also $N = 1$ SUSY is required to make massive, by creating gauge singlets, the extra fermions appearing from the non-zero intersections between the extra branes e^i and the branes $c, d, \dots$.

- The most important result of these non-supersymmetric GUT constructions is the existence of $N = 1$ SUSY in some open sectors which gives rise to relations among the parameters of the RR tadpole cancellation conditions. The latter simultaneously solve the conditions of the extra U(1)'s (beyond the SM one's) which survive massless the Green-Schwarz anomaly cancellation mechanism. We note that models based on toroidal orientifold GUTS [14], even though they become automatically free of tachyons have as an open question the issue of their full stability as NSNS tadpoles are being left over [28]. Nevertheless, as no definite statement can be made about the full stability of non-supersymmetric toroidal orientifolds, in the present work we turn out attention to non-supersymmetric 4D chiral SU(5) and flipped SU(5) GUT orientifold constructions which involve $D6$ branes intersecting at angles and possess orbifold symmetries [28]. In this way, complex structure moduli will be fixed from the orbifold symmetry and the associated tadpoles vanish. We note that $N = 1$ supersymmetric SU(5) models have been first constructed in [21] and systematically explored in [22], even though at present there are no models which are free of exotic massless matter, present, to low energies. On the other hand non-SUSY SU(5) GUTS have been considered before on [28]. These models were suspected to suffer from serious shortcomings such as the absence of an appropriate identification for the electroweak (EW) 5-plets. Indeed both the tree level SU(5) couplings $\mathbf{10} \cdot \mathbf{10} \cdot \mathbf{5}$

[2]Which are based on the Pati-Salam gauge group structure $SU(4)_C \times SU(2)_L \times SU(2)_R$.

[3]Model based on D6-branes intersecting at angles are T-dual to models with magnetic deformations [31, 32].

responsible for giving masses to the (u,c,t) quarks and the Dirac mass terms needed for the realization of the see-saw mechanism were not allowed.[4] The flipped SU(5) GUTS were also considered previously [29] in IBW's. The proposed models, however, have several problems including the presence of extra massless matter at low energies [29]. In this work, we take a fresh look in the construction of SU(5) and flipped SU(5) GUTS. In particular, we will focus our attention to the construction of phenomenologically interesting SU(5) [1] and flipped SU(5) [35, 33] non-supersymmetric GUTS, that break to exactly the Standard Model (SM) at low energies without extra matter and/or additional gauge group factors.[5] The models we will present do not have baryon number as a gauged symmetry. A resolution to the doublet-triplet splitting problem thus guarantees phenomenologically acceptable long proton lifetime. We will identify appropriately the EW pentaplet Higgses for the presented classes of GUTS [28] and demonstrate the presence of a see-saw mechanism. To that end, we show that the existence of electroweak 5-plets is independent of the existence or not of tachyon bifundamental scalars. The latter fields break, in the SU(5) GUTS, the extra U(1) which survive massless the Green-Schwarz anomaly cancellation mechanism.

The paper is organized as follows: In section 2 we describe the general rules for building chiral GUT models in four dimensional $\mathbb{Z}_3$ orientifolded T^6 compactifications of IIA theory with D6 branes intersecting at angles. In section 3, we discuss the building of the usual SU(5) GUTS in these constructions by identifying appropriately the 5-plet electroweak Higgses. We also discuss the realization of the see-saw mechanism as well as the presence of Yukawa couplings in the above models. The second part of this work, is focused on the construction of flipped SU(5) GUTS from intersecting branes. In section 4, we describe explicitly the construction, fermion spectra, of the new classes of flipped SU(5) GUTS which break to the low energy without gauge group factors and/or extra fermions. In subsection 4.1, we discuss the GUT set of Higgses in the models and in subsection 4.2 the specific realization of the electroweak Higgs as previously massive tachyon bidoublets. In section 5, we discuss the issue of quark-neutrino-lepton masses in flipped SU(5) GUTS. In section 6 we discuss issues related to the proton decay modes in general SU(5) constructions from intersecting brane worlds, where baryon numbers is not a gauged symmetry. We discuss first the SU(5) GUTS. Then the flipped SU(5) GUTS are discussed, where the mechanism of doublet-triplet splitting mechanism, in a non-supersysmmetric framework, which suppress scalar mediated proton decay modes, is tested against its stability due to higher order non-renormalizable interactions. Finally in section 7, we present our conclusions.

2. Geometry of $\frac{T^6}{\Omega\times\mathcal{R}\times\mathbb{Z}_3}$ orientifolds in intersecting brane worlds

We consider type I theory with D9 branes with magnetic fluxes. Also let us assume that we have a six dimensional tori, which is decomposed as a product of three two dimensional

[4]The absence of the mass couplings $\mathbf{10}\cdot\mathbf{10}\cdot\mathbf{5}$ persists in the 4D N=1 supersymmetric $U(5)\times U(1)^n$ standard-like models of [22].

[5]We note that even these models are overall non-SUSY they may have in cases N=1 supersymmetric sectors that may offer a partial protection of the Higgs doublets against the quadratic mass renormalization.

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tori $T^6 = (T^2)^I \otimes (T^2)^J \otimes (T^2)^K$ and where we have introduced complex coordinates $Z^l = X^l + iY^l$, $l = I, J, K$ defined on the three tori. After performing a T-duality along e.g. the Y^l direction our theory becomes an orientifold of type IIA with D6-branes intersecting at non-trivial angles. Imposing a further left-right symmetric $\mathbb{Z}_3$ orbifold symmetry θ : $Z^l \to e^{\frac{2\pi i}{3}} Z^l$, our theory becomes an orientifold of

$$\frac{(\mathrm{TypeIIA})/\mathbb{Z}_6}{\{\mathbb{Z}_3 + \Omega R \mathbb{Z}_3\}}\,. \tag{2.1}$$

In order to cancel the orientifold charge in six dimensional lattices, which have[6] the form AAA AAB, ABB, BBB, we introduce D6-branes at arbitrary angles which satisfy the following RR tadpole conditions [28]

$$\sum_a N_a Z_a = 2\,. \tag{2.2}$$

The net number of bifundamental massless chiral fermions in the models is defined as

$$\begin{aligned} (\bar{N}_a, N_b)_L :\ I_{ab} &= Z_a Y_b - Y_a Z_b \\ (N_a, N_b)_L :\ I_{ab^\star} &= Z_a Y_b + Y_a Z_b\,. \end{aligned} \tag{2.3}$$

Also present in the models are chiral fermions transforming in the symmetric (S) and antisymmetric (A) representations of the gauge group as follows

$$\begin{aligned} (A+S)_L &= Y_a \left(Z_a - \frac{1}{2} \right) \\ (A)_L &= Y_a\,. \end{aligned} \tag{2.4}$$

These S, R representations appear after the localization of open strings stretching between the $D6_a$ brane and its $\Omega\mathcal{R}\Theta^k$ images. Also non-chiral matter is generally present, but since is non-chiral it will be of no interest to us. In general it becomes massive by pairing up with adjoint scalars. The Z_a, Y_a, are characterized as effective wrapping numbers, which are functions of the wrappings (n^i, m^i), $i = 1, 2, 3$; define the homology cycle that the D6 brane wraps around the six dimensional toroidal internal space.

Also due to a generalized Green-Schwarz mechanism that involve BF type of couplings, the combination of U(1) F_a fields

$$\sum_a N_a Y_a F_a \tag{2.5}$$

gets massive by having a non-zero coupling to the corresponding RR field.

3. SU(5) GUTS from intersecting branes

In [28] the simplest construction of an SU(5) GUT was partially considered. In its minimal version the construction involves two stacks of D6-branes at the string scale M_s, the first

[6] The A lattice is defined by the complex structure moduli $U^A = 1/2 + i\sqrt{3}/2$, while the complex structure of the B-lattice is defined by $U^B = 1/2 + i1/2\sqrt{3}$. See [28] for more details.

Sector name	Multiplicity	SU(5)	$U(1)_a$	$U(1)_b$	$U(1)^{\text{mass}}$
{ 51 }	3	$\bar{\mathbf{5}}$	-1	1	$-6/5$
A_a	3	$\mathbf{10}$	2	0	$2/5$
S_b	3	$\mathbf{1}$	0	-2	2

Table 1: Chiral Spectrum of a two D6-brane stack three generation $SU(5) \otimes U(1)^{\text{mass}}$ with right handed neutrinos model. Also shown: the charges under the $U(1)^{\text{mass(less)}}$ gauge symmetry, which when rescaled appropriately (and remains unbroken) converts the original SU(5) model to the three generation flipped $SU(5) \times U(1)^{\text{fl}}$ of table 4.

one corresponding to a U(5) gauge group while the second one to a U(1) gauge group. Its effective wrapping numbers are

$$(Y_a, Z_a) = \left(3, \frac{1}{2}\right), \qquad (Y_b, Z_b) = \left(3, -\frac{1}{2}\right). \tag{3.1}$$

Under the decomposition $U(5) \subset SU(5) \times U(1)_a$, the models become effectively an $SU(5) \times U(1)_a \otimes U(1)_b$ class of models. One combination of U(1)'s become massive due to its coupling to the corresponding RR field. Another one remains massless to low energies. The latter combination will be finally broken by an appropriate vev as we will comment later.

The spectrum of these models is given in table 1, where the first two rows have the chiral content of the standard SU(5) generations and the third row is associated with the presence of right handed neutrino. Choices of values for the (n^i, m^i) wrappings satisfying the RR tadpoles (2.2) include e.g. for the AAA lattice

$$U(5): \ [(-3,2)(0,1)(0,-1)]; \qquad U(1): \ [(-3,2)(1,-1)(-1,0)] \tag{3.2}$$

or

$$U(5): \ [(0,1) \ (-1,1) \ (1,-3)]; \qquad U(1): \ [(-1,1) \ (1,0) \ (3,1)]. \tag{3.3}$$

The anomaly free U(1) symmetry surviving massless the Green-Schwarz mechanism (see (2.5)) is given by

$$U(1)^{\text{mass}} = \frac{1}{5} U(1)_a - U(1)_b. \tag{3.4}$$

The latter symmetry may be broken when the massive scalar superpartner of the right handed neutrino becomes massless and develops a vev. As was mentioned in [28] that may always happen as a tachyonic direction $s^B = \mathbf{1}^B_{(0,-2)}$ may always appear by open strings stretching between the branes that support the orbit of $U(1)_b$. In this case, the extra U(1) (3.4) gets broken by the $\langle s^B \rangle$ and the $U(5) \times U(1)$ model becomes an SU(5) class of GUTS with right handed neutrinos. In this case, the low energy chiral matter multiplet content, of table 1, is as follows :

$$\mathbf{10} = (Q, u^c, e^c), \qquad \bar{\mathbf{5}} = (d^c, L); \qquad \mathbf{1} = \nu^c. \tag{3.5}$$

Intersection	EW Higgs	repr.	Q_a	Q_b	$U(1)^{\text{mass}}$
$\{51^\star\}$	h_1	$\mathbf{5}$	1	1	$-4/5$
$\{51^\star\}$	h_2	$\bar{\mathbf{5}}$	-1	-1	$4/5$

Table 2: Higgs fields responsible for EW symmetry breaking in the SU(5) GUT.

Intersection	State	$(\text{Mass})^2$
$\{51^\star\}$	$h^- \to (-1+\vartheta_1, 0, \vartheta_3, 0)$	$\alpha'(\text{Mass})^2_{h^-} = \frac{Z_2^{(bc)}}{4\pi^2} + \frac{1}{2}(\vartheta_3 - \vartheta_1)$
$\{51^\star\}$	$h^+ \to (\vartheta_1, 0, -1+\vartheta_3, 0)$	$\alpha'(\text{Mass})^2_{h^-} = \frac{Z_2^{(bc)}}{4\pi^2} + \frac{1}{2}(\vartheta_1 - \vartheta_3)$

Table 3: States and $(Mass)^2$ in the SU(5) GUTS from intersecting branes

3.1 GUT and electroweak Higgs sector

After the breaking of the $U(1)^{\text{mass}}$ gauge symmetry, we still face the following two problems. Firstly we have to break the SU(5) symmetry down to the SM gauge symmetry and secondly to find the Higgs **5**-plets needed for electroweak symmetry breaking.

The first problem is solved by the use of the adjoint scalar **24**, part of the N=4 Yang-Mills in the aa-sector, which breaks the GUT symmetry to the $SU(3) \times SU(2) \times U(1)_Y$ [28].

On the other hand, the simultaneous presence of electroweak 5-plets was excluding the simultaneous presence of tachyon 1^B singlets, and vice-versa, in all lattices used in [28].

Lets us now see how the latter problem may be evaded in a way independent of the particular lattice involved. The electroweak **5**-plets needed, may be found in the NS sector $\{51^\star\}$. We remind the alert reader that there are no chiral fermions contributing to the spectrum of the models from the R sector $\{51^\star\}$. Hence the EW set of Higgs may be found as part of the massive N=2 hypermultiplet spectrum localized in this sector. These bifundamental Higgs states may be localized as they become tachyonic, as we vary the distances between the parallel a, b branes. They may be seen[7] in table 2.

We note that, for two branes belonging to different homology classes [5], [1], associated with the $U(5)_a$, $U(1)_b$ D6-branes respectively, the $(mass)^2$ operator receives contributions from open strings stretching between the a-brane and the $\Omega\mathcal{R}\Theta^k$ image of the b-brane. Thus the electroweak **5**-plets will receive contributions from the three different sectors just described.

The typical form of such a contribution to the $(mass)^2$ operator in the $\{51^\star\}$ sector is depicted in table 3.

Therein $\mathbb{Z}_2^{(bc)}$ is the relative distance in transverse space along the second torus from the orientifold plane; ϑ_1, ϑ_3, are the (relative) angles between the 5_a, $1_{b^\star}$ D6 branes in the first and third complex planes. Note that we have made the assumption that the 5_a, $1_{b^\star}$ D6 branes are parallel across the second complex plane. In this way it will become transparent in what follows which is the effective Higgs combination in this particular orbit. In fact, one may show that by using a particular set of wrappings, e.g. the one's in (3.2) that the

[7] We note that identification of electroweak Higgses may proceed along the same lines in the $N = 1$ supersymmetric SU(5) models of [22].

$(mass)^2$ operator receives contributions from the three different image orbits $\Omega\mathcal{R}\Theta^k$, and that the pair of 'rotated' 5_a, $1_{b^\star}$ D6 branes are parallel along different complex planes, across the different image orbits.

The presence of scalar doublets $h^\pm$ defined as

$$h^{\pm} = \frac{1}{2}(h_1^* \pm h_2)\,, \tag{3.6}$$

can be seen as coming from the field theory mass matrix

$$\begin{pmatrix} h_1^* & h_2 \end{pmatrix} \left(\mathbf{M^2}\right) \begin{pmatrix} h_1 \\ h_2^* \end{pmatrix} + \text{h.c.} \tag{3.7}$$

where

$$\mathbf{M^2} = M_s^2 \begin{pmatrix} Z_2^{(bc)}(4\pi^2)^{-1} & \frac{1}{2}|\vartheta_1^{(bc)} - \vartheta_3^{(bc)}| \\ \frac{1}{2}|\vartheta_1^{(bc)} - \vartheta_3^{(bc)}| & Z_2^{(bc)}(4\pi^2)^{-1} \end{pmatrix}. \tag{3.8}$$

Hence the effective potential which corresponds to the spectrum of electroweak Higgs h_1, h_2 may be expressed as

$$V_{\text{Higgs}}^{\text{bc}} = \overline{m}_H^2(|h_1|^2 + |h_2|^2) \;+\; (\overline{m}_B^2 h_1 h_2 + \text{h.c.})\,, \tag{3.9}$$

where

$$\overline{m}_H^2 = \frac{Z_2^{(bc)}}{4\pi^2\alpha'}\,; \qquad \overline{m}_B^2 \;=\; \frac{1}{2\alpha'}|\vartheta_1^{(bc)} - \vartheta_3^{(bc)}|\,. \tag{3.10}$$

It is obvious from (3.6) that the presence of EW **5**-plets of table 2, may be interpreted from the low energy point of view as an effective combination of the fields h_1 with charges $(1,1)$ and its conjugate representation h_2 with charges $(-1,-1)$. The latter comment will be particularly useful in the construction of flipped SU(5) GUTS later on.

3.2 Mass generation and Yukawa couplings

In this section, we will discuss the allowed Yukawa couplings responsible for giving masses to the up-down quarks. We also discuss the realization of the see-saw mechanism. The existence of this mechanism is particularly important for the phenomenology of the models as it may be responsible at disk level, for generating small neutrino masses in consistency with the neutrino oscillation experiments.

See-Saw mechanism. In the SU(5) theories described by the chiral spectrum of table 1, baryon and lepton number is not a gauged symmetry but rather it is the combination *(B-L)* which becomes gauged. This means that physical processes violate baryon and lepton number, e.g. $\triangle(B-L) = 0$. The violation of lepton number (VLN), e.g. by two units, may be seen as one of the most difficult problems in model building, namely the generation of small neutrino masses. The VLM may be easily accommodated in the presence of the Majorana mass term for right handed neutrinos in the see-saw mechanism.

In the presence of a lepton number violating term describing the right handed neutrino the Yukawa interactions give rise to the see-saw mechanism. Within our choice of electroweak Higgses takes the usual form

$$\mathcal{L} = Y_{ij}^{\nu_L\nu_R} \cdot \bar{\mathbf{5}}_i \cdot \mathbf{1}_j \cdot \mathbf{5}^B \;+\; Y^{\nu_R} \cdot \frac{1}{M_s} \cdot \mathbf{1}_i \cdot \mathbf{1}_j \cdot \bar{\mathbf{1}}_i^B \cdot \bar{\mathbf{1}}_j^B$$

or

$$\mathcal{L} = Y^{\nu_L \nu_R}_{ij} \cdot \bar{\mathbf{5}}_i \cdot \mathbf{1}_j \cdot h_2 \ + \ Y^{\nu_R} \cdot \frac{1}{M_s} \cdot \mathbf{1}_i \cdot \mathbf{1}_j \cdot \bar{\mathbf{1}}^B_i \cdot \bar{\mathbf{1}}^B_j \,. \tag{3.11}$$

The standard version of the see-saw mass matrix

$$(\, \nu \nu^c \,) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} (\, \nu \quad \nu^c \,) \tag{3.12}$$

is realized with

$$m = Y^{\nu_L \nu_R} \cdot \ \langle h_2 \rangle \sim Y^{\nu_L \nu_R} \cdot v \,, \qquad M = Y^{\nu_R} \cdot \frac{\langle \bar{\mathbf{1}}^B_j \rangle \cdot \langle \bar{\mathbf{1}}^B_j \rangle}{M_s} \sim \ M_s \,, \tag{3.13}$$

where the indices i, j are generation indices and we have chosen $Y^{\nu_L \nu_R} \ = e^{-A_1}$, $Y^{\nu_R} \sim e^{-A_2}$ and the hierarchy of neutrino masses is generated[8] by an interplay of the areas involved in in (3.13). The eigenvalues of the see-saw (3.12) are the heavy one M_1, which corresponds to the right handed neutrino, and the light one, M_2 which corresponds to the left handed neutrino

$$M_1 = M \,, \qquad M_2 = \frac{m^2}{M_1} \,. \tag{3.14}$$

The presence of the see-saw mechanism, renders the right handed neutrino sufficiently massive (of the order of the string scale M_s), such that it cannot be found at scales of the electroweak order. Therefore after the implementation of the see-saw (3.12) and the breaking of the U(1) (3.4), one is left with an SU(5) type of GUT, which breaks with the use of the adjoint vector multiplet, a **24**, to the $SU(3) \times SU(2) \times U(1)_Y$. Subsequently, the EW bifundamental Higgs **5**-plets of table 2 break the electroweak symmetry.

Masses for down quarks. Lets us focus our attention first to the d- type quarks. The Yukawa couplings responsible for giving masses to the d-type quarks[9] are given by the 'tree' level expression

$$Y^d \cdot \mathbf{10} \cdot \bar{\mathbf{5}} \cdot \bar{\mathbf{5}}^B = \ Y^d \cdot \langle h_2 \rangle \cdot \mathbf{10} \cdot \bar{\mathbf{5}} \,. \tag{3.15}$$

The factor Y^d parametrizes[10] the classical dependence of the Yukawa couplings on the worldsheet area A connecting the three vertices. As this coupling is of order $e^{-A} \cdot v$, the physical mass of the d-quark, $m_d = 0.01\,\mathrm{GeV}$ is reached naturally from above by choosing the area $A = 10.11$.

Masses for up quarks. The candidate 'tree' level coupling for giving mass to the (u, c, t) quarks given by $\mathbf{10} \cdot \mathbf{10} \cdot \mathbf{5}$ does not exist from charge conservation. The same coupling is also absent in attempts to build a consistent 3G 4D SU(5) model in [28] and also in 3G 4D supersymmetric SU(5)-like constructions [22]. Necessarily, the mass term responsible for up-quark generation may come from higher order non-renormalizable couplings.

Field	Sector name	Multiplicity	SU(5)	$U(1)_a$	$U(1)_b$	$U(1)^{\rm mass}$	$U(1)^{\rm fl} = 52 \times U(1)^{\rm mass}$
f	{ 51 }	3	$\bar{\mathbf{5}}$	-1	1	$-6/5$	-3
F	A_a	3	$\mathbf{10}$	2	0	2/5	1
l^c	S_b	3	$\mathbf{1}$	0	-2	2	5

Table 4: Chiral Spectrum of a two intersecting D6-brane stacks in a three generation flipped $SU(5) \otimes U(1)^{\rm mass}$ model. Note that the charges under the $U(1)^{\rm fl}$ gauge symmetry, when rescaled appropriately (and $U(1)^{\rm fl}$ gets broken) 'converts' the flipped SU(5) model to the three generation SU(5) of table 1.

4. Construction of ***flipped*** SU(5) GUTS

In [29] it was noticed that if one leaves unbroken the $U(1)^{\rm mass}$ factor, which remains massless after the implementation of the Green-Schwarz anomaly cencellation mechanism, and its charge is appropriately rescaled, the chiral content of table 1 is that of a three generation flipped SU(5) model. The relevant charges for the flipped SU(5) model may be seen in the last column of table 4. However, the 3G flipped SU(5) models produced in [29] have extra massless chiral matter remaining at low energies scales of the order of the electroweak scale and an incomplete GUT and/or electroweak (EW) Higgs sector.

In this section, we will achieve the task of obtaining a 3G flipped SU(5) GUT from intersecting D6 branes without extra matter and with a complete GUT and EW Higgs sector. Thus these models will achieve naturally the breaking to the SM gauge group of electroweak interactions, without extra matter and/or gauge group factors. Subsequently the electroweak Higgses will break the SM to the $SU(3)_c \times U(1)_{EM}$.

In a SU(5) GUT with the flipped chiral content, the fifteen fermions of the SM plus the right handed neutrino ν^c belong to the [35]

$$F = \mathbf{10_1} = (u, d, d^c, \nu^c)\,, \qquad f = \bar{\mathbf{5}}_{-\mathbf{3}} = (u^c, \nu, e)\,, \qquad l^c = \mathbf{1_5} = e^c \tag{4.1}$$

chiral multiplets. On the other hand the flipped SU(5) gauge group needs to be broken at the grand unification scale M_{GUT} by the vacuum expectation values of two fields[11] $\mathbf{10_1^B}$, $\mathbf{10^B_{-1}}$, where

$$H = \mathbf{10_1^B} = (u_H, d_H, d_H^c, \nu_H^c)\,, \qquad \bar{H} = \overline{\mathbf{10}}^{\mathbf{B}}_{-\mathbf{1}} = (\bar{u}_H, \bar{d}_H, \bar{d}_H^c, \bar{\nu}_H^c)\,. \tag{4.2}$$

Also, the electroweak symmetry breaking needs a Higgs sector that guarantees the presence of the multiplets $\mathbf{5_2^B}$, $\bar{\mathbf{5}}^{\mathbf{B}}_{-\mathbf{2}}$

$$h_3 = \mathbf{5^B_{-2}} = (D_1, D_2, D_3, h^-, h^0)\,, \qquad h_4 = \bar{\mathbf{5}}^{\mathbf{B}}_{\mathbf{2}} = (\bar{D}_1, \bar{D}_2, \bar{D}_3, h^+, \bar{h}^0)\,. \tag{4.3}$$

In what follows, we demonstrate that these two issues will be dealt with and solved independently of the presence of lattices on which the orbifold symmetry acts. The U(1) charge of the flipped $SU(5) \times U(1)$ GUT from intersecting D6-branes is depicted in table 4.

[8] As it has been shown explicitly in the first reference of [14], different choices of wrapping numbers involved in the leading worldsheet area contributions to the see-saw mass matrix Yukawa couplings, may always generate a hierarchy of neutrino masses in consistency with neutrino oscillation experiments.

[9] We are interested only in the couplings of the first generation.

[10] Y^u in the case of u-type Yukawa's.

[11] The subscript denotes the U(1) charge under the $U(1)^{\rm fl}$ factor of table 4.

Intersection	GUT Higgses	repr.	Q_a	Q_b	Q^{fl}
$\{a, \tilde{O}6\}$	H_1	$\mathbf{10}$	2	0	1
$\{a, \tilde{O}6\}$	H_2	$\overline{\mathbf{10}}$	-2	0	-1

Table 5: Flipped SU(5) $\otimes$ U^{fl} GUT symmetry breaking scalars which are part of the massive excitation spectrum in the appropriate sector. The last column denotes the flipped U(1) charge; the latter is defined explicitly in table 4.

Intersection	EW Higgs	repr.	Q_a	Q_b	Q^{fl}
$\{51^\star\}$	h_3	$\mathbf{5}$	1	1	-2
$\{51^\star\}$	h_4	$\bar{\mathbf{5}}$	-1	-1	$+2$

Table 6: Higgs fields responsible for EW symmetry breaking in the flipped SU(5) GUTS.

4.1 GUT Higgses for flipped SU(5)

GUT breaking Higgses may be found in the 'vicinity' of the chiral spectrum of table 4. The necessary Higgs GUT multiplets may come from the massive spectrum of the sector localizing the **10**-plet fermions seen in table 4. The lowest order Higgs in this sector, let us call them H_1, H_2 have quantum numbers as those given in table 5.

By looking at the last column of table 5, we realize that the Higgs H_1, H_2 are the GUT symmetry breaking Higgses of a standard flipped SU(5) GUT. By dublicating the analysis of section 3.1, one may conclude that what it appears in the effective theory as GUT breaking Higgs scalars, is the linear combination

$$H^G = H_1 + H_2^\star \,. \tag{4.4}$$

Hence, if for example the number of GUT Higgses is found to be n_H, that means that we have n_H intersections, with H^G scalars localized at each intersection.

Thus the necessary GUT Higgses for the breaking of the flipped SU(5) $\otimes$ U(1)$^{\text{fl}}$ get localized[12] in the sector $\{a, \tilde{O}6\}$. The latter sector, involves open strings stretching between a D6-brane belonging to the U(5)-stack of branes and the Θ^k images of the 06 planes.

4.2 Electroweak Higgses for flipped SU(5)

The presence of EW Higgses for flipped SU(5) in the intersecting brane world context, as in the EW Higgses of the SU(5) GUTS considered in section 3.1, is independent of the particular lattices on which the tadpole conditions are defined. In fact, their presence is valid for the tadpole conditions defined in the presence of the AAA, AAB, ABB, BBB, torus lattices [28], in eqn. (2.2).

The EW Higgses are 'made of' scalar particles[13] that are part of the massive spectrum localized in the intersection $\{51^\star\}$. Under the flipped U(1)$^{\text{fl}}$ symmetry, the charges of these

[12] In [29] extra sectors, localizing chiral fermions in the 10_1, 10_{-1} representations were added, in an attempt to localize from the corresponding massive spectrum the required GUT Higgses. In this way, extra chiral matter was introduced that survived massless to low energies.

[13] These particles were not found in [29] as extra chiral fermions in the representations 5_2, $\bar{5}_{-2}$ were added, in order to localize part of their massive superpartners — in the same representations — as EW Higgses.

EW Higgses localized in the intersection $\{51^{\star}\}$ may be seen in table 6. By looking at table 6 we can now argue that the charges of the Higgs **5**-plets h_3, h_4 under the flipped U(1) symmetry, are exactly the one's to play the role of electroweak scalars in a flipped SU(5) GUT. The same Higgses are responsible for EW symmetry breaking in the SU(5) GUT of section 3. We must keep in mind that in this case the flipped $U(1)^{\mathrm{fl}}$ symmetry was broken. As it is obvious from table 6, the representation under which the EW h_3 transforms is exactly the conjugate of that of h_4. For clarity of notation we avoided the identification **5**-plet for h_3 and its conjugate for h_4, since their charges are equal and opposite under the flipped $U(1)^{\mathrm{fl}}$ symmetry. By repeating the analysis of section 3.1, it is the effective combination

$$h_3 + h_4^{\star} \tag{4.5}$$

which gets localized at the intersection $\{51^{\star}\}$. Hence, we have shown that the necessary EW Higgses are present in the flipped classes of GUTS and thus the models will achieve naturally electroweak symmetry breaking to $SU(3)_C \otimes U(1)_{EM}$.

5. Quark-lepton-neutrino masses in flipped SU(5)

5.1 Quark masses

The classes of models we discuss in this work are based on the $\mathbb{Z}_3$ orientifold backgrounds of [28]. We can now make use of the fact that that the complex structure modulus is fixed at the $\mathbb{Z}_3$ orientifold backgrounds, in order to discuss the general form of the trilinear Yukawa couplings. It arises from the stretching of the worldsheet between the D6-branes that cross at these intersections. Namely two fermions F_L^i, F_R^j and one Higgs H^k, take the form, to leading order

$$Y^{ijk} = e^{-A} = e^{-\frac{R_1 R_2}{\alpha'} \ A_{ijk}} = e^{-\sqrt{3} \ R_2^2 \ A_{ijk}}\,, \tag{5.1}$$

where A_{ijk} may be of order one. We assume that the worldsheet areas involved in the interactions across the two dimensional tori in the second and third complex planes are close to zero, and thus the leading area dependence arises from the first complex plane.

In the flipped SU(5) GUTS the u-quark gets naturally a mass of order $\langle v \rangle$. Its precise value is controlled by the Ψ^u Yukawa coupling

$$\Psi^u \cdot \mathbf{10} \cdot \bar{\mathbf{5}} \cdot \bar{\mathbf{5}}^B\,. \tag{5.2}$$

The physical value

$$m_u = \Psi^u \cdot v \sim e^{-A^d} \cdot v \tag{5.3}$$

for the u-quark mass, $m_u = 0.005\,\mathrm{GeV}$ is approached hierarchically, from above, by having a worldsheet area $A^u = 10.08$. It is thus naturally connected to the electroweak scale of the theory. By implementing relation (5.1) we find that the value of the u-quark mass is

In this way, extra chiral matter was introduced into the 3G chiral content of flipped SU(5) that survived massless to low energies.

compatible with a tori radii, $R_2 = 2.4$. We note that on hierarchy grounds υ is the natural scale of the u-quark mass. We also note the absence of the tree level coupling $\mathbf{10} \cdot \mathbf{10} \cdot \mathbf{5}$ normally responsible for the d-quark mass generation. Hopefully, such a coupling may instead be induced by non-renormalizable terms.

5.2 Neutrino masses

The flipped SU(5) naturally incorporates in its representation context the right handed neutrino ν^c neutrino as part of the 10-plet. The see-saw mechanism appears to be the most plausible mechanism for generating large values for its mass.

The see-saw mechanism is generated by the interaction

$$\mathcal{L} = \tilde{Y}^{\nu_L \nu_R} \cdot \mathbf{10} \cdot \bar{\mathbf{5}} \cdot \bar{h}_4 \; + \tilde{Y}^{\nu_R} \cdot \frac{1}{M_s} \cdot \left(\mathbf{10} \cdot \overline{\mathbf{10}}^B\right) \left(\mathbf{10} \cdot \overline{\mathbf{10}}^B\right), \tag{5.4}$$

where its standard version (3.12) can be generated by choosing

$$\langle h_4 \rangle = \upsilon \,, \qquad \langle \mathbf{10}_i^B \rangle = M_s \,. \tag{5.5}$$

5.3 Lepton masses

The mass term for charged leptons, of order of the electroweak scale (times the usual exponential suppression from the Yukawa couplings), exists naturally within the context of D-brane model building from the present backgrounds. It is given by

$$Y^l \cdot f \cdot l^c \cdot \langle h_3 \rangle + \text{c.c.} \tag{5.6}$$

and the hierarchy of the lepton masses is naturally generated by varying the worldsheet area within the Y^l Yukawa coupling.

6. Proton decay and doublet-triplet splitting

The embedding of the standard model $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ into a higher group, the grand unified group, GUT, was the original idea[14] of [2]. In this context, one has to justify the mass scale of the extra, beyond the SM gauge bosons involved in the theory. In the present SU(5) and flipped SU(5) GUT models respectively one has to justify - from first principles - the difference between the high energy scale M_{GUT}, set out by the presence of the extra gauge bosons mediating the proton decay dimension six[15] baryon violating [37] couplings

$$p \to e^+ \pi^0 : \; \sim \frac{1}{M_s^2} \; (\bar{u}_L^c)^i \, (u_L)^j \; \left(\bar{e}^+_{L,R}\right) (d_{L,R})^k \, \epsilon^{ijk}, \tag{6.1}$$

$$p \to \bar{\nu}_L \; \pi^+ \sim \frac{1}{M_s^2} \; \left((\bar{d}_R^c)_\alpha \, (u_R)_\beta\right) \left((\bar{d}_L^c)_\gamma \, \nu_L\right) \epsilon^{\alpha\beta\gamma}, \tag{6.2}$$

$$n \to e^+ \pi^- \sim \frac{1}{M_s^2} \; \left((\bar{u}_L^c)_\alpha \, (d_L)_\beta\right) \left((\bar{u}_R^c)_\gamma \, e_R\right) \epsilon^{\alpha\beta\gamma}\,, \tag{6.3}$$

and the low scale set out by the masses of the quarks and leptons.

[14] See [2] for the first realization of this idea and also [3] for a review of problems in gauge theory GUTS including proton decay.

[15] where ϵ^{ijk}, $\epsilon^{\alpha\beta\gamma}$, the totally antisymmetric SU(3) tensor with $\epsilon^{123} \equiv +1$.

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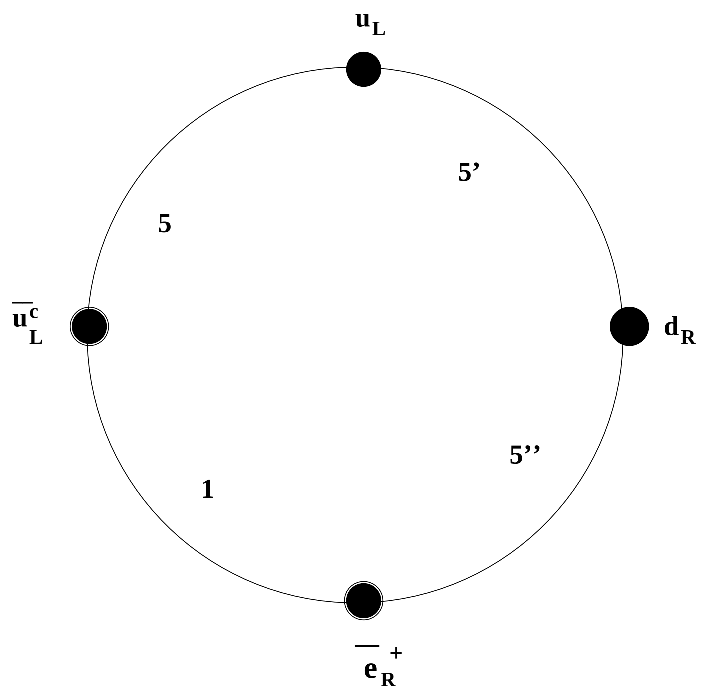

Figure 1: Proton decay mode $p \to e^+\pi^0$ for flipped SU(5) GUTS from intersecting branes.

In the present (SU(5) and flipped SU(5)) GUTS, baryon number is not a gauged symmetry. In fact, one can show that gauge boson mediated dimension six operators, written in an $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y$ invariant form, and described by the four-fermion interactions of (6.1)–(6.3) do exist. The following proton decay modes are allowed[16] in SU(5)

$$\sim \frac{1}{M_s^2}\ (\bar{u}_L^c\ u_L)\ \left(\bar{e}^+_{L,R}\ d_{L,R}\right), \tag{6.4}$$

$$\sim \frac{1}{M_s^2}\ \left(\bar{d}_R^c\ u_R\right)\left(\bar{d}_L^c\ \nu_L\right), \tag{6.5}$$

$$\sim \frac{1}{M_s^2}\ (\bar{u}_L^c\ d_L)\,(\bar{u}_R^c\ e_R) \tag{6.6}$$

and flipped SU(5) GUTS

$$\sim \frac{1}{M_s^2}\ (\bar{u}_L^c\ u_L)\ \left(\bar{e}^+_R\ d_R\right), \tag{6.7}$$

$$\sim \frac{1}{M_s^2}\ \left(\bar{d}_R^c\ u_R\right)\left(\bar{d}_L^c\ \nu_L\right). \tag{6.8}$$

The relevant disc diagrams can be seen in figures 1–5. The numbers shown in the boundary indicate the $D6_a$ brane that the disk boundary is attached.

Thus for example the depicted proton decay mode associated with e_L^+ in figure 3 is associated with the SU(5) structure $\mathbf{10}^2 \cdot \overline{\mathbf{10}}^{\mathbf{2}}$ and has been calculated in a $N = 1$ supersymmetric context in [18], for another class of models. On the other hand flipped

[16] In the following for simplicity reasons we will omit SU(3) indices.

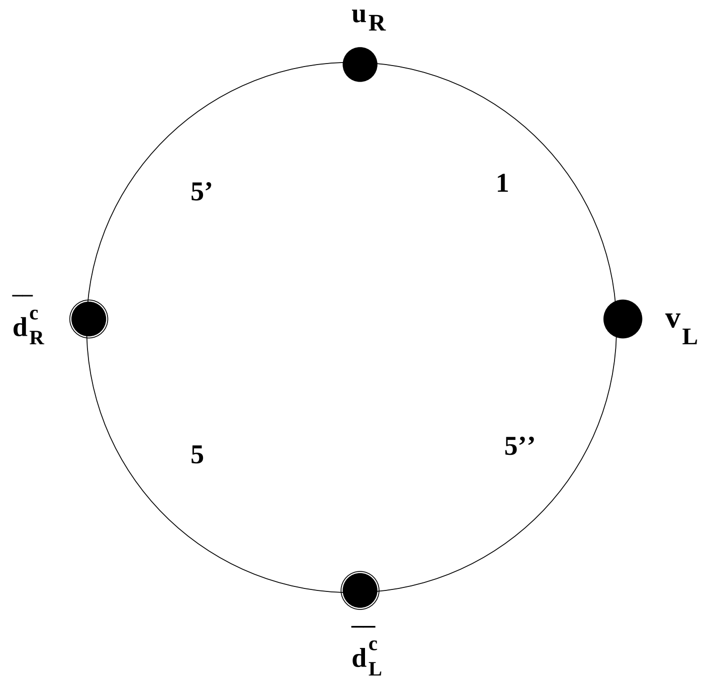

Figure 2: Proton decay mode $p \to \bar{\nu}_L\ \pi^+$ for flipped SU(5) GUTS from intersecting branes.

SU(5) offers another kind of decay modes - seen in figures 1 and 2 - which have the SU(5) structure $\mathbf{10} \cdot \mathbf{5} \cdot \overline{\mathbf{10}} \cdot \bar{\mathbf{5}}$. It will be interesting to perform the calculation of the latter amplitude, to see the differences of the flipped SU(5) proton decay amplitude against the amplitude studied in [18].

In addition, we note the presence of the decay modes $p \to e^+\pi^0$, $p \to \pi^+\nu$ associated with the SU(5) structure $\mathbf{10} \cdot \overline{\mathbf{10}}\ \mathbf{5} \cdot \bar{\mathbf{5}}$. The presence of these modes which exist in a general global four dimensional GUT, did not arise in the models examined in [18]. We also note that the same amplitudes may exist in a $N = 1$ supersymmetric context of the models as the charge structure which supports these reactions, essentially the chiral matter context of the models incorporating the three generation representations, remains identical. It will also be interesting to perform these calculations.

As the reactions (6.1)–(6.3) associated to the various decay modes, get mediated by the extra, beyond the SM gauge bosons with a mass[17] of order M_X, we have to rather choose $M_X = M_s = 10^{16}$ GeV, in order to enhance the proton decay rate beyond experimental observation. Related observations have been made in [18].

Also we note that for a GUT scale of order of the 10^{16} GeV, proton decay modes mediated by dimension six operators are the dominant one's.

In this case, gauge mediated proton decay may be enhanced beyond the superK bound [38] $\Gamma^{-1}(p \to e^+\pi^0)_{expected} \geq 10^{33}$ yrs. However, this is not enough to save the proton. It is expected that there will also be scalar mediated proton decay modes in a general GUT model. These dangerous triplet scalars are part of the electroweak Higgses

[17]For simplicity we consider that all the beyond the SM gauge bosons have the same mass, namely M_X.

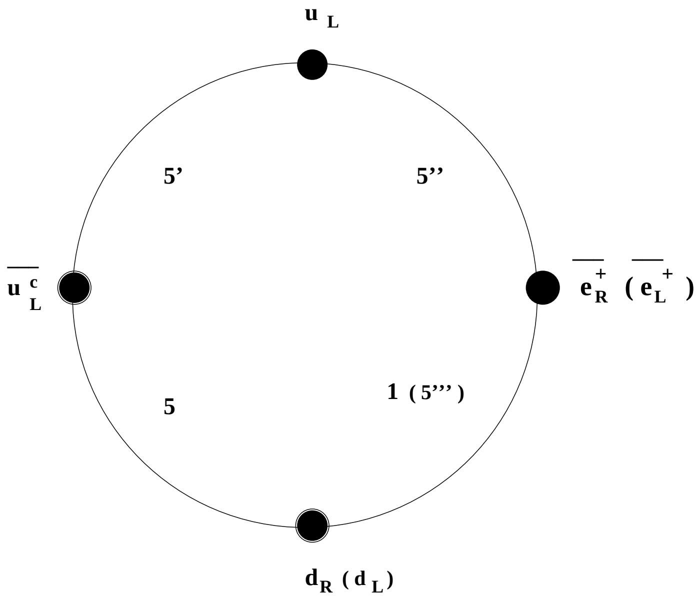

Figure 3: Proton decay mode $p \to e^+\pi^0$ for SU(5) GUTS from intersecting branes.

for SU(5) GUTS, but for GUTS based[18] on the flipped SU(5) GUT [35], these scalars are part of the electroweak 5-plets and GUT 10-plets, and have been denoted earlier as D, d_H^c respectively.

In fact, baryon number violating problems associated with the existence of a light mass for these triplets may be absent, if we can show that the coloured triplet mediating scalars have a mass of order M_{GUT}. This constitutes the famous doublet-triplet splitting (DTS) problem.[19]

In a $N = 1$ supersymmetric context, the DTS solution demands the presence of certain mass couplings that have its origin in the superpotential of the theory. This is to be contrasted with the origin of the DTS solution in a non-supersymmetric context, which demands the presence of the appropriate couplings in the effective scalar potential. In this case the scalar potential is able to break the GUT symmetry and simultaneously give masses to the coloured triplets. Thus the usual SU(5) theories, as the one's examined in the first part of this work solve the DTS problem directly using the effective scalar potential [39].

Let us now focus our attention to the DTS solution of the flipped SU(5) GUTS. In the SUSY SU(5) DTS is achieved by using large representations that may be absent in string theories. On the other hand the field theoretical version of $N = 1$ SUSY flipped SU(5) [1] offers a most economical solution to the gauge hierarchy problem by using[20] only the 10-plets part of the GUT scalars, that allow the DTS solution to arise from the presence of the term HHh in the superpotential of the theory.

[18] A flipped SU(5) GUT is not really a GUT in the sence of the simple SU(5) group but, in this context, neither it is the original Pati-Salam GUT $SU(4)_c \times SU(2)_L \times SU(2)_R$ [2].

[19] For global SUSY SU(5) GUTS it was discussed in [34].

[20] The solution of the doublet-triplet problem proceed along similar lines in the fermionic formulation version of flipped SU(5) [36].

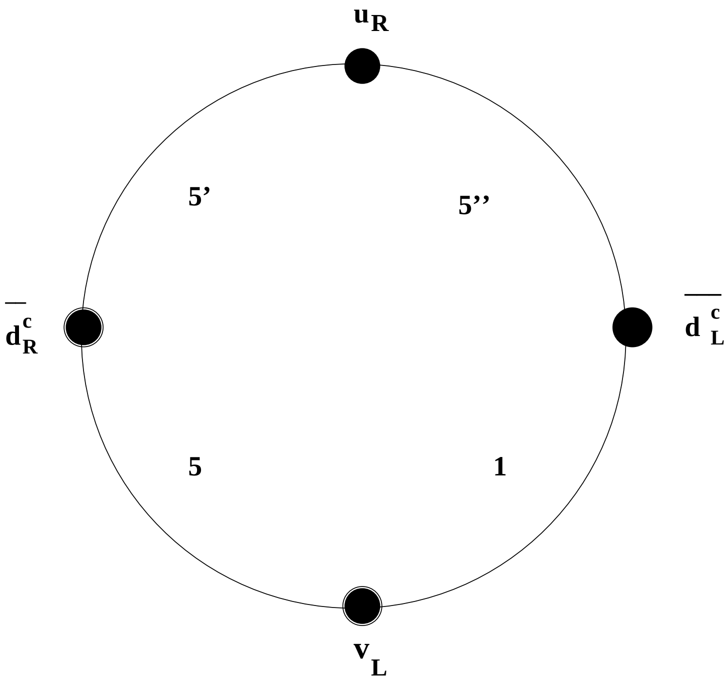

Figure 4: Proton decay mode $p \to \bar{\nu}_L\ \pi^+$ for SU(5) GUTS from intersecting branes.

We note that in the past, there have been attempts in a $N = 1$ four dimensional heterotic string compactification context, to solve the doublet-triplet splitting by excluding the presence of triplet scalars with either the use of continuous Wilson lines [40, 41], or by the use of discrete symmetries in the context of M-theory compactifications [42].

Because, from charge conservation, the term HHh is not allowed in the present flipped SU(5) GUTS the invariants that may be written by using this term involve a variety of physical fields. Their form necessarily will be based on higher non-renormalizable terms. We keep in mind that our GUT classes of models are non-supersymmetric and thus a direct use of a superpotential tool is not possible. Instead, we may write down the solution to the doublet-triplet splitting problem by writing down the following effective scalar potential terms

$$\frac{r}{M_s^3}(HHh)(\bar{F}\bar{F}\bar{h}) + m(\bar{h}h)(\bar{H}H) + \kappa(\bar{H}H)(\bar{H}H)\,, \tag{6.9}$$

$$\frac{r}{M_s^3}(\langle H\rangle Hh)(\bar{F}\bar{F}\langle\bar{h}\rangle) + m(\bar{h}h)(\langle\bar{H}\rangle\langle H\rangle) + \kappa(\bar{H}H)(\langle\bar{H}\rangle\langle H\rangle) \tag{6.10}$$

$$r\frac{M_{GUT}\cdot\upsilon\cdot\langle d_L d_R\rangle}{M_s^3}(d_c^H D) + m\cdot(D\bar{D})(\langle\bar{H}\rangle\langle H\rangle + \kappa\cdot\bar{d}_H^c d_H^c(\langle\bar{H}\rangle\langle H\rangle) \tag{6.11}$$

where r, m, k Yukawa coupling coefficients. From (6.11) we get the eigenvalues

$$M_D \approx m^{1/2} M_{\rm GUT}\ \left(1 + \frac{r^2}{(m-k)m}\omega\right), \qquad M_{d_H^c} \approx \kappa^{1/2} M_{GUT}\left(1 - \frac{r^2}{(m-k)k}\omega\right), \tag{6.12}$$

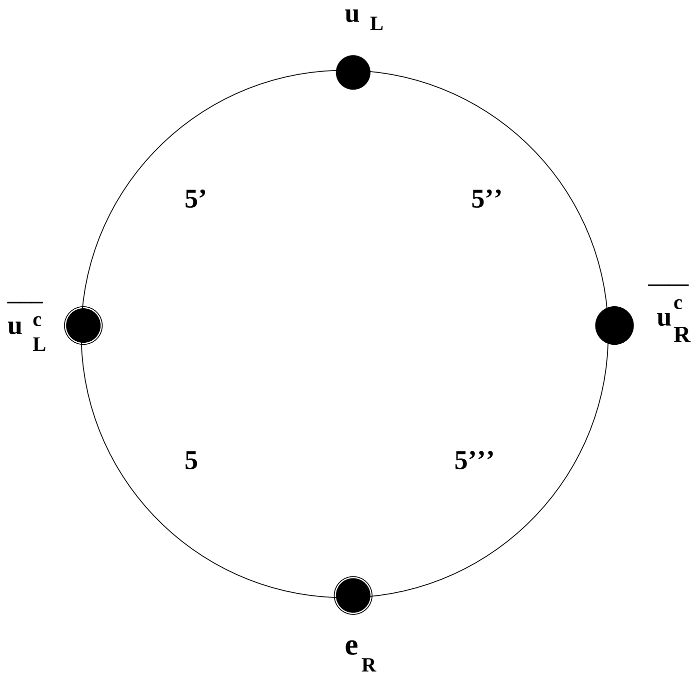

Figure 5: Proton decay mode $n \to e^+\pi^-$ for SU(5) GUTS from intersecting branes.

for the d^c, D triplets respectively, where we have defined

$$\lambda = \frac{M_{GUT} \cdot \upsilon \cdot \langle d_L d_R \rangle}{M_s^3}\,, \qquad \omega = \frac{\upsilon^2 \langle d_L d_R \rangle^2}{M_{GUT}^2 M_s^6}$$
$$m^{1/2} \sim e^{-\frac{A_m}{2}}\,, \qquad k^{1/2} \sim e^{-\frac{A_k}{2}}\,, \tag{6.13}$$

where A_m, A_k the worldsheet areas associated with the couplings seen in (6.10). Note that because of the presence of the triplet mixing term in (6.10) we don't have to choose the GUT scale equal to the string scale.

The triplet mixing term affects only slightly the triplet masses and its presence can test the fluctuation of the values of the triplet masses around the GUT scale. In fact, the invariants involved in the triplet mass matrix (6.11) are the lowest dimensional one's consistent with gauge invariance and charge conservation.

By choosing $M_{GUT} = 10^{16}$ GeV, $M_s = 10^{17}$ GeV, $\upsilon = 246$ GeV and substituting in the value of the chiral condensate $< d_L d_R > \approx (220\,\text{MeV})^3$ [43], we find that

$$\omega = \mathcal{O}(10^{-134}) \tag{6.14}$$

which is a very small number. Thus the triplet mixing term leaves for all practical purposes unaffected the triplet masses of order of the GUT scale. Clearly, the same conclusion may be reached if higher order non-renormalizable contributions to the triplet mass matrix are included.

7. Conclusions

In this work, we have presented general structural elements of four dimensional SU(5) GUT intersecting D6-brane model building, which are included in a large class of type IIA orientifold with orbifold symmetries [28].

The basic properties enjoyed by these GUT constructions are :

- RR tadpole cancellation, which guarantees the cancellation of the cubic gauge anomaly in the effective theory of light modes.
- absence of NSNS tadpoles associated with the complex structure moduli. We note that as a dilaton tadpole remains at one loop level, the dilaton runs away to zero coupling.[21]

We explored two possibilities in SU(5) GUT model building, one with a purely SU(5) symmetry and one with a flipped SU(5) $\times$ U(1) symmetry. In this work we have lifted the restriction of the electroweak pentaplet Higgs identification. Also, we have appropriately identified the GUT breaking scalars for general flipped SU(5) GUTS (also applicable to $\mathbb{Z}_N$ and $\mathbb{Z}_N \times \mathbb{Z}_M$ orientifolds). Let us now review the phenomenological properties of the SU(5) GUTS considered in the present work.

In both cases, SU(5) and flipped SU(5) type of GUTS respectively:

- we presented a model which does not include any surviving at low energies exotic matter states, and thus the models have only the SM at low energy. They may also achieve naturally the electroweak symmetry breaking as a consequence of the appropriate identification of the electroweak scalar pentaplet Higgses.
- We showed that the phenomenological features of these GUTS, include hierarchical values (HV) for neutrino masses (eqn's (3.11), (5.4) respectively) due to the see-saw mechanism [14], and also tree level HV Yukawa couplings for leptons and for the (d, s, b), (u, c, t) quarks respectively. We observe that we have not been able, to generate higher order non-renormalizable Yukawa couplings for the (u, c, t), (d, s, b) quarks respectively. This is due to the fact that the usual tree level coupling term $10 \cdot 10 \cdot 5$ coupling which is of order of the electroweak symmetry breaking scale v, is not allowed by charge conservation. The resolution of this problem may be attributed to non-renormalizable couplings. We hope to return to this issue in the future.
- We note that while baryon number is not a gauged symmetry in the SU(5) and flipped SU(5) GUTS constructed in this work from intersecting brane worlds, gauge mediated dimension six operators do exist. They may be appropriately getting suppressed if a large GUT scale is chosen of the order of the 10^{16} GeV. Moreover, the solution to the doublet-triplet splitting problem guarantees the suppression of scalar mediated proton decay dimension six operators. In conclusion, non-supersymmetric models from intersecting brane world orbifolds may be fully safe against proton decay.

[21] See [28] for a discussion how this latter problem might be cured. Also, note that running dilaton moduli is a general property of $N = 1$ heterotic string compactifications without fluxes.

Finally, because the scale of the models is large enough one expects quadratic loop corrections to the EW Higgs masses to appear. This, in fact, we identify as the low energy manifestation of the gauge hierarchy problem. Indeed as the models may possess $N = 1$ supersymmetric sectors for particular choices of wrapping numbers, one might expect that quadratic Higgs divergences may cancel at one loop [19] (and possibly higher). Thus a full solution to the gauge hierarchy at the weak scale remains an open issue in the present classes of non-supersymmetric GUTS.

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References

[1] H. Georgi and S.L. Glashow, *Unity of all elementary particle forces*, *Phys. Rev. Lett.* **32** (1974) 438.

[2] A. Salam, J. Strathdee, J.C. Pati and A. Salam, *Unified lepton-hadron symmetry and a gauge theory of the basic interactions*, *Phys. Rev.* **D 8** (1973) 1240.

[3] J.C. Pati, *Probing grand unification through neutrino oscillations, leptogenesis and proton decay*, hep-ph/0305221;
J.C. Pati, *Confronting the conventional ideas of grand unification with fermion masses, neutrino oscillations and proton decay*, hep-ph/0204240;
S. Raby, *Proton decay*, hep-ph/0211024;
B. Bajc, P.F. Perez and G. Senjanovic, *Minimal supersymmetric* SU(5) *theory and proton decay: where do we stand?*, hep-ph/0210374;
J. Hisano, *Proton decay in the supersymmetric grand unified models*, hep-ph/0004266.

[4] P. Langacker, *Grand unified theories and proton decay*, *Phys. Rept.* **72** (1981) 185.

[5] S. Dimopoulos and H. Georgi, *Softly broken supersymmetry and* SU(5), *Nucl. Phys.* **B 193** (1981) 150.

[6] H.P. Nilles, *Supersymmetry, supergravity and particle physics*, *Phys. Rept.* **110** (1984) 1;
A.B. Lahanas and D.V. Nanopoulos, *The road to no scale supergravity*, *Phys. Rept.* **145** (1987) 1.

[7] M.B. Green, J.H. Schwarz and E. Witten, *Superstring theory*, Cambridge University Press, Cambridge 1987.

[8] K.R. Dienes, *String theory and the path to unification: a review of recent developments*, *Phys. Rept.* **287** (1997) 447 [hep-th/9602045];
A.E. Faraggi, *Superstring phenomenology: present and future perspective*, hep-ph/9707311;
Z. Kakushadze, G. Shiu, S.H.H. Tye and Y. Vtorov-Karevsky, *A review of three-family grand unified string models*, *Int. J. Mod. Phys.* **A 13** (1998) 2551 [hep-th/9710149].

[9] J. Polchinski, *String theory*, Cambridge University Press, Cambridge 1998.

[10] L.E. Ibáñez, F. Marchesano and R. Rabadán, *Getting just the Standard Model at intersecting branes*, *J. High Energy Phys.* **11** (2001) 002 [hep-th/0105155].

[11] C. Kokorelis, *New standard model vacua from intersecting branes*, *J. High Energy Phys.* **09** (2002) 029 [hep-th/0205147].

[12] C. Kokorelis, *Exact standard model compactifications from intersecting branes*, *J. High Energy Phys.* **08** (2002) 036 [hep-th/0206108].

[13] I. Antoniadis, E. Kiritsis and T.N. Tomaras, *A D-brane alternative to unification*, *Phys. Lett.* **B 486** (2000) 186 [hep-ph/0004214]; *A D-brane alternative to unification*, *Phys. Lett.* **B 486** (2000) 186 [hep-ph/0004214].

[14] For detailed realizations of the Pati-Salam structure $\mathrm{SU}(4)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ in intersecting brane worlds and its phenomenological consequences see C. Kokorelis, *GUT model hierarchies from intersecting branes*, *J. High Energy Phys.* **08** (2002) 018 [hep-th/0203187]; *Deformed intersecting D6-brane GUTS, I*, *J. High Energy Phys.* **11** (2002) 027 [hep-th/0209202]; *Exact Standard Model structures from intersecting branes*, in *Proc. of the 1st International Conference on Superstring Phenomenology*, SP02 0xford, U.K., S. Abel and A. Faraggi, A. Ibarra and M. Plümacher eds., [hep-th/0210004]; *Deformed intersecting D6-brane GUTS, II*, hep-th/0210200;
C. Kokorelis, *Standard model compactifications from intersecting branes*, in *Proc. of the 10th International Conference on Supesymmetry and the Unification of Fundamental Interactions*, SUSY02, (DESY) [hep-th/0211091];
C. Kokorelis, *Deformed intersecting D6-brane GUTS and $N = 1$ SUSY*, hep-th/0212281.

[15] R. Blumenhagen, B. Körs and D. Lüst, *Type i strings with F- and B-flux*, *J. High Energy Phys.* **02** (2001) 030 [hep-th/0012156].

[16] D. Cremades, L.E. Ibáñez and F. Marchesano, *Standard model at intersecting D5-branes: lowering the string scale*, *Nucl. Phys.* **B 643** (2002) 93 [hep-th/0205074].

[17] C. Kokorelis, *Exact standard model structures from intersecting D5-branes*, hep-th/0207234.

[18] I.R. Klebanov and E. Witten, *Proton decay in intersecting D-brane models*, *Nucl. Phys.* **B 664** (2003) 3 [hep-th/0304079].

[19] D. Cremades, L.E. Ibáñez and F. Marchesano, *Intersecting brane models of particle physics and the Higgs mechanism*, *J. High Energy Phys.* **07** (2002) 022 [hep-th/0203160]; *SUSY quivers, intersecting branes and the modest hierarchy problem*, *J. High Energy Phys.* **07** (2002) 009 [hep-th/0201205]; *Yukawa couplings in intersecting D-brane models*, *J. High Energy Phys.* **07** (2003) 038 [hep-th/0302105]; *More about the standard model at intersecting branes*, hep-ph/0212048; *Towards a theory of quark masses, mixings and CP-violation*, hep-ph/0212064.

[20] G. Aldazabal, L.E. Ibáñez and A.M. Uranga, *Gauging away the strong CP problem*, hep-ph/0205250.

[21] M. Cvetič, G. Shiu and A.M. Uranga, *Chiral four-dimensional $N = 1$ supersymmetric type-IIA orientifolds from intersecting d6-branes*, *Nucl. Phys.* **B 615** (2001) 3 [hep-th/0107166].

[22] M. Cvetič, I. Papadimitriou and G. Shiu, *Supersymmetric three family* SU(5) *grand unified models from type-IIA orientifolds with intersecting D6-branes*, hep-th/0212177.

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[23] M. Cvetič, G. Shiu and A.M. Uranga, *Chiral four-dimensional $N = 1$ supersymmetric type-IIA orientifolds from intersecting d6-branes*, *Nucl. Phys.* **B 615** (2001) 3 [hep-th/0107166];
M. Cvetič, P. Langacker and G. Shiu, *A three-family standard-like orientifold model: Yukawa couplings and hierarchy*, *Nucl. Phys.* **B 642** (2002) 139 [hep-th/0206115];
M. Cvetič and I. Papadimitriou, *Conformal field theory couplings for intersecting D-branes on orientifolds*, *Phys. Rev.* **D 68** (2003) 046001 [hep-th/0303083].

[24] K. Hashimoto and S. Nagaoka, *Recombination of intersecting D-branes by local tachyon condensation*, *J. High Energy Phys.* **06** (2003) 034 [hep-th/0303204];
W.-H. Huang, *Recombination of intersecting D-branes in tachyon field theory*, *Phys. Lett.* **B 564** (2003) 155 [hep-th/0304171];
T. Sato, *A quantum analysis on recombination process and dynamics of Dp-branes at one angle*, hep-th/0304237.

[25] G. Honecker, *Chiral supersymmetric models on an orientifold of $Z_4 \times Z_2$ with intersecting D6-branes*, *Nucl. Phys.* **B 666** (2003) 175 [hep-th/0303015];
G. Honecker, *Intersecting brane world models from D8-branes on $(T^2 \times T^4/\mathbb{Z}_3)/\Omega\mathcal{R}^1$ type-IIA orientifolds*, *J. High Energy Phys.* **01** (2002) 025 [hep-th/0201037].

[26] D. Lüst and S. Stieberger, *Gauge threshold corrections in intersecting brane world models*, hep-th/0302221.

[27] S.A. Abel and A.W. Owen, *Interactions in intersecting brane models*, *Nucl. Phys.* **B 663** (2003) 197 [hep-th/0303124];
S.A. Abel, M. Masip and J. Santiago, *Flavour changing neutral currents in intersecting brane models*, *J. High Energy Phys.* **04** (2003) 057 [hep-ph/0303087].

[28] R. Blumenhagen, B. Körs, D. Lüst and T. Ott, *The Standard Model from stable intersecting brane world orbifolds*, *Nucl. Phys.* **B 616** (2001) 3 [hep-th/0107138].

[29] J.R. Ellis, P. Kanti and D.V. Nanopoulos, *Intersecting branes flip* SU(5), *Nucl. Phys.* **B 647** (2002) 235 [hep-th/0206087].

[30] T. Li and T. Liu, *Supersymmetric G^3 unification from intersecting D6-branes on type-IIA orientifolds*, hep-th/0304258.

[31] C. Angelantonj, I. Antoniadis, E. Dudas and A. Sagnotti, *Type-I strings on magnetised orbifolds and brane transmutation*, *Phys. Lett.* **B 489** (2000) 223 [hep-th/0007090].

[32] M. Larosa and G. Pradisi, *Magnetized four-dimensional $Z_2 \times Z_2$ orientifolds*, *Nucl. Phys.* **B 667** (2003) 261 [hep-th/0305224].

[33] I. Antoniadis, J.R. Ellis, J.S. Hagelin and D.V. Nanopoulos, *Supersymmetric flipped* SU(5) *revitalized*, *Phys. Lett.* **B 194** (1987) 231.

[34] S. Dimopoulos and F. Wilczek, *Supersymmetric unified models*, in Erice proceedings, *The unity of the fundamental interactions*, 1981 pp. 237–249;
B. Grinstein, *A supersymmetric* SU(5) *gauge theory with no gauge hierarchy problem*, *Nucl. Phys.* **B 206** (1982) 387.

[35] S.M. Barr, *A new symmetry breaking pattern for* SO(10) *and proton decay*, *Phys. Lett.* **B 112** (1982) 219.

[36] I. Antoniadis, J.R. Ellis, J.S. Hagelin and D.V. Nanopoulos, *The flipped* SU(5) × U(1) *string model revamped*, *Phys. Lett.* **B 231** (1989) 65.

[37] S. Weinberg, *Baryon and lepton nonconserving processes*, *Phys. Rev. Lett.* **43** (1979) 1566.

[38] SuperK collaboration, M. Vagins, *Report on superK results*, presented at *WHEPP-7 meeting*, Allahadad, India, January 6, 2002.

[39] For the DTS solution in SU(5) see A.J. Buras, J. Ellis, M.K. Gaillard and D.V. Nanopoulos, *Aspects of the grand unification of strong, weak and electromagnetic interactions*, *Nucl. Phys.* **B 135** (1978) 66.

[40] L.E. Ibáñez, J.E. Kim, H.P. Nilles and F. Quevedo, *Orbifold compactifications with three families of* $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)^n$, *Phys. Lett.* **B 191** (1987) 282.

[41] A.E. Faraggi, *Doublet-triplet splitting in realistic heterotic string derived models*, *Phys. Lett.* **B 520** (2001) 337 [hep-ph/0107094].

[42] E. Witten, *Deconstruction, G_2 holonomy and doublet-triplet splitting*, hep-ph/0201018.

[43] L. Giusti, F. Rapuano, M. Talevi and A. Vladikas, *The QCD chiral condensate from the lattice*, *Nucl. Phys.* **B 538** (1999) 249 [hep-lat/9807014];
H.G. Dosch and S. Narison, *Direct extraction of the chiral quark condensate and bounds on the light quark masses*, *Phys. Lett.* **B 417** (1998) 173 [hep-ph/9709215].