TYPE IIA FLUX MODEL BUILDING

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I. Introduction

The goal of string phenomenology is to construct the SM or MSSM as an effective theory of the string-based models [a].

D-brane model buidling on Type II orientifolds where the open string spectrum contains chiral fermions localized at the D-brane intersections [b].

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[a] M. B. Green, J. H. Schwarz and E. Witten, “Superstring Theory”; J. Polchinski, “String Theory”; and references therein.

[b] M. Berkooz, M. R. Douglas and R. G. Leigh.

A lot of non-supersymmetric three-family Standard-like models and grand unified models, were constructed on the Type IIA orientifolds with D6-brane intersections during last several years [a].

Generic Problems:

- Uncancelled NSNS tadpoles.
- Gauge hierarchy problem.

[a] R. Blumenhagen, L. Görlich, B. Körs and D. Lüst; R. Blumenhagen, B. Körs and D. Lüst; G. Aldazabal, S. Franco, L. E. Ibáñez, R. Rabadán and A. M. Uranga; L. E. Ibáñez, F. Marchesano and R. Rabadán; C. Angelantonj, I. Antoniadis, E. Dudas and A. Sagnotti; S. Förste, G. Honecker and R. Schreyer; R. Blumenhagen, B. Körs, D. Lüst and T. Ott; D. Cremades, L. E. Ibanez and F. Marchesano; D. Bailin, G. V. Kraniotis, and A. Love; J. R. Ellis, P. Kanti and D. V. Nanopoulos; C. Kokorelis.

The supersymmetric models with the quasi-realistic features have been constructed in Type IIA theory on various orientifolds with intersecting D6-branes

- $T^6/Z_2 \times Z_2$ orientifold [a].
- T^6/Z_4 orientifold [b].
- $T^6/(Z_4 \times Z_2)$ orientifold [c].
- T^6/Z_6 orientifold [d].
- T^6/Z_N orientifold [e].
- $T^6/(Z_3 \times Z_3)$ orientifold [f].

The point: we can introduce more orientifold planes to cancel the RR tadpoles and keep the supersymmetric D-brane configuration.

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[a] M. Cvetič, G. Shiu and A. M. Uranga
[b] R. Blumenhagen, L. Gorlich and T. Ott
[c] G. Honecker
[d] G. Honecker and T. Ott
[e] R. Blumenhagen, J. P. Conlon and K. Suruliz
[f] C. Kokorelis.

II Type IIA/B Model Building and Challenges

Constaints on model building:

- RR tadpole cancellation conditions
- 4-dimensional $N = 1$ supersymmetric D-brane configuration
- K-theory anomaly free conditions

$SU(5)$ [a] and flipped $SU(5)$ [b]

- Gauge coupling unification
- Gauge symmetry breaking via D-brane splitting
- No Doublet-triplet splitting problem
- No exact three-family models
- Quite a few exotic particles
- No up/down-type quark Yukawa couplings

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[a] M. Cvetič, I. Papadimitriou and G. Shiu

[b] J. R. Ellis, P. Kanti and D. V. Nanopoulos; C. Kokorelis; C. M. Chen, G. V. Kraniotis, V. E. Mayes, D. V. Nanopoulos and J. W. Walker

Trinification model [a]

- Gauge symmetry breaking via D-brane splitting and Higgs mechanism
- No lepton-type Yukawa couplings

[a] Ching-Ming Chen, Tianjun Li and Dimitri V. Nanopoulos

Standard-Like Model

- One stack of D-branes for $U(3)_C$ ($U(1)_B \subset U(3)_C$)
- One stack of D-branes for $U(2)_L$
- Two stacks of D-branes for $U(1)_{\rm L}$ and $U(1)_{\rm I_{3R}}$

$$Q_Y = Q_{I_{3R}} + \frac{Q_B - Q_{\rm L}}{2} \, .$$

The $U(1)$ gauge symmetry, which comes from a non-abelian symmetry, is anomaly free and its gauge field is massless.

Therefore, to forbid the gauge field of $U(1)_{I_{3R}}$ to obtain a mass via $B \wedge F$ couplings, the $U(1)_{I_{3R}}$ can only come from a $U(2)_R$ symmetry or Sp group. To have the anomaly free $U(1)_{\rm B-L}$, we put the $U(3)_C$ and $U(1)_{\rm L}$ stacks of D6-branes on the top of each other. So, before the D6-brane splitting, we have one stack of $U(4)_C$ branes.

Thus, the interesting Standard-like models arise from the Pati-Salam or Pati-Salam like models.

Pati-Salam models ($SU(4)_C \times SU(2)_L \times SU(2)_R$)

- All the SM fermions and Higgs fields from bifundamental representations.
- The Yukawa couplings can in principle be allowed by $U(1)$ symmetries.

Classifications of PS model buildings [a]

- Type I PS: $U(4)_C \times U(2)_L \times U(2)_R$.
- Type II PS: $U(4)_C \times Sp(2n)_L \times Sp(2m)_R$.
- Type III PS: Mixed Type I and II PS, e.g, $U(4)_C \times U(2)_L \times Sp(2n)_R$ or $U(4)_C \times Sp(2n)_L \times U(2)_R$.

[a] Mirjam Cvetič, Tianjun Li and Tao Liu

(1) $U(4)_C \times U(2)_L \times U(2)_R$ Models [a]

- At least two gaugino condensations in the hidden sector so that the moduli may be stabilized and supersymmetry might be broken.
- The Pati-Salam gauge symmetry can be broken down to the SM gauge symmetry via D6-brane splittings and Higgs mechanism which preserves the SUSY.
- Exact three families of the SM fermions, and less pair of the Higgs bidoublets.
- The $SU(2)_L$ and $SU(2)_R$ gauge coupling unification in two models.
- Yukawa couplings are allowed in some models.

[a] Mirjam Cvetič, Tianjun Li and Tao Liu

Challenge: Only one family of the SM fermions can have masses.

Point: The left-chiral fermions, the right-chiral fermions and bidoublet Higgs fields arise from the intersections on different two tori.

(2) $U(4)_C \times Sp(2)_L \times Sp(2)_R$ Models

The $U(4)_C \times Sp(2)_L \times Sp(2)_R$ model [a] without flux [b] and the model with flux [c].

- There are three families of the SM fermions, and only two/one bidoublet Higgs fields.
- The beta function for the Sp group in the hidden sector is negative.

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[a]The non-supersymmetric model was proposed by D. Cremades, L. E. Ibáñez and F. Marchesano
[b]M. Cvetič, P. Langacker, T. Li and T. Liu
[c]F. Marchesano and G. Shiu.

Challenges:

- The $SU(2)_R \times U(1)_{B-L}$ can be broken down to the $U(1)_Y$ only by giving VEVs to the scalar components of the right-handed neutrino chiral superfields at the TeV scale. And R parity is violated.
- Only one family of the SM fermions can have masses. And the fermion masses and mixings are wrong even if one assumed the most general Yukawa couplings.

IV Type IIA Flux Model Building Rules

Extra Dimensions: $T^6 = T^2 \times T^2 \times T^2$

Fluxes [a]:

- NSNS flux
- RR flux
- Metric flux

There are seven moduli: S, T_i, and U_i.

[a] G. Villadoro and F. Zwirner; P. G. Camara, A. Font and L. E. Ibanez

Major Constraints:

(1) 4-Dimensional $N = 1$ Supersymmetric D6-Brane Configuration

$$\theta_1 + \theta_2 + \theta_3 = 0 \bmod 2\pi \ .$$

(2) RR Tadpole Cancellation Conditions [a]

Set-Up:

- Supersymmetric AdS vacua.
- $T_1 = T_2 = T_3$.
- A solution to the Jacobi identities for metric fluxes.

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[a] G. Villadoro and F. Zwirner; P. G. Camara, A. Font and L. E. Ibanez; Ching-Ming Chen, Tianjun Li, Dimitri V. Nanopoulos

RR Tadpole Cancellation Conditions [a]

$$
\begin{aligned}
2^k N^{(1)} - \sum_a N_a A_a + \frac{1}{2}(h_0 m + 3aq) &= 16 , \\
-2^{\beta_1} N^{(2)} + \sum_a 2^{-\beta_2-\beta3} N_a B_a - \frac{1}{2\chi_2\chi_3}(h_0 m + 3aq) &= -2^{4-\beta_2-\beta_3} , \\
-2^{\beta_2} N^{(3)} + \sum_a 2^{-\beta_1-\beta_3} N_a C_a - \frac{1}{2\chi_1\chi_3}(h_0 m + 3aq) &= -2^{4-\beta_1-\beta_3} , \\
-2^{\beta_3} N^{(4)} + \sum_a 2^{-\beta_1-\beta_2} N_a D_a - \frac{1}{2\chi_1\chi_2}(h_0 m + 3aq) &= -2^{4-\beta_1-\beta_2} .
\end{aligned}
$$

where $k = \beta_1 + \beta_2 + \beta_3$,

$A_a \equiv -n_a^1 n_a^2 n_a^3, \; B_a \equiv n_a^1 l_a^2 l_a^3, \; C_a \equiv l_a^1 n_a^2 l_a^3, \; D_a \equiv l_a^1 l_a^2 n_a^3.$

[a] Ching-Ming Chen, Tianjun Li, Dimitri V. Nanopoulos

Key Points:

- If $h_0 m + 3aq < 0$, the NSNS, RR, and metric fluxes can contribute to the negative D6-brane charges for all the RR tadpole cancellation conditions.
- We can neglect the RR tadpole cancellation conditions, and the supersymmetric D6-brane configurations are the only major constraints on consistent intersecting D6-brane model building.
- We can consider the T^6 orientifold.

Can we construct the better models?

Minor Constraints:

(1) The Freed-Witten anomaly cancellation conditions, which are automatically satisfied for supersymmetric AdS vacua.

(2) K-theory anomaly free conditions.

VI. Models

(A) Pati-Salam models [a]

Three stacks of D6-branes, a, b, and c for $SU(4)_C$, $SU(2)_L$ and $SU(2)_R$ gauge symmetries, respectively.

[a] Ching-Ming Chen, Tianjun Li, Dimitri V. Nanopoulos

The SM fermion masses and mixings:

(1) Conditions for Intersecting Numbers:

$$I_{ab} \; = \; 3 \; , \; I_{ab'} \; = \; 0 \text{ if } \mathrm{SU}(2)_{\mathrm{L}} \text{ from } \mathrm{U}(2)_{\mathrm{L}} \; ,$$

$$I_{ac} \; = \; -3 \; , \; I_{ac'} \; = \; 0 \; ,$$

$$I_{bc} \; \geq \; 2 \; .$$

(2) All the SM fermions and Higgs fields arise from the intersections on the same two torus.

The gauge symmetry is $U(4)_C \times U(2)_L \times U(2)_R$ or $U(4)_C \times USp(2)_L \times U(2)_R$.

The gauge symmetry can be broken down to $SU(3)_C \times SU(2)_L \times U(1)_{I3R} \times U(1)_{\mathrm{B-L}}$ by brane splittings.

stack	N	$(n_1,l_1)(n_2,l_2)(n_3,l_3)$	A	S	b	b'	c	c'	d	d'	e	e'	$O6$
a	4	(0,-1)(1, 1)(3, 1)	1	-1	3	0(1)	-3	0(3)	2	0(2)	-3	-	1
b	2	(-1,-1)(2, 0)(-3, 1)	0	0	-	-	6	0(3)	-1	-5	6	-	0(1)
c	2	(1,-1)(-1, 1)(0,-2)	-2	2	-	-	-	-	0(10)	2	0(1)	-	-2
d	2	(2, 3)(1,-1)(2, 0)	0	0	-	-	-	-	-	-	6	-	0(3)
e	1	(1, 0)(0,-2)(0, 2)	0	0	-	-	-	-	-	-	-	-	0(4)
$O6$	5	(1, 0)(2, 0)(2, 0)	-	-	-	-	-	-	-	-	-	-	-

Table 1: (1) Type IIA $\mathbf{T^6}$ orientifold; (2) $[U(4)_C \times U(2)_L \times U(2)_R]_{observable} \times [U(2) \times USp(2) \times USp(10)]_{hidden}$; (3) The SM fermions and three Higgs fields arise from the intersections on the third two-torus; (4) $6\chi_1 = 2\chi_2 = \chi_3 = 2\sqrt{6}$; (5) $h_0 = -12(q+2)$, $m = 2$, and $a = 8$. So, $h_0 m + 3aq = -48$.

Representation	Multiplicity	$U(1)_a$	$U(1)_b$	$U(1)_c$
$(4_a, \bar{2}_b)$	3	1	-1	0
$(\bar{4}_a, 2_c)$	3	-1	0	1
$(2_b, \bar{2}_c)$	6	0	1	-1
$(4_a, 2_c)$	3	1	0	1
$(\bar{4}_a, \bar{2}_c)$	3	-1	0	-1

Table 2: The particle spectrum in observable sector.

stack	N	$(n_1,l_1)(n_2,l_2)(n_3,l_3)$	A	S	b	b'	c	c'	d	d'	e	e'	f	f'	g	g'	h	h'	$O6$
a	4	(1, 0) (-1,-1) (-3, 1)	0	0	3	-	-3	0(1)	-2	0(1)	1	-2	2	0(2)	2	1	0(2)	0(8)	0(1)
b	1	(0,-1) (1, 0) (0, 2)	0	0	-	-	3	-	6	-	-3	-	0(1)	-	0(1)	-	-3	-	0(2)
c	2	(-1,-1) (0, 1) (3, 1)	2	-2	-	-	-	-	2	4	0(8)	0(2)	-2	-1	-2	0(2)	2	-1	1
d	2	(-3,-1) (-1, 1) (2, 0)	0	0	-	-	-	-	-	-	6	0(1)	0(3)	-6	-4	-2	4	2	0(1)
e	1	(3,-1) (0, 1) (1,-1)	-2	2	-	-	-	-	-	-	-	-	0(3)	3	2	0(4)	0(1)	-1	-1
f	1	(0,-1) (1,-1) (-1, 1)	-2	2	-	-	-	-	-	-	-	-	-	-	-1	0(1)	0(4)	2	-1
g	1	(1,-1) (1, 0) (1, 1)	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-3	0(3)	0(1)
h	1	(1, 0) (-1,-3) (-1, 1)	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0(3)
$O6$	1	(1, 0) (1, 0) (2, 0)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3: (1) Type IIA $\mathbf{T^6}$ orientifold; (2) $[U(4)_C \times USp(2)_L \times U(2)_R]_{observable} \times [U(2) \times U(1)^4 \times USp(2)]_{hidden}$; (3) All the SM fermions and Higgs fields arise from the intersections on the third two-torus; (4) $2\chi_1 = 6\chi_2 = \chi_3 = 2\sqrt{3}$; (5) $h_0 = -6(q+2)$, $m = 2$, and $a = 4$. So, $h_0 m + 3aq = -24$.

Representation	Multiplicity	$U(1)_a$	$U(1)_b$	$U(1)_c$
$(4_a, \bar{2}_b)$	3	1	-1	0
$(\bar{4}_a, 2_c)$	3	-1	0	1
$(2_b, \bar{2}_c)$	3	0	1	-1
$(4_a, 2_c)$	1	1	0	1
$(\bar{4}_a, \bar{2}_c)$	1	-1	0	-1

Table 4: The particle spectrum in observable sector.

Properties in Pati-Salam models:

- Three families of SM fermions. And the suitable SM fermion masses and mixings (except the neutrino masses) can be generated at the stringy tree level.
- The Pati-Salam gauge symmetry can be broken down to SM gauge symmetry via D6-brane splittings and supersymmetry preserving Higgs mechanism.

$$
\begin{aligned}
SU(4) \times SU(2)_L \times SU(2)_R \quad & \xrightarrow{a \rightarrow a_1 + a_2} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
& \xrightarrow{c \rightarrow c_1 + c_2} SU(3)_C \times SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L} \\
& \xrightarrow{\text{Higgs Mechanism}} SU(3)_C \times SU(2)_L \times U(1)_Y \ .
\end{aligned}
$$

(A) $SU(5)$ models [a]

We can construct the $SU(5)$ models with exact three families of the SM fermions.

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[a] Ching-Ming Chen, Tianjun Li, Dimitri V. Nanopoulos

stk	N	$(n_1,l_1)(n_2,l_2)(n_3,l_3)$	A	S	b	b'	c	c'	d	d'	e	e'	f	f'	g	g'	$O6$
a	5	(1, 1) (-1,-1) (-1, 3)	3	0	0(2)	-3	-3	0(6)	3	0(0)	0(3)	0(1)	1	-	-3	-	3
b	1	(0, 2) (1,-3) (1,-3)	-9	9	-	-	-9	0(3)	-3	0(2)	3	0(1)	2	-	0(3)	-	-18
c	1	(1,-1) (1, 3) (2, 0)	0	0	-	-	-	-	0(6)	3	-3	0(3)	-2	-	0(1)	-	0(3)
d	1	(-1, 1) (1,-1) (-1,-3)	-3	0	-	-	-	-	-	-	0(1)	0(3)	-1	-	3	-	-3
e	1	(-1,-1) (0, 2) (1, 3)	3	-3	-	-	-	-	-	-	-	-	0(1)	-	0(3)	-	6
f	6	(2, 0) (0,-2) (0, 2)	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-
g	4	(0,-2) (0, 2) (2, 0)	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-
$O6$	2	(2, 0) (2, 0) (2, 0)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 5: (1) Type IIA $\mathbf{T^6}$ orientifold; (2) $U(5)\times U(1)^4\times USp(12)\times USp(8)\times USp(4)$; (3) $\chi_1 = 2\sqrt{3/5}, \quad \chi_2 = 2\sqrt{1/15}$, and $\chi_3 = 2\sqrt{15}/9$; (4) $h_0 = -4(3q+2)$, $a = 8$, and $m = 2$. So, $h_0 m + 3aq = -24$.

Properties in $SU(5)$ models:

- Gauge coupling unification
- Gauge symmetry breaking via D-brane splitting
- No doublet-triplet splitting problem
- Exact three-family SM fermions. No exotic particles that are charged under $SU(5)$ due to anomaly cancellation.
- No up-type quark Yukawa couplings

Generic Properties in Type IIA flux model building:

- The complex structure parameters are determined by supersymmetric D6-brane configurations.

- The real parts of all the moduli are stabilized. The imaginary parts of T_i can be stabilized, while only one combinations of the imaginary parts of the S and U_i can be stabilized.

$$\mathrm{ImS} + \frac{\mathrm{ImU}_1}{\chi_2\chi_3} + \frac{\mathrm{ImU}_2}{\chi_3\chi_1} + \frac{\mathrm{ImU}_3}{\chi_1\chi_2} .$$

- With large q, we can have the large physical T^6 volume, and small ten-dimensional dilaton. These AdS vacua are in the perturbative region. Also, the absolute value of cosmological constant will decrese when we increase q.

Comments on the supersymmetric AdS vacua:

- Similar to the KKLT mechanism [a], we may uplift the supersymmetric AdS vacua to the metastable dS vacua by adding a small number of the $\overline{\mathrm{D6}}$-branes.

- If we introduce the non-geometric fluxes and Type IIB "S-dual" fluxes, we may have the supersymmetric Minkowski vacua where the RR tadpole cancellation conditions can be relaxed. Then, we can construct the similar Pati-Salam models and $SU(5)$ models.

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[a] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi

VI. Conclusion.

I briefly review the model building on Type II orientifolds and point out their problems.

In Type IIA flux model building for supersymmetric AdS vacua, the RR tadpole cancellation conditions can be relaxed. We can construct the three-family Pati-Salam models where we can explain the SM fermion masses and mixings (except the neutrino masses). We can also construct the SU(5) models with exact three families of the SM fermions and without $SU(5)$ chiral exotic particles.