We summarize some recent progress in constructing four-dimensional supersymmetric chiral models from Type II orientifolds. We present the construction of a supersymmetric Standard-like Model and a supersymmetric GUT model to illustrate the new features of this approach and its connection to M theory on compact, singular $G_2$ holonomy spaces. The Standard-like model presented is the first example of a three-family supersymmetric orientifold model with the Standard Model as part of the gauge structure. We also discuss the connection of how chiral fermions arise in this class of models with recent results of M theory compactified on $G_2$ holonomy spaces.

1 Introduction

If string theory is relevant to Nature, at low energies it should give rise to an effective theory containing the Standard Model. Whether string theory can live up to this promise depends on how the string vacuum describing the observable world is selected among a highly degenerate moduli space – a question that we know very little about. Nevertheless, one can use experimental constraints as guiding principles to construct semi-realistic models, and explore with judicious assumptions, the resulting physical implications, in particular to particle physics. This is the basic premise of string phenomenology – hopefully, by exploring the generic features of string derived models, we can learn some new stringy physics that are important for low energy predictions.
Until a few years ago, the construction of four-dimensional string theory solutions was carried out mainly in the framework of weakly coupled heterotic string, in which a number of semi-realistic models have been constructed and analyzed. Meanwhile, model building from other string theories did not seem very promising, partly due to the no-go theorem of perturbative Type II strings. However, M theory unification made important progress in uncovering non-perturbative aspects of string theory: we now understand that these perturbative models represent only a corner of M theory – the true string vacuum may well be in a completely different regime in which the perturbative heterotic string description breaks down.

Our view of string phenomenology changed drastically with the advent of D-branes. The techniques of conformal field theory in describing D-branes and orientifold planes allow, in principle for the construction of semi-realistic string models in another calculable regime of M theory, as illustrated by the various four-dimensional $N = 1$ supersymmetric Type II orientifolds. In these models, chiral fermions appear on the worldvolume of the D-branes since they are located at orbifold singularities in the internal space. Semi-realistic models from non-supersymmetric type IIB orientifolds of this kind have been constructed in several papers, with supersymmetry breaking due to the presence of brane-antibrane configurations in the model.

An alternative to obtain chiral fermions, which has only recently been exploited in model building is to consider branes at angles. In certain configurations of intersecting D-branes, the spectrum of open strings stretched between them may contain chiral fermions, localized at the intersection. This fact was employed in several papers in the construction of non-supersymmetric brane world models. However, the dynamics to determine the stability of non-supersymmetric models are not well understood. The purpose of this work is to explore orientifold models with branes at angles that preserve $N = 1$ supersymmetry in four dimensions.

This general class of supersymmetric orientifold models corresponds in the strong coupling limit to M theory compactification on purely geometrical backgrounds admitting a $G_2$ holonomy metric. We also discuss the relation of this work with the recent results about the appearance of four-dimensional chiral fermions in compactifications of M theory on singular $G_2$ holonomy spaces.
2 Model Building from Orientifolds and Intersecting D6-branes

In this section we shall provide the key features of the construction. We refer the readers to the original papers \[1, 2\] for more detailed discussions.

For concreteness, we consider an orientifold of type IIA on $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$. Generalization to other orbifolds would involve similar techniques, and presumably analogous final results. The orbifold actions have generators $\theta, \omega$ acting as $\theta: (z_1, z_2, z_3) \rightarrow (-z_1, -z_2, z_3)$, and $\omega: (z_1, z_2, z_3) \rightarrow (z_1, -z_2, -z_3)$ on the complex coordinates $z_i$ of $T^6$, which is assumed to be factorizable.

The orientifold action is $\Omega R$, where $\Omega$ is world-sheet parity, and $R$ acts by $R: (z_1, z_2, z_3) \rightarrow (z_1, z_2, -z_3)$. The model contains four kinds of O6-planes, associated to the actions of $\Omega R, \Omega R\theta, \Omega R\omega, \Omega R\theta\omega$. The cancellation of the RR crosscap tadpoles requires an introduction of $K$ stacks of $N_a$ D6-branes ($a = 1, \ldots, K$) wrapped on three-cycles (taken to be the product of 1-cycles $(n^i_a, m^i_a)$ in the $i^{th}$ two-torus), and their images under $\Omega R$, wrapped on cycles $(n^i_a, -m^i_a)$. In the case where D6-branes are chosen parallel to the O6-planes (orientifold 6-planes), the resulting model is related by T-duality to the orientifold in $\mathbb{T}^6$, and is non-chiral. Chirality is however achieved using D6-branes intersecting at non-trivial angles.

The cancellation of untwisted tadpoles impose constraints on the number of D6-branes and the types of 3-cycles that they wrap around. The cancellation of twisted tadpoles determines the orbifold actions on the Chan-Paton indices of the branes (which are explicitly given in \[1, 2\]).

The condition that the system of branes preserves $\mathcal{N} = 1$ supersymmetry requires that each stack of D6-branes is related to the O6-planes by a rotation in $SU(3)$: denoting by $\theta_i$ the angles the D6-brane forms with the horizontal direction in the $i^{th}$ two-torus, supersymmetry preserving configurations must satisfy $\theta_1 + \theta_2 + \theta_3 = 0$. This in turn impose a constraint on the wrapping numbers and the complex structure moduli $\chi_i = R^2_i/R^4_i$.

The rules to compute the spectrum are analogous to those in \[19\]. Here, we summarize the resulting chiral spectrum in Table 1 found in \[1, 2\], where

$$I_{ab} = (n^1_a m^1_b - m^1_a n^1_b)(n^2_a m^2_b - m^2_a n^2_b)(n^3_a m^3_b - m^3_a n^3_b) \quad (1)$$

2.1 Standard-Like Model

Let us present an example leading to a three-family Standard-like Model massless spectrum. The D6-brane configuration is provided in Table 2, and satisfies
| Sector       | Representation                                      |
|--------------|-----------------------------------------------------|
| $aa$         | $U(N_a/2)$ vector multiplet                           |
|              | $3$ Adj. chiral multiplets                            |
| $ab + ba$    | $I_{ab}$ chiral multiplets in $(N_a/2, N_b/2)$ rep.   |
| $ab' + b'a$  | $I_{ab'}$ chiral multiplets in $(N_a/2, N_b/2)$ rep.  |
| $aa' + a'b'$ | $-\frac{1}{2}(I_{aa'} - \frac{1}{2}I_{a',O6})$ chiral multiplets in sym. rep. of $U(N_a/2)$ |
|              | $-\frac{1}{2}(I_{aa'} + \frac{1}{2}I_{a',O6})$ chiral multiplets in antisym. rep. of $U(N_a/2)$ |

Table 1. General spectrum on D6-branes at generic angles (namely, not parallel to any O6-plane in all three tori). The spectrum is valid for tilted tori. The models may contain additional non-chiral pieces in the $aa'$ sector and in $ab$, $ab'$ sectors with zero intersection, if the relevant branes overlap.

the tadpole cancellation conditions. The configuration is supersymmetric for $\chi_1 : \chi_2 : \chi_3 = 1 : 3 : 2$.

| Type | $N_a$ | $\begin{pmatrix} n^1_a, & m^1_a \end{pmatrix} \times \begin{pmatrix} n^2_a, & m^2_a \end{pmatrix} \times \begin{pmatrix} n^3_a, & m^3_a \end{pmatrix}$ |
|------|-------|----------------------------------------------------------------------------------------------------------------------------------|
| $A_1$ | 8     | $(0,1) \times (0,-1) \times (2,0)$                                                                                               |
| $A_2$ | 2     | $(1,0) \times (1,0) \times (2,0)$                                                                                               |
| $B_1$ | 4     | $(1,0) \times (1,-1) \times (1,3/2)$                                                                                             |
| $B_2$ | 2     | $(1,0) \times (0,1) \times (0,-1)$                                                                                               |
| $C_1$ | 6+2   | $(1,-1) \times (0,0) \times (1,1/2)$                                                                                             |
| $C_2$ | 4     | $(0,1) \times (1,0) \times (0,-1)$                                                                                               |

Table 2. D6-brane configuration for the three-family model.

The resulting spectrum is given in table 1, where the last column provides the charges under a particular anomaly-free $U(1)$ linear combination which plays the role of hypercharge. The spectrum of chiral multiplets, regarding their quantum numbers under the Standard Model group $SU(3) \times SU(2) \times U(1)_{Y}$, corresponds to three quark-lepton generations, plus a number of vector-like Higgs doubles, as well as an anomaly-free set of chiral exotic matter. This last set of states is chiral under the Standard Model group, so it cannot be made massive until electroweak symmetry breaking. Hence the model suffers from the presence of light exotics which most likely render it unrealistic. Our main point in presenting it is, however, to illustrate the possibility of building semirealistic models in our setup. It is conceivable that one can construct more realistic models with this approach such that
these phenomenological problems are absent.

Table 3. Chiral Spectrum of the open string sector in the three-family model. The non-Abelian gauge group is $SU(3) \times SU(2) \times USp(2) \times USp(2) \times USp(4)$. Some vector-like sectors have not been included for the sake of clarity.

| Sector | Non-Abelian Reps. | $Q_3$ | $Q_1$ | $Q_2$ | $Q_1'$ | $Q_Y$ |
|--------|------------------|------|------|------|-------|------|
| $A_1B_1$ | $3 \times 2 \times (1, \overline{2}, 1, 1, 1)$ | 0 | 0 | -1 | ±1 | $\pm \frac{1}{2}$ |
| $3 \times 2 \times (\overline{3}, 1, 1, 1, 1)$ | 0 | 0 | -1 | 0 | ±1 | $\pm \frac{1}{2}$ |
| $A_1C_1$ | $2 \times (\overline{3}, 1, 1, 1, 1)$ | -1 | 0 | 0 | ±1 | $\pm \frac{1}{2}$ |
| $2 \times (3, 1, 1, 1, 1)$ | -1 | 0 | 0 | 0 | ±1 | $\pm \frac{1}{2}$ |
| $2 \times (1, 1, 1, 1, 1)$ | 0 | -1 | 0 | ±1 | 0 | 1, 0 |
| $B_1C_1$ | $(3, \overline{2}, 1, 1, 1)$ | 1 | 0 | -1 | 0 | 0 | $\frac{1}{2}$ |
| $(1, \overline{2}, 1, 1, 1)$ | 0 | 1 | -1 | 0 | 0 | $\frac{1}{2}$ |
| $B_1C_2$ | $(1, 2, 1, 1, 4)$ | 0 | 0 | 1 | 0 | 0 | 0 |
| $B_2C_1$ | $(3, 1, 2, 1, 1)$ | 1 | 0 | 0 | 0 | 0 | $\frac{1}{2}$ |
| $(1, 1, 2, 1, 1)$ | 0 | 1 | 0 | 0 | 0 | $\frac{1}{2}$ |
| $B_1C_1'$ | $2 \times (3, 2, 1, 1, 1)$ | 1 | 0 | 1 | 0 | 0 | $\frac{1}{2}$ |
| $2 \times (1, 2, 1, 1, 1)$ | 0 | 1 | 1 | 0 | 0 | $\frac{1}{2}$ |
| $B_1B_1'$ | $2 \times (1, 1, 1, 1, 1)$ | 0 | 0 | -2 | 0 | 0 | 0 |
| $2 \times (1, 3, 1, 1, 1)$ | 0 | 0 | 2 | 0 | 0 | 0 |

2.2 GUT Model

Here we present a string model leading to a four-family $SU(5)$ grand unified theory. The D6-brane configuration is

$N_a = (n_a^+, m_a^+) \times (n_a^-, m_a^-) \times (n_a^0, m_a^0)$

| $N_a$ | $(n_a^+, m_a^+) \times (n_a^-, m_a^-) \times (n_a^0, m_a^0)$ |
|-------|----------------------------------------------------------|
| 10 + 6 | (1, 1) × (1, -1) × (1, 1/2) |
| 16    | (0, 1) × (1, 0) × (0, -1) |

which is supersymmetric for $\arctan \chi_1 - \arctan \chi_2 + \arctan(\chi_3/2) = 0$. We consider that the first set of 16 branes is split in two parallel stacks of 10 and 6. The resulting spectrum is

$U(5) \times U(3) \times USp(16)$

$3(24 + 1, 1, 1) + 3(1, 8 + 1, 1) + 3(1, 1, 119 + 1)$

$4(10, 1, 1) + 4(5, 1, 16) + 4(3, 3, 1) + 4(1, 3, 16) + 4(1, 3, 1)$

The model is a four-family $SU(5)$ GUT, with additional gauge groups and matter content. Notice that turning on suitable vev’s for the adjoint mul-
tiplets the model corresponds to splitting the $U(5)$ branes. This provides a geometric interpretation of the GUT Higgsing to the Standard Model group upon splitting $U(5) \rightarrow U(3) \times U(2) \times U(1)$.

3 Relation to compactification of M theory on $G_2$ holonomy spaces

M theory compactification on a manifold $X$ with $G_2$ holonomy gives rise to an $\mathcal{N} = 1$ theory in four dimensions. If $X$ is smooth, the low energy theory is relatively uninteresting since it contains (in addition to $\mathcal{N} = 1$ supergravity) only abelian vector multiplets and neutral chiral multiplets. However, non-Abelian gauge symmetries and chiral fermions can arise when the manifold $X$ is singular. Isolated conical singularities of $G_2$ manifolds have been studied recently from different points of view. We now discuss how some of these results can be understood within the orientifold setup.

A useful approach to building $G_2$ holonomy spaces is to construct type IIA configurations preserving four supercharges and lifting them to M theory. However, not all four-dimensional $\mathcal{N} = 1$ supersymmetric vacua from M theory correspond to $G_2$ holonomy compactifications, since the M theory lifts may contain additional sources, i.e. M-branes or G-fluxes, other than a pure gravitational background. Hence one needs to start with IIA configurations containing D6-branes, O6-planes (and/or RR 1-form backgrounds, which are absent in our setup), only. When lifted to M theory, a collection of $N$ D6-branes becomes a multi-centered Taub-NUT space, whereas an O6-plane becomes an Atiyah-Hitchin manifold. Hence, IIA configurations involving these ingredients, and preserving four supercharges, when lifted to M theory correspond to a purely geometrical background, i.e., of 11 dimensional space-time compactified on a $G_2$ holonomy space. In this respect, the models considered here correspond to M theory compactified on $G_2$ holonomy space which give rise to non-Abelian gauge symmetries and chiral fermions. The origin of the non-Abelian gauge symmetries is well-known: gauge bosons arises from the massless M2-brane states wrapped in the collapsed 2-cycles in the multi-Taub-NUT lift of overlapping IIA D6-branes. In the following we remark on the appearance of chiral fermions from the M theory viewpoint.

In configurations where the RR 7-form charges are locally cancelled (namely, 2 D6-branes and their 2 images are located on top of each O6-plane), the M theory lift is remarkably simple. The M theory circle is constant over

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$a$On the other hand, smooth special holonomy spaces provide suitable backgrounds for constructing regular fractional brane configurations as viable gravity duals of strongly coupled field theories. For a review, see and references therein.
the base space $B_6$, leading to a total variety $(B_6 \times S^1)/\mathbb{Z}_2$, where the $\mathbb{Z}_2$ flips the coordinate parametrizing the M theory circle, and acts on $B_6$ as an antiholomorphic involution (hence changing the holomorphic 3-form to its conjugate). This is the type of configurations considered in $\text{[13,14]}$ and the resulting models are non-chiral.

In models with D6-branes at angles, chiral fermions arise. In fact, the type IIA description with intersecting D6-branes allows to identify the nature of the singularities of the $G_2$ holonomy space which lead to chiral fermions. The following analysis also makes contact with $\text{[16]}$. Away from the intersections of IIA D6-branes and/or O6-planes, the IIA configuration corresponds to D6-branes and O6-planes wrapped on (disjoint) smooth supersymmetric 3-cycles, which we denote generically by $Q$. The corresponding $G_2$ holonomy space hence corresponds to fibering a suitable hyperkahler four-manifold over each component of $Q$. That is, an $A$-type ALE singularity for $N$ overlapping D6-branes, and a $D$-type ALE space for D6-branes on top of O6-planes (with the Atiyah-Hitchin manifold for no D6-brane, and its double covering for two D6-branes etc., as follows from $\text{[16]}$). Intersections of objects in type IIA therefore lift to co-dimension 7-singularities, which are isolated up to orbifold singularities. It is evident from the IIA picture that the chiral fermions are localized at these singularities.

The structure of these singularities has been studies in $\text{[38]}$, and is similar to certain Calabi-Yau threefold singularities used in geometric engineering in $\text{[45]}$. One starts by considering the (possibly partial) smoothing of a hyperkahler ADE singularity to a milder singular space, parametrized by a triplet of resolution parameters (D-terms or moment maps in the Hyperkähler construction of the space). The kind of 7-dimensional singularities of interest are obtained by considering a 3-dimensional base parametrizing the resolution parameters, on which one fibers the corresponding resolved Hyperkähler space. The geometry is said to be the unfolding of the higher singularity into the lower one. This construction guarantees the total geometry admits a $G_2$ holonomy metric. To determine the matter content arising from the singularity, one decomposes the adjoint representation of the A-D-E group associated to the higher singularity with respect to that of the lower. One obtains chiral fermions with quantum numbers in the corresponding coset, and multiplicity given by an index which for an isolates singularity is one.

It is easy to realize this construction arises in the M theory lift of the models presented in the previous section. For example, at points where two stacks of $N$ D6-branes and $M$ D6-branes intersect, the M theory lift corresponds to a singularity of the $G_2$ holonomy space that represents the unfolding of an $A_{M+N-1}$ singularity into a 4-manifold with an $A_M$, and an $A_{N-1}$ sing-
ularity. By the decomposition of the adjoint representation of $A_{M+N-1}$, we expect the charged matter to be in the bi-fundamental representation of the $SU(N) \times SU(M)$ gauge group, in agreement with the IIA picture. A different kind of intersection arises when $N$ D6-branes intersect with an O6-plane, and consequently with the $N$ D6-brane images. The M theory lift corresponds to the unfolding of a $D_N$ type singularity into an $A_{N-1}$ singularity. The decomposition of the adjoint representation predicts the appearance of chiral fermions in the antisymmetric representation of $SU(N)$, in agreement with the IIA picture. In fact this is the origin of the $10$ representations in our previous $SU(5)$ model.

We would also like to note that the generic class of models described here may exhibit some interesting phenomena, e.g., the existence of non-perturbative equivalences among seemingly different models, which nonetheless share the same M theory lift, in analogy with [4]. On the other hand the type IIA transitions in which intersecting D6-branes recombine (which are T-dual of small instanton transitions) would have interesting M theory descriptions, in which the topology of the $G_2$ holonomy space changes. It would be interesting to explore possible connections of such process with [44]. We hope that our explicit constructions may provide a useful laboratory to probe new ideas in the studies of manifolds with $G_2$ holonomy.

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