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Aspects of Type 0 String Theory §

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Abstract. A construction of compact tachyon-free orientifolds of the non-supersymmetric Type 0B string theory is presented. Moreover, we study effective non-supersymmetric gauge theories arising on self-dual D3-branes in Type 0B orbifolds and orientifolds.

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1. Introduction

If one would like superstring theory to give rise to some testable predictions in the low energy regime, at some point one has to explain how supersymmetry is broken somewhere between the Planck and the weak scale. In another approach one might contemplate to start already with a non-supersymmetric string theory at the Planck scale. However, generically non-supersymmetric string theories are plagued with problems luckily absent in supersymmetric string theories. As in the bosonic string theory, in most non-supersymmetric theories tachyons appear, which in the best of all imaginable scenarios indicate a phase transition into some stable background. Moreover, without supersymmetry a big cosmological constant is generated by loop corrections in conflict with the small value of the cosmological constant we observe at least in our universe. Non-supersymmetric string theories with vanishing cosmological constant have been studied in [1]. Moreover, the cosmological constant serves as a dilaton potential leading to the request for stabilization of the dilaton, i.e. of the string coupling constant. Analogously, scalar potentials for all other moduli are usually generated, which must be stabilized, as well. Concerning establishing string dualities, one is also on less solid ground as compared to supersymmetric string theories. In particular, there is no notion of BPS like objects and masses receive quantum corrections.

In this paper we will mainly deal with the first of the problems mentioned above, namely we will construct non-supersymmetric models free of tachyonic modes. More concretely we will consider special orientifolds of the Type 0B string theory, where the tachyon does not survive the orientifold projection. We will discuss models in ten, six and four space-time dimensions. In all these models the second of the problems from above is present, as a dilaton tadpole is generated on the disc world-sheet. In the second part we will study the effective gauge theories arising on self-dual D3-branes in non-compact Type 0B orbifolds and orientifolds. This approach was initiated in [2, 3] where a generalization of AdS-CFT duality to the supersymmetric Type 0B backgrounds was presented. Here we will mainly focus on the CFT side.

This talk is based on [4, 5, 6] where more details can be found.

2. Non-tachyonic orientifolds of Type 0B

There exist two different constructions of Type 0B string theory. It can be regarded first as the superstring with the projection

$$P = \frac{1}{2}(1 + (-1)^{F_L + F_R}), \quad (1)$$

and second as Type IIB divided out by the space-time fermion number $(-1)^{F_s}$. This leads to a modular invariant partition function containing a tachyon, a graviton, a dilaton and an antisymmetric two form in the NSNS sector and two further scalars, two antisymmetric 2-forms and a 4-form in the RR sector. Except the tachyon all these states are massless. Since compared to the Type IIB models all fields in the RR

sector are doubled, the D-brane content is doubled, as well. The explicit form of the corresponding boundary states was derived in [7]. The two types of D-branes of the same dimension p are denoted as Dp - and Dp' -branes in the following. Studying the annulus amplitude in tree channel using the boundary states and transforming back into loop channel one derives that for open strings stretched between the same type of Dp -branes the world-sheet fermions have half-integer mode expansion, whereas for open strings stretched between a Dp - and a Dp' -brane they have integer mode expansion. In the first case one gets space-time bosons and the second case space-time fermions. Thus, even though the closed string Type 0B theory is purely bosonic, fermions appear in the D-brane sector.

As was first realized in [8, 9] there exist different orientifold projections in Type 0B. The usual orientifold by the world-sheet parity transformation Ω yields a model still containing the tachyon. In [7, 8] it was shown that the dilaton tadpole can be cancelled by introducing 32 D9 and 32 anti D9-branes into the background leading to a gauge group $SO(32) \times SO(32)$ and an open string tachyon in the bi-fundamental representation of the gauge group. The introduction of anti-branes was necessary to cancel the dangerous RR tadpole. The model above was conjectured to be strong-weak dual to the bosonic string compactified on the root lattice of $SO(32)$. Moreover, the orientifold model still contains a tachyonic tadpole, which can only be cancelled by introducing instead 16 D9, 16 D9', 16 $\overline{D9}$ and 16 $\overline{D9}'$ -branes in the background. This model has gauge group $SO(16) \times SO(16) \times SO(16) \times SO(16)$ and was conjectured to be related to the tachyon-free $SO(16) \times SO(16)$ heterotic string in [6].

An independent model is defined by combining the world-sheet parity transformation with the right moving world-sheet fermion number operator $\Omega' = \Omega(-1)^{f_R}$. In this case there appear RR tadpoles in the Klein bottle amplitude which can be cancelled by 32 D9- and 32 D9'-branes. However, from the annulus amplitude there remains an uncancelled dilaton tadpole which leads to a shift in the expectation values of the background fields via the Fischler-Susskind mechanism [10]. The massless closed string spectrum is given by the bosonic part of Type IIB spectrum and the self-dual D9-branes support a $U(32)$ gauge group with Majorana-Weyl fermions in the $\mathbf{496} \oplus \overline{\mathbf{496}}$ representation. The closed and open string together cancel the R^6 and F^6 anomalies. Note, that in contrast to Type I string theory this orientifold still contains Dp-branes for every odd number of p . This orientifold model was conjectured to be related to the tachyonic $U(16)$ heterotic string theory. For completeness we mention that there exists a third orientifold projection. The world-sheet parity transformation is combined with the right moving space-time fermion number operator leading to a tachyon tadpole in the Klein bottle amplitude.

The question is whether the absence of tachyons holds under toroidal orbifold compactifications. It was argued in [11] that in general this is not the case, as the world-sheet parity transformation exchanges a g twisted sector with the g^{-1} twisted sector implying that some linear combinations of the twisted sector tachyons survive the projection. Orientifolds in which the twisted sectors are invariant under Ω were

discussed in [12, 13] and might have interesting non-supersymmetric generalizations.

From the set of supersymmetric orbifolds there are however two models in which all tachyons are projected out. In six flat space-time dimensions one has the \mathbb{Z}_2 orbifold of T^4 with action $z_i \rightarrow -z_i$ for each of the two complex coordinates. Performing the tadpole cancellation condition, one realizes that all RR tadpoles can be cancelled by introducing 32 self-dual D9-branes and 32 self-dual D5-branes in the background. At the massless level the closed string sector contains the graviton, the dilaton, 20 self dual 2-forms, 4 anti-self dual 2-forms and 98 further scalars. In the open string sector one gets gauge group $G=U(16) \times U(16)|_9 \times U(16) \times U(16)|_5$, where the first two factors live on the D9-branes and the second two on the D5-branes. The open strings connecting the various kinds of D-branes and D'-branes yield the following massless matter states

$$\begin{aligned}
& 4 \times \{(\mathbf{16}, \overline{\mathbf{16}}; \mathbf{1}, \mathbf{1}) + (\overline{\mathbf{16}}, \mathbf{16}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{16}, \overline{\mathbf{16}}) + (\mathbf{1}, \mathbf{1}; \overline{\mathbf{16}}, \mathbf{16})\}_{1,1} \\
& 2 \times \{(\mathbf{16}, \mathbf{1}; \overline{\mathbf{16}}, \mathbf{1}) + (\overline{\mathbf{16}}, \mathbf{1}; \mathbf{16}, \mathbf{1}) + (\mathbf{1}, \mathbf{16}; \mathbf{1}, \overline{\mathbf{16}}) + (\mathbf{1}, \overline{\mathbf{16}}; \mathbf{1}, \mathbf{16})\}_{(1,1)} \\
& 2 \times \{(\mathbf{120} \oplus \overline{\mathbf{120}}, \mathbf{1}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{120} \oplus \overline{\mathbf{120}}; \mathbf{1}, \mathbf{1}) + \\
& \quad (\mathbf{1}, \mathbf{1}; \mathbf{120} \oplus \overline{\mathbf{120}}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{1}, \mathbf{120} \oplus \overline{\mathbf{120}})\}_{(1,2)} \\
& 2 \times \{(\mathbf{16}, \mathbf{16}; \mathbf{1}, \mathbf{1}) + (\overline{\mathbf{16}}, \overline{\mathbf{16}}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{16}, \mathbf{16}) + (\mathbf{1}, \mathbf{1}; \overline{\mathbf{16}}, \overline{\mathbf{16}})\}_{(2,1)} \\
& 1 \times \{(\mathbf{16}, \mathbf{1}; \mathbf{1}, \mathbf{16}) + (\overline{\mathbf{16}}, \mathbf{1}; \mathbf{1}, \overline{\mathbf{16}}) + (\mathbf{1}, \mathbf{16}; \mathbf{16}, \mathbf{1}) + (\mathbf{1}, \overline{\mathbf{16}}; \overline{\mathbf{16}}, \mathbf{1})\}_{(1,2)}
\end{aligned} \tag{2}$$

where the index indicates the representation under the $SU(2) \times SU(2)$ Lorentz-group in six-dimensions. For the complete closed and open spectrum both the R^4 and the F^4 anomaly cancels.

In four flat space-time dimensions the orientifold on T^6/\mathbb{Z}_3 is free of tachyons. Note, that it is only for the \mathbb{Z}_3 orbifold that the twisted sector ground state energy vanishes. In this case all RR tadpoles can be cancelled by self-dual D9-branes. In the closed string sector one gets the graviton plus 10 scalars, including the dilaton and internal metric moduli, and additional 20 RR-scalars and one vector that arises from the 4-form. In the twisted sector appears another 27 NS-NS massless scalars and 54 R-R massless scalars. In the open string sector one obtains gauge group $G=U(12) \times U(12) \times U(8)$ with bosonic and fermionic matter

$$\begin{aligned}
& 3 \times \{(\mathbf{12}, \overline{\mathbf{12}}, \mathbf{1}) + (\mathbf{1}, \mathbf{12}, \overline{\mathbf{8}}) + (\overline{\mathbf{12}}, \mathbf{1}, \mathbf{8}) + c.c.\}_{B} \\
& 1 \times \{(\mathbf{12}, \mathbf{12}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \mathbf{28}) + (\overline{\mathbf{12}}, \overline{\mathbf{12}}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \overline{\mathbf{28}})\}_{L} \\
& 3 \times \{(\mathbf{66}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{12}, \mathbf{8}) + (\mathbf{1}, \overline{\mathbf{66}}, \mathbf{1}) + (\overline{\mathbf{12}}, \mathbf{1}, \overline{\mathbf{8}})\}_{L}.
\end{aligned} \tag{3}$$

This spectrum is chiral and free of non-Abelian gauge anomalies. Concerning the $U(1)$ factors, there is one non-anomalous and two anomalous combinations whose anomaly could presumably be cancelled by a generalized Green-Schwarz mechanism.

So far we have only considered orbifolds preserving some supersymmetry in the Type IIB setting. Since Type 0B is non-supersymmetric anyway, we are free to consider more general orbifold actions. One non-tachyonic four dimensional examples of this sort was discussed in [6]. One simply takes T^6 and divides out by the \mathbb{Z}_2 action $z_i \rightarrow z_i$ for all three complex coordinates. Note, that in Type IIB this orbifold would not satisfy level-matching. In particular, the level-matching condition would be violated in the

NS-R sector, but precisely this sector is absent in Type 0B. One subtlety arises in the Ramond sector where the action of the \mathbb{Z}_2 on the ground states is

$$R|s_1 s_2 s_3 s_4\rangle = e^{\pi i(s_2+s_3+s_4)}|s_1 s_2 s_3 s_4\rangle = \pm i|s_1 s_2 s_3 s_4\rangle \quad (4)$$

with $s_i = \pm 1/2$. This action is rather \mathbb{Z}_4 than \mathbb{Z}_2 . In the closed string sector the left-moving Ramond sector is always paired with the right-moving Ramond sector, so that the action is really \mathbb{Z}_2 , but in the open string sector this \mathbb{Z}_4 action on the Ramond ground states has to be compensated by a \mathbb{Z}_4 action on the Chan-Paton factors. Moreover, the Klein bottle amplitude for this model leads to tadpoles which can be cancelled by 32 self-dual D9 -and self-dual D3-branes. The technical aspects of this model are discussed in length in [6] and everything works out just right to eventually lead to a chiral but anomaly free massless spectrum. The closed string sector contributes the graviton, the dilaton and 117 further scalars and the branes support a gauge group $G=U(16)\times U(16)|_9 \times U(16) \times U(16)|_3$ with matter

$$\begin{aligned} & 6 \times \{(\mathbf{16}, \overline{\mathbf{16}}; \mathbf{1}, \mathbf{1}) + (\overline{\mathbf{16}}, \mathbf{16}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{16}, \overline{\mathbf{16}}) + (\mathbf{1}, \mathbf{1}; \overline{\mathbf{16}}, \mathbf{16})\}_B \\ & 4 \times \{(\mathbf{120}, \mathbf{1}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{120}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{120}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{1}, \mathbf{120})\}_L \\ & 4 \times \{(\overline{\mathbf{16}}, \overline{\mathbf{16}}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \overline{\mathbf{16}}, \overline{\mathbf{16}})\}_L \\ & 1 \times \{(\mathbf{16}, \mathbf{1}; \mathbf{16}, \mathbf{1}) + (\mathbf{1}, \mathbf{16}; \mathbf{1}, \mathbf{16})\}_L \end{aligned} \quad (5)$$

Thus, we have constructed a couple of tachyon-free non-supersymmetric orientifolds in various space-time dimensions. The spectra we obtained are of course only correct at tree-level. Quantum corrections will lead to an effective potential for the brane moduli, the minima of which will determine the final positions of the branes and therefore the gauge symmetry. In the computation of the massless spectra we have implicitly assumed that all branes of the same dimension lie on top of each other. Taking quantum corrections into account this might simply not be a minimum of the effective potential. The analysis of [14] might suggest that maybe all non-supersymmetric models are driven by quantum induced potentials for the moduli to supersymmetric configurations, so that maybe all stable vacua of string theory are supersymmetric. However, in particular for the non-supersymmetric orientifold T^6/\mathbb{Z}_2 we find it hard to imagine a candidate supersymmetric vacuum to which it might flow.

3. Effective gauge theories on D3-branes

It was suggested in [15] to study the dynamics of non-supersymmetric gauge theories by viewing them as effective theories arising on D3-branes in Type 0B string theory. This idea was worked out in [2], where the low energy effective action of Type 0B was computed. Since this action contains a coupling of the tachyon to the square of the RR 5-form field strength, introducing RR 5-form flux into the background can cure the tachyonic instability. For self-dual D3-branes the tachyon decouples and a generalized AdS-CFT correspondence was established in [3] which turned out to be stable as long as the 't Hooft coupling satisfies $\lambda = g_{YM}^2 N < 100$.

The effective theory arising on N parallel self-dual D3-branes in Type 0B has gauge group $SU(N) \times SU(N)$ and three complex bosons in the $(\mathbf{Adj}, \mathbf{1})$ and $(\mathbf{1}, \mathbf{Adj})$ representation. Moreover, there arise four Weyl-fermions in the $(\mathbf{N}, \overline{\mathbf{N}}) + (\overline{\mathbf{N}}, \mathbf{N})$ representation of the gauge group. It is easily shown that the one-loop β -function vanishes identically for this matter spectrum and the two-loop β -function vanishes only in the large N limit. Thus, as expected for non-supersymmetric gauge theories the AdS-CFT correspondence only tells us that the gauge theory is conformal only in the large N limit. There are non-zero $1/N$ corrections which correspond to string loop corrections to the AdS_5 geometry. The exact vanishing of the one-loop β -function is related to the vanishing of the annulus amplitude for self-dual D-branes in Type 0B. The non-vanishing of the two-loop β -function therefore tells us, that the two loop string partition function will be non-zero. In fact, the observation that Type 0B can be regarded as an orbifold of Type IIB and the general arguments given in [16] imply that all higher loop β -functions vanish in the large N limit. Unfortunately, it is so far out of reach of our methods to decide whether there exists a non-trivial fixed point of the entire renormalization group flow even for finite value of N . In the following we will study what kinds of gauge theories one gets by taking orbifolds and orientifolds of the original model.

3.1. Orbifolds

We are placing N self-dual D3-branes on a non-compact \mathbb{Z}_K orbifold. Similar to the compact case discussed in Section 2 we are free to choose orbifolds preserving $N=2$ [17], $N=1$ or even no supersymmetry at all. We compute the annulus amplitude

$$A = \int_0^\infty \frac{dt}{t} \text{Tr}_{open} \left[\left(\frac{1}{K} \sum_{i=0}^{K-1} \Theta^i \right) e^{-2\pi t L_0} \right] \quad (6)$$

for self-dual D3-branes and require the absence of both linear and logarithmic ultraviolet divergences. This leads to conditions for the action γ_{Θ^i} of the symmetry on the Chan-Paton factors. Since we are in a non-compact setting and have the same number of D3- and D3'-branes, there arises no massless or tachyonic tadpole in the untwisted sector. Therefore there exists no restriction on γ_1 and the number of D3-branes is arbitrary. In the orbifold case, the twisted tadpole conditions are simply $\gamma_{\Theta^i} = 0$ for $i = 1, \dots, K$. Explicit results can be found in [5], here we just mention the general features. Since the annulus amplitude vanishes exactly, all spectra are bose-fermi degenerated and the one-loop β -functions are zero, as well. At two loop order one encounters $1/N$ corrections. Moreover, all gauge groups are of the type $\prod_i SU(n_i)^2$, thus every unitary gauge group appears twice. In order to get more general gauge groups, like single $SU(n)$ factors or orthogonal and symplectic gauge groups, one has to consider orientifolds.

3.2. Orientifolds

As in the compact case, one has to distinguish between two different orientifold projections. One can consider first non-compact orientifolds with the T-dual of the

Ω operation and second orientifolds with the T-dual of $\Omega(-1)^{f_R}$. Note, that we need to take the T-dual operators, $\omega = \Omega J(-1)^{f_L}$ and $\omega' = \Omega(-1)^{f_R} J(-1)^{f_L}$ with $J : z_{1,2,3} \rightarrow -z_{1,2,3}$, as we are interested in effective four dimensional models and therefore need D3-branes instead of D9-branes.

3.2.1. ω orientifolds These are orientifolds by the group $G + \omega G$ with $G = \mathbb{Z}_K$. In the compact case the untwisted RR tadpole cancellation condition forced us to introduce anti-branes and therefore open string tachyons into the background. However in the non-compact case there are only twisted sector RR tadpoles, which are cancelled by choosing $\gamma_{\Theta^i} = 0$ for $i = 1, \dots, K$. Therefore, there is no need to introduce anti-branes and one gets stable gauge theories on the self-dual D3-branes. Here we would like to only discuss the easiest case with trivial G, more complicated examples can be found in [5]. For $G = 1$ we find the two allowed gauge groups $G = \text{SO}(N) \times \text{SO}(N)$ and $G' = \text{SP}(N) \times \text{SP}(N)$ and three complex bosons in the $(\mathbf{Adj}, \mathbf{1})$ and $(\mathbf{1}, \mathbf{Adj})$ representation. Moreover, we have four Weyl-fermions in the (\mathbf{N}, \mathbf{N}) representation of the gauge group. In all orientifold models the one-loop β -function of the gauge coupling vanishes only in the large N limit, namely in this case it is $b_1 = 0 \text{ N} \mp 16/3$. From the string theoretic point of view this is simply due to the fact that, even though the annulus amplitude is still vanishing, the Möbius amplitude is non-zero. Thus, there is a one-loop cosmological constant generated, which causes the dilaton and therefore the gauge coupling to run. Since the Möbius amplitude is $1/N$ suppressed against the annulus amplitude, this running is a $1/N$ effect in the one-loop β -function. For the two-loop β -function we obtain $b_2 = \pm 64/3(N \mp 1/2)$ where the N^2 term vanishes. Note, that b_1 and b_2 have opposite sign so that there is a chance to find a non-trivial fixed point at some finite value of g . Of course, we can not prove that such a fixed point really exists. Going to more general orbifold groups G does not change the general patterns mentioned above, it only produces more general gauge and matter contents.

3.2.2. ω' orientifolds These are orientifolds by the group $G + \omega' G$ with $G = \mathbb{Z}_K$. One finds the same RR-tadpole cancellation conditions as in the corresponding Type IIB orientifold

$$\text{Tr}(\gamma_{\Theta^{2k}}) = \pm \frac{1}{\prod_{i=1}^3 \cos\left(\frac{\pi k v_i}{K}\right)}, \quad (7)$$

where Θ denotes the generator of \mathbb{Z}_K and acts on the three complex coordinates transversal the D3-branes as $\Theta z_i \rightarrow \exp(2\pi i v_i / K) z_i$. There arises no untwisted dilaton tadpole but there are new twisted sector NSNS tadpoles. Since the trace of γ_1 is proportional to N and the relation (7) holds, they are $1/N$ suppressed. Choosing the trivial orbifold group G leads to a gauge group $G = \text{SU}(N)$, three complex bosons in the (\mathbf{Adj}) and four Weyl-fermions in the $(\mathbf{A} + \overline{\mathbf{A}})$ or $(\mathbf{S} + \overline{\mathbf{S}})$ representation of the gauge group. For the one-loop β -function we find $b_1 = 0 \text{ N} \pm 16/3$ and the two-loop β -function consistently vanishes in the large N limit. For this class of orientifolds generally one

finds an odd number of $SU(n)$ gauge factors but no orthogonal or symplectic gauge groups.

4. Conclusions

In [5, 18] the T-dual description of the models presented here was discussed. These are the Type 0A generalizations of Hanany-Witten set-ups including self-dual D4-branes stretched between NS5-branes. The rules for determining the massless spectra are easily derived and one finds as the general feature, that the one-loop β -function of the coupling in the non-supersymmetric gauge theory is the same as the one-loop β -function in the corresponding supersymmetric Type IIA gauge theory. It is this property which distinguishes the Type 0 models from the general class of non-supersymmetric models discussed in [19]. It would be interesting to see how far the methods and results derived in the supersymmetric case could be generalized to the non-supersymmetric case at least qualitatively. In particular one would like to embed the Hanany-Witten set-ups into M-theory by using the conjectured duality [20] of Type 0A to M-theory on $S^1/(-1)^{F_S}S$ where S denotes the shift around the half-circle.

Moreover, a better understanding of the process of tachyon condensation and which models are related by that is desirable [21]. It was proposed in [22] to solve the gauge hierarchy problem via conformal field theories. The realization of this idea strongly depends on the existence of non-trivial renormalization group fixed points in non-supersymmetric gauge theories. It would be nice if string theoretic methods could give some new insights into the existence of such fixed points.

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