Supersymmetric Composite Models on Intersecting D-branes

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Abstract

We construct supersymmetric composite models of quarks and leptons from type IIA $T^6/(Z_2 \times Z_2)$ orientifolds with intersecting D6-branes. In case of $T^6 = T^2 \times T^2 \times T^2$ with no tilted $T^2$, a composite model of supersymmetric SU(5) grand unified theory with three generations is constructed. In case of that one $T^2$ is tilted, a composite model with SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ gauge symmetry with three generations is constructed. These models are not realistic, but contain fewer additional exotic particles and U(1) gauge symmetries due to the introduction of the compositeness of quarks and leptons. The masses of some exotic particles are naturally generated through the Yukawa interactions among “preons”.

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1. INTRODUCTION

The particle models on the intersecting D-branes in superstring theories (see Refs. [1, 2, 3] for the essential idea) have some advantages in comparison with the models based on the field theory. In addition to the fact that the gravity is naturally included, non-gauge interactions (Yukawa interactions, higher-dimensional interactions, and so on) are naturally introduced in the calculable way, in principle. Namely, all the interactions are well-determined, in principle. Therefore, there is a possibility to explain the Yukawa coupling hierarchy in the standard model, and to justify the assumptions on the higher-dimensional interactions in many particle models beyond the standard model. Especially, the models with low-energy supersymmetry [3, 4, 5, 6, 7, 8] is interesting, because the model can be constructed as a stable solution of the superstring theory. The low-energy supersymmetry can be spontaneously broken by the non-perturbative dynamics of gauge interactions [9]. In this paper, we concentrate on supersymmetric models.

The construction of the realistic model is not easy. The model usually contains many additional exotic particles and additional gauge symmetries. Technically speaking, this is due to that many additional D6-branes are required in addition to the D6-brane for SU(5) or SU(3)\(_c\)×SU(2)\(_L\)×U(1)\(_Y\) gauge symmetry to satisfy the tadpole cancellation conditions. Each additional D6-brane gives additional gauge symmetry. It is natural to consider that the additional gauge interactions may also act some important roles in nature. The composite model of quarks and leptons is one way to be investigated, since the confining force requires additional gauge interactions. In this paper, we construct two supersymmetric composite models following the prescription given in Ref. [3].

Consider the type IIA superstring theory compactified on \(T^6/(Z_2 \times Z_2)\) orientifold, where \(T^6 = T^2 \times T^2 \times T^2\). The type IIA theory is invariant under the \(Z_2 \times Z_2\) transformation

\[
\theta : \quad X_k^+ \rightarrow e^{\pm i\pi v_k} X_k^-, \\
\omega : \quad X_k^+ \rightarrow e^{\pm i\pi w_k} X_k^-,
\]

(1)

where \(v = (0, 0, 1/2, -1/2, 0)\) and \(w = (0, 0, 0, 1/2, -1/2)\) and

\[
X_k^\pm = \begin{cases} \\
\frac{1}{\sqrt{2}} (\pm X^{2k} + X^{2k+1}), & \text{for } k = 0, \\
\frac{1}{\sqrt{2}} (X^{2k} \pm iX^{2k+1}), & \text{for } k = 1, 2, 3, 4
\end{cases}
\]

(3)
with space-time coordinates $X^\mu$, $\mu = 0, 1, \cdots, 9$. The type IIA theory is also invariant under the $\Omega R$ transformation, where $\Omega$ is the world-sheet parity transformation and

$$
R : \begin{cases} 
X^i \to X^i, & \text{for } i = 0, 1, 2, 3, 4, 6, 8, \\
X^j \to -X^j, & \text{for } j = 5, 7, 9.
\end{cases}
$$

We mod out this theory by the action of $\theta$, $\omega$, $\Omega R$ and their independent combinations.

A $D6_a$-brane stretching over our three-dimensional space and winding in compact $T^2 \times T^2 \times T^2$ space is specified by the winding numbers in each torus:

$$[(n_1^a, m_1^a), (n_2^a, m_2^a), (n_3^a, m_3^a)].$$

A $D6_a$-brane is always accompanied by its orientifold image $D6_a'$ whose winding numbers are

$$[(n_1^a, -m_1^a), (n_2^a, -m_2^a), (n_3^a, -m_3^a)].$$

The number of intersection between $D6_a$-brane and $D6_b$-brane is given by

$$I_{ab} = \prod_{i=1}^{3} \left( n_i^a m_b^i - m_i^a n_b^i \right).$$

The intersecting angles, $\theta_i^a$, in each torus between $D6_a$-brane and $X^4$, $X^6$ and $X^8$ axes are described as

$$\theta_i^a = \tan^{-1} \left( \frac{\chi_i}{n_i^a} \right),$$

where $\chi_i$ are the ratios of two radii of each torus (complex structure moduli). The system is supersymmetric, if $\theta_1^a + \theta_2^a + \theta_3^a = 0$ is satisfied for all $a$. The configuration of intersecting D6-branes should satisfy the following tadpole cancellation conditions.

$$\sum_a N_a n_1^a n_2^a n_3^a = 16,$$

$$\sum_a N_a n_1^a m_2^a m_3^a = -16,$$

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where $N_a$ is the multiplicity of $D6_a$-brane, and we are assuming three rectangular (untitled) tori. In case of some tori are tilted, the tadpole cancellation conditions are modified. For
In the next section we construct a composite supersymmetric SU(5) grand unified model of Ref. [10] on intersecting D-branes. In section III we construct a composite supersymmetric SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ model of Refs. [11, 12]. These two models are not realistic in many points. Especially, they contain additional light exotic particles and additional U(1) gauge symmetries. We will see, however, that these models contain relatively fewer number of exotic particles and additional U(1) gauge symmetries by virtue of the compositeness of quarks and leptons. We will also see that the configuration of intersecting D-branes is very

| sector | field |
|--------|-------|
| $aa$   | U($N_a/2$) or USp($N_a$) gauge multiplet. 3 U($N_a/2$) adjoint or 3 USp($N_a$) anti-symmetric tensor chiral multiplets. |
| $ab + ba$ | $I_{ab}$ ($\Box_a, \Box_b$) chiral multiplets. |
| $ab' + b'a$ | $I_{ab'}$ ($\Box_a, \Box_b$) chiral multiplets. |
| $aa' + a'a$ | $\frac{1}{2} (I_{aa'} - \frac{4}{3\pi} I_{aO6})$ symmetric tensor chiral multiplets. $\frac{1}{2} (I_{aa'} + \frac{4}{3\pi} I_{aO6})$ anti-symmetric tensor chiral multiplets. |

TABLE I: General massless field contents on intersecting D6-branes. In $aa$ sector, the gauge symmetry is USp($N_a$) or U($N_a/2$) corresponding to whether D6$_a$-brane is parallel or not to some O6-plane, respectively. In $aa' + a'a$ sector, $k$ is the number of tilted torus, and $I_{aO6}$ is the sum of the intersection numbers between D6$_a$-brane and all O6-planes.

example, in case of the third torus is tilted, the conditions become

\[
\sum_a N_a n_a^1 n_a^2 n_a^3 = 16,
\]
(13)

\[
\sum_a N_a m_a^1 m_a^2 \tilde{m}_a^3 = -8,
\]
(14)

\[
\sum_a N_a m_a^1 n_a^2 \tilde{m}_a^3 = -8,
\]
(15)

\[
\sum_a N_a m_a^1 m_a^2 n_a^3 = -16,
\]
(16)

where $\tilde{m}_a^3 \equiv m_a^3 + n_a^3/2$.

There are four sectors of open string corresponding to on which D6-branes two ends of open string are fixed: $aa$, $ab + ba$, $ab' + b'a$, $aa' + a'a$ sectors. Each sector gives the matter fields in low-energy four-dimensional space-time. The general massless field contents are given in Table I.

In the next section we construct a composite supersymmetric SU(5) grand unified model of Ref. [10] on intersecting D-branes. In section III we construct a composite supersymmetric SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ model of Refs. [11, 12]. These two models are not realistic in many points. Especially, they contain additional light exotic particles and additional U(1) gauge symmetries. We will see, however, that these models contain relatively fewer number of exotic particles and additional U(1) gauge symmetries by virtue of the compositeness of quarks and leptons. We will also see that the configuration of intersecting D-branes is very


In the supersymmetric composite SU(5) grand unified model of Ref. [10], the fields of 10 in SU(5) are composite and the fields of 5 and 5* in SU(5) are elementary. The confining forces are strong SU(2) interactions for each generation. The particle contents of one generation are as follows.

\[
\begin{array}{c|c|c}
\text{SU(2)} & \text{SU(5)} \\
\hline
P & 2 & 5 \\
N & 2 & 1 \\
\Phi_1 & 1 & 5^* \\
\Phi_2 & 1 & 5^* \\
\end{array}
\]

The fields \(P\) and \(N\) are “preons”. The \(PP\) bound state becomes field of 10 in SU(5), and \(PN\) bound state becomes field of 5 in SU(5). The fact that all the fields belong to the fundamental or anti-fundamental representation of the gauge group is a good feature to realize this model on intersecting D-branes.

The configuration of the intersecting D6-branes for this composite model is given in Table III. This configuration is supersymmetric when \(\chi_1 = \chi_2 = \chi_3\), and satisfies the tadpole cancellation conditions. A schematic picture of the configuration is given in Fig.

| D6-brane | winding number | multiplicity |
|----------|----------------|--------------|
| D6_1     | \[(1, 0), (1, -1), (1, 1)\] | 10           |
| D6_2     | \[(1, 1), (1, 0), (1, -1)\] | 2            |
| D6_3     | \[(1, 0), (1, 0), (1, 0)\] | 4            |
| D6_4     | \[(1, 0), (0, 1), (0, -1)\] | 6            |
| D6_5     | \[(0, 1), (1, 0), (0, -1)\] | 14           |
| D6_6     | \[(0, 1), (0, -1), (1, 0)\] | 16           |

TABLE II: Configuration of the intersecting D6-branes for supersymmetric composite SU(5) grand unified model. All three tori are rectangular (untilted). Four D6-branes, D6_3, D6_4, D6_5 and D6_6, are on top of some O6-planes.

simple in each model. In section IV we present our conclusions.
FIG. 1: Schematic picture of the configuration of the intersecting D6-branes for composite supersymmetric SU(5) grand unified model. This picture describes only the situation of the intersection of D6-branes each other, and the relative place of each D6-brane has no meaning. The number at the intersection point between D6\textsubscript{a} and D6\textsubscript{b} branes denotes intersection number $I_{ab}$ with $a < b$.

The D6\textsubscript{1}-brane the grand unified gauge group SU(5) is realized. On the D6\textsubscript{2}-brane we have $U(1)_{D6_2}$ gauge symmetry whose anomaly is cancelled by the Green-Schwarz mechanism, and its gauge boson has a mass of the order of the string scale. In this configuration we have only $aa$ and $ab + ba$ sectors, and $ab' + b'a$ and $aa' + a'a$ sectors do not appear.

The gauge symmetries of the D6-branes which are on top of some O6-planes can be reduced in the following way\cite{3, 8}.

\begin{align}
\text{USp}(16) &\rightarrow \text{USp}(2)_1 \times \text{USp}(2)_2 \times \text{USp}(2)_3 \times (U(1))^3, \\
\text{USp}(14) &\rightarrow (U(1))^4, \\
\text{USp}(6) &\rightarrow (U(1))^2.
\end{align}

This can be done by moving D6-branes away from O6-planes in a way consistent with the orientifold projections. For the reduction of Eq.(17), we have to assume some non-trivial
TABLE III: Low-energy particle contents of composite SU(5) grand unified model before “hypercolor” confinement. The fields from aa sectors are neglected for simplicity.

| sector | SU(5) × USp(2)$_1$ × USp(2)$_2$ × USp(2)$_3$ field |
|--------|--------------------------------------------------|
| $D6_1 · D6_2$ | $(5^*, 1, 1, 1) × 2$ | $\bar{H}_{1,2}$ |
| $D6_1 · D6_5$ | $(5^*, 1, 1, 1) × 14$ | |
| $D6_1 · D6_6$ | $(5, 2, 1, 1)$ | $P_1$ |
| | $(5, 1, 2, 1)$ | $P_2$ |
| | $(5, 1, 1, 2)$ | $P_3$ |
| | $(5, 1, 1, 1) × 10$ | |
| $D6_2 · D6_4$ | $(1, 1, 1, 1) × 6$ | |
| $D6_2 · D6_6$ | $(1, 2, 1, 1)$ | $N_1$ |
| | $(1, 1, 2, 1)$ | $N_2$ |
| | $(1, 1, 1, 2)$ | $N_3$ |
| | $(1, 1, 1, 1) × 10$ | |

The vacuum expectation values of the fields in the anti-symmetric tensor representation in aa sector. Each USp(2) gauge interaction corresponds to the additional strong interaction, “hypercolor”, for the confinement of “preons” in each generation. (See Ref.[14] for the dynamics of USp($N$) supersymmetric gauge theories.) The low-energy particle contents before “hypercolor” confinement is given in Table III. The fields $P_i$ and $N_i$ with $i = 1, 2, 3$ are “preons” in first, second and third generations, respectively.

The value of the U($N$) gauge coupling $g$ at the string scale is determined by

$$g^2 \kappa^{-1}_4 = \sqrt{4 \pi M_s \frac{V_6}{V_3}}, \quad (20)$$

where $\kappa_4 = \sqrt{8 \pi G_N}$, $M_s = 1/\sqrt{\alpha'}$, $V_6$ is the volume of compact six-dimensional space and $V_3$ is the volume of corresponding D6-brane in compact six-dimensional space[9]. In case of that the D6-brane is parallel to some O6-plane, the corresponding USp($N$) gauge coupling is given by

$$g^2 \kappa^{-1}_4 = 2 \sqrt{4 \pi M_s \frac{V_6}{V_3}}, \quad (21)$$

which has an additional factor 2[15]. In our model, the “hypercolor” USp(2) has the largest coupling at the string scale because of the smallest $V_3$ and the additional factor 2.
sector | $SU(5) \times U(1)_{D6_2}$ | field  \\
---|---|---  \\
$D6_1 \cdot D6_2$ | $(5^*,1) \times 2$ | $\tilde{H}_{1,2}$  \\
$D6_1 \cdot D6_5$ | $(5^*,0) \times 14$ | $\Phi_{1,2,3}$ and exotics  \\
$D6_1 \cdot D6_6 \text{ and } D6_2 \cdot D6_6$ | $(10,0) \times 3$ | $\Sigma_{1,2,3} \sim [PP]_i$  \\
| | $(5,-1) \times 3$ | $H_{1,2,3} \sim [PN]_i$  \\
| | $(5,0) \times 10$ | exotics  \\
| | $(1,-1) \times 10$ | singlets  \\
$D6_2 \cdot D6_4$ | $(1,1) \times 6$ | singlets  \\

TABLE IV: Particle contents of composite SU(5) grand unified model after “hypercolor” confinement. The fields from $aa$ sectors are neglected for simplicity.

As it is easily understood from Fig. 1, we have Yukawa couplings among fields in $D6_1 \cdot D6_2$, $D6_1 \cdot D6_6$ and $D6_2 \cdot D6_6$ sectors\[13\]. There are following Yukawa interactions:

$$g_1 \tilde{H}_i P_i N_i,$$ (22)

$$g_2 \tilde{H}_i P_i N_i$$ (23)

with $i = 1, 2, 3$. The Yukawa coupling $g_2$ is exponentially smaller than the Yukawa coupling $g_1 \sim 1$. These interactions become mass terms after “hypercolor” confinement.

The particle contents after “hypercolor” confinement is given in Table IV. We have three pairs of 10 and 5* ($\Sigma$ and $\Phi$, or quarks and leptons) in SU(5), one massive pair of 5 and 5*, twelve massless pairs of 5 and 5* (Higgs multiplets), and sixteen singlets. We also have three SU(5) adjoint fields and many singlet fields in $aa$ sector. It is remarkable that odd number of generations is realized in this simple D6-brane configuration with three untilted tori. There are eleven additional U(1) gauge symmetries (two of them are anomalous).

A supersymmetric mass of one pair of 5 and 5* in SU(5) are generated through the Yukawa couplings of Eqs.(22) and (23), since the three composite operators $P_i N_i$ are replaced by three fields $H_i$. The value of the mass is of the order of the scale of dynamics of $USp(2)$.

The Yukawa couplings for the mass generation of up-type quarks, $\Sigma_i \Sigma_i H_i$ with $i = 1, 2, 3$, are dynamically generated. The values of the coupling constants are of the order of unity, which is appropriate to explain large top quark mass.

The $D6_3 \cdot D6_3$ sector is the hidden sector, since D6$^3$-brane has no intersections with other D6-branes. Only the interactions which are mediated by closed string states connect this
sector with the other sectors. If the dynamics of USp(4) gauge interaction with three chiral multiplets in anti-symmetric tensor representation and with supergravity fields from closed string states dynamically breaks supersymmetry, the “sequestering scenario” of the mediation of supersymmetry breaking[16] is naturally realized.

In the next section we construct a composite SU(3)\(c\)×SU(2)\(L\)×U(1)\(Y\) model with fewer exotic particles and U(1) gauge symmetries.

III. COMPOSITE SU(3)\(c\)×SU(2)\(L\)×U(1)\(Y\) MODEL

The particle contents of one generation of the composite model of Refs.[11, 12] are as follows.

| SU(2)\(H\) | SU(3)\(c\) | SU(2)\(L\) | U(1)\(Y\) |
|---|---|---|---|
| \(C\) | 2 | 3 | 1 | \(-\frac{1}{3}\) |
| \(D\) | 2 | 1 | 2 | \(\frac{1}{2}\) |
| \(N\) | 2 | 1 | 1 | 0 |
| \(\bar{d}\) | 1 | 3* | 1 | \(\frac{1}{3}\) |
| \(l\) | 1 | 1 | 2 | \(-\frac{1}{2}\) |
| \(\bar{\nu}\) | 1 | 1 | 1 | 0 |
| \(\Phi\) | 1 | 3* | 1 | \(\frac{1}{3}\) |
| \(\bar{H}\) | 1 | 1 | 2 | \(-\frac{1}{2}\) |

The fields \(C\), \(D\) and \(N\) are “preons”. The bound states of \(CC\), \(CD\), \(DD\), \(CN\) and \(DN\) become a right-handed up-type quark, a quark doublet, a right-handed charged lepton, a colored Higgs and a Higgs doublet, respectively. We construct a composite model similar to this model (the hypercharge assignment will be different) on intersecting D6-branes. We assume that only the third torus is tilted. The intersecting D6-brane configuration is given in Table\(\nabla\). This configuration is supersymmetric when \(\chi_1 : \chi_2 : \chi_3 = 1 : 1 : 2\), and satisfies the tadpole cancellation conditions. A schematic picture of the intersection of D6-branes is given in Fig. 2. In this configuration we have only \(aa\) and \(ab + ba\) sectors, and \(ab' + b'a\) and \(aa' + a'a\) sectors do not appear.

On the D6\(_1\)-brane the gauge symmetry of SU(3)\(c\)×U(1)\(_c\)×U(1) is realized, where SU(3)\(c\)×U(1)\(_c\) comes from the D6\(_1\)-brane of multiplicity 6 and U(1) comes from the D6\(_1\)-brane of multiplicity 2. The charges of these two U(1) gauge symmetries are denoted as \(Q_c\)
D6-brane | winding number | multiplicity
--- | --- | ---
D6₁ | [(1, 0), (1, -1), (1, 1/2)] | 6 + 2
D6₂ | [(1, 1), (1, 0), (1, -1/2)] | 4
D6₃ | [(1, 0), (1, 0), (2, 0)] | 2
D6₄ | [(1, 0), (0, 1), (0, -1)] | 4
D6₅ | [(0, 1), (1, 0), (0, -1)] | 6
D6₆ | [(0, 1), (0, -1), (2, 0)] | 8

TABLE V: Configuration of the intersecting D6-branes for supersymmetric composite SU(3)_c × SU(2)_L × U(1)_Y model. Only the third torus is tilted. Four D6-branes, D6₃, D6₄, D6₅ and D6₆, are parallel to O6-planes. D6₁-brane consists of two parallel D6-branes with multiplicities 6 and 2.

and Q. The U(1) symmetry which is generated by Q_c/3 − Q is anomaly free. On the D6₂-brane the gauge symmetry of SU(2)_L × U(1)_L is realized. The anomaly of U(1)_L is cancelled by the Green-Schwarz mechanism, and the corresponding gauge boson has a mass of the string scale.

The gauge symmetries of the D6-branes which are on top of some O6-planes are reduced as follows.

D6₄ : \( \text{USp}(4) \rightarrow U(1)_{D6₄} \)  \hspace{1cm} \hspace{1cm} (24)
D6₅ : \( \text{USp}(6) \rightarrow \text{USp}(4) \times \text{USp}(2) \rightarrow U(1)_{D6₅,1} \times U(1)_{D6₅,2} \)  \hspace{1cm} \hspace{1cm} (25)
D6₆ : \( \text{USp}(8) \rightarrow \text{USp}(2)_1 \times \text{USp}(2)_2 \times \text{USp}(2)_3 \times \text{USp}(2)_4 \)  \hspace{1cm} \hspace{1cm} (26)

This can be done by moving D6-branes away from O6-planes in a way consistent with the orientifold projections. For the reduction of Eq. 26, we have to assume some non-trivial vacuum expectation values of the fields in the anti-symmetric tensor representation in aa sector. All these three U(1) gauge symmetries are anomaly free. The charges of these U(1) gauge symmetries are denoted as \( Q_{D6₄} \), \( Q_{D6₅,1} \) and \( Q_{D6₅,2} \). Four USp(2) gauge interactions are all strong coupling “hypercolor” gauge interactions with the largest coupling constants at the string scale. D6₃-brane with USp(2) gauge symmetry is the hidden sector, since it has no intersections with other D6-branes.

The low-energy particle contents before “hypercolor” confinement is given in Table VI.
FIG. 2: Schematic picture of the configuration of the intersection of D6-branes for composite supersymmetric SU(3)_c × SU(2)_L × U(1)_Y model. This picture describes only the situation of the intersection of D6-branes each other, and the relative place of each D6-brane has no meaning. The number at the intersection point between D6_a and D6_b branes denotes intersection number I_{ab} with a < b.

The fields C_i, D_i and N_i with i = 1, 2, 3, 4 are “preons” in first, second, third and fourth generations, respectively. It is easy to understand that there are Yukawa interactions of

\[ \bar{q} C_i D_i, \quad (27) \]

\[ H N_i D_i \quad (28) \]

with i = 1, 2, 3, 4. All the coupling constants of these Yukawa interactions are of the order of unity. These Yukawa interactions become mass terms of the exotics \( \bar{q} \) and \( \bar{l} \) after “hypercolor” confinement.

The particle contents after “hypercolor” confinement is given in Table VII. The hypercharge is defined as

\[ \frac{Y}{2} = \frac{1}{2} \left( \frac{Q_c}{3} - Q \right) + \frac{1}{2} (Q_{D6_4} + Q_{D6_5,1} + Q_{D6_5,2}) \]. \quad (29) \]
We can see that the particle contents of three generations of quarks and leptons are included. The hypercharge assignment of “preons” are different from that in the model of Refs. [11, 12].

The exotic $\bar{q}$ gets a mass with one linear combination of $q_{1,2,3,4}$ through the Yukawa coupling of Eq. (27), and three left-handed doublet quarks remain massless. The exotic $\bar{l}$ gets a mass with one linear combination of $l_{1,2,3,4}$ through the Yukawa coupling of Eq. (28), and three left-handed doublet leptons remain massless. The values of these masses are of the order of the scale of dynamics of USp(2).

| sector | SU(3)$_c$ $\times$ SU(2)$_L$ $\times$ USp(2)$_1$ $\times$ USp(2)$_2$ $\times$ USp(2)$_3$ $\times$ USp(2)$_4$ | field |
|--------|---------------------------------------------------------------------------------|-------|
| $D6_1 \cdot D6_2$ | $(3^*, 2, 1, 1, 1, 1)(-1/3, 0, 0, 0)$, $(1, 2, 1, 1, 1, 1)(+1, 0, 0, 0)$ | $\bar{q}$, $\bar{l}$ |
| $D6_1 \cdot D6_5$ | $(3^*, 1, 1, 1, 1, 1)(-1/3, 0, \pm 1, 0) \times 2$, $(3^*, 1, 1, 1, 1, 1)(-1/3, 0, 0, \pm 1)$, $(1, 1, 1, 1, 1, 1)(+1, 0, 0, \pm 1) \times 2$, $(1, 1, 1, 1, 1, 1)(+1, 0, 0, \pm 1)$ | $C_1$, $C_2$, $C_3$, $C_4$, $N_1$, $N_2$, $N_3$, $N_4$ |
| $D6_1 \cdot D6_6$ | $(3, 1, 2, 1, 1, 1)(1/3, 0, 0, 0)$, $(3, 1, 1, 2, 1, 1)(1/3, 0, 0, 0)$, $(3, 1, 1, 1, 2, 1)(1/3, 0, 0, 0)$, $(3, 1, 1, 1, 1, 2)(1/3, 0, 0, 0)$, $(1, 1, 2, 1, 1, 1)(-1, 0, 0, 0)$, $(1, 1, 1, 2, 1, 1)(-1, 0, 0, 0)$, $(1, 1, 1, 1, 2, 1)(-1, 0, 0, 0)$, $(1, 1, 1, 1, 1, 2)(-1, 0, 0, 0)$ | $C_1$, $C_2$, $C_3$, $C_4$, $N_1$, $N_2$, $N_3$, $N_4$ |
| $D6_2 \cdot D6_4$ | $(1, 2, 1, 1, 1, 1)(0, 0, 0, 0, 0)$ | $D_1$, $D_2$, $D_3$, $D_4$ |
| $D6_2 \cdot D6_6$ | $(1, 2, 2, 1, 1, 1)(0, 0, 0, 0, 0)$, $(1, 2, 1, 2, 1, 1)(0, 0, 0, 0, 0)$, $(1, 2, 1, 2, 1, 1)(0, 0, 0, 0, 0)$, $(1, 2, 1, 1, 1, 2)(0, 0, 0, 0, 0)$ |

**TABLE VI**: Low-energy particle contents of SU(3)$_c$ $\times$ SU(2)$_L$ $\times$ U(1)$_Y$ model before “hypercolor” confinement. The fields from $aa$ sectors are neglected for simplicity.
sector | SU(3)_c × SU(2)_L × U(1)_Y | field |
--- | --- | --- |
D6_1 · D6_2 | (3\*, 2)_{−1/6} | \bar{q} |
| (1, 2)_{1/2} | \bar{l} |
D6_1 · D6_5 | (3\*, 1)_{1/3} × 3 | \bar{d}_{1,2,3} |
| (3\*, 1)_{−2/3} × 3 | \bar{u}_{1,2,3} |
| (1, 1)_0 × 3 | \bar{v}_{1,2,3} |
| (1, 1)_1 × 3 | \bar{e}_{1,2,3} |
D6_1 · D6_6 and D6_2 · D6_6 | (3\*, 1)_{1/3} × 4 | \bar{d}_{1,2,3,4} \sim [CC]_i |
| (3, 2)_{1/6} × 4 | q_{1,2,3,4} \sim [CD]_i |
| (1, 1)_0 × 4 | S_{1,2,3,4} \sim [DD]_i |
| (3, 1)_{−1/3} × 4 | \Phi_{1,2,3,4} \sim [CN]_i |
| (1, 2)_{−1/2} × 4 | l_{1,2,3,4} \sim [DN]_i |
D6_2 · D6_4 | (1, 2)_{1/2} × 2 | \bar{H}_{1,2} |
| (1, 2)_{−1/2} × 2 | \bar{H}_{1,2} |

TABLE VII: The particle contents of composite SU(3)_c × SU(2)_L × U(1)_Y model after “hypercolor” confinement. The fields from \(a a\) sectors are neglected for simplicity.

The following Yukawa interactions are dynamically generated with the coupling constants of the order of unity.

\[ \bar{d}_i q_i l_i, \quad \bar{d}_i \Phi_i S_i, \quad q_i q_i \Phi_i \]  
(30)

with \(i = 1, 2, 3, 4\). If singlets \(S_i\) have vacuum expectation value, the exotics of \(\bar{d}_i\) and \(\Phi_i\) become massive. There is no mechanism for giving mass to two pairs of Higgs doublets, \(H_{1,2}\) and \(\bar{H}_{1,2}\).

Three SU(3)_c adjoint chiral multiplets, three SU(2)_L adjoint chiral multiplets, and many singlets in \(a a\) sector remain massless. In addition to the standard model gauge symmetry, there are five additional U(1) gauge symmetries (two of them are anomalous).

The D6_3·D6_3 sector is the hidden sector, since D6_3-brane has no intersections with other D6-branes. Only the interactions which are mediated by closed string states connect this sector with the other sectors. The system of this sector is the supersymmetric USp(2) Yang-Mills theory with supergravity fields from closed string states. If the supersymmetry is dynamically broken in this sector, the “sequestering scenario” of the mediation of
supersymmetry breaking is naturally realized.

This model has almost the same features of the model constructed in the previous section, but contain fewer number of the exotic particles and additional U(1) gauge symmetries.

IV. CONCLUSIONS

We have constructed two composite models of quarks and leptons from type IIA $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$ orientifolds with intersecting D6-branes. The configuration of the intersecting D6-branes of each model is very simple. The number of the exotic particles and additional U(1) gauge symmetries is relatively fewer than in the models previously constructed by virtue of the compositeness of quarks and leptons. Since the compositeness requires additional physical gauge interactions, “hypercolors”, the number of additional unphysical gauge symmetries is reduced. Once the number of additional unphysical gauge symmetries is reduced, the number of additional exotic particles is also reduced, since the exotic particles are required for the anomaly cancellation of the additional gauge symmetries.

One interesting feature in these models is the generation of masses of exotic particles through the Yukawa couplings among “preons”. This mechanism can be applied to give masses to exotic particles in more realistic models.

It is also interesting that the hidden or “sequestering” sector is naturally emerged in these models. The dynamics in this hidden sector might give supersymmetry breaking and a source of the dark energy.

It would be very interesting to explore more realistic models from more general intersecting D-brane configurations.

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