

Open string models with Scherk-Schwarz SUSY breaking

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Abstract

We apply the well-known Scherk-Schwarz supersymmetry breaking mechanism in an open string context. We construct a new $\mathbf{Z}_3 \times \mathbf{Z}'_3$ model, containing only $D9$ -branes, and rederive from a more geometric perspective the known $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ model, containing $D9$, $D5$ and $\bar{D}5$ branes. We show recent results about the study of quantum instability of these models.

In the last years great efforts have been devoted to studying a way to embed the well-established knowledges about the Standard Model (SM) in a more fundamental microscopic theory. String theory is one of the most promising candidates along this path, but we do not have a complete solution to the problem yet.

In this pattern supersymmetry (SUSY) plays a crucial role, for example explaining how the hierarchy problem can be solved, but also stabilizing the various string models one can build. It is also clear that a phenomenologically appealing string model must contain a mechanism that breaks SUSY at a suitable scale (TeV), and this makes things difficult, because it is extremely hard to build truly stable non-SUSY vacua in string theory.

To this purpose we have taken into account the so-called Scherk-Schwarz (SS) symmetry-breaking mechanism [1], applicable on theories with compact extra dimensions. As described in the next section, it consists in suitably twisting the periodicity conditions of each field along some compact directions. In this way, one obtains a non-local, perturbative and calculable symmetry breaking mechanism. String models of this type can be constructed by deforming supersymmetric orbifold models [2]; a variety of four-dimensional (4D) closed string models, mainly based on \mathbf{Z}_2 orbifolds, have been constructed in this way [3]. More in general, SS symmetry breaking can be achieved through freely-acting orbifold projections [4]. This fact has been recently exploited in [5] to construct a novel class of closed string examples, including a model based on a \mathbf{Z}_3 orbifold. Unfortunately, a low compactification scale is quite unnatural for closed string models, where the fundamental string scale M_s is tied to the Planck one, and can be achieved only in very specific situations [7] (see also [8]). The situation is different for open strings, where M_s can be very low [9], and interesting open string models with SS SUSY breaking have been derived in [10, 11, 12]. Recently, the SS mechanism has been the object of renewed interest also from a more phenomenological “bottom-up” viewpoint, where it has been used in combination with orbifold projections to construct realistic 5D non-SUSY extensions of the SM [13, 14].

We will describe the general ideas proposed in [5] and build chiral IIB orientifold models with SS supersymmetry breaking. The most appealing common feature of these models is that they are tachyon-free for a suitable choice of the compactification moduli, so that instabilities, at least at the classical level, are still avoided. Recently new studies [6] have been performed to analyze the quantum stability more deeply, in particular the potential for the crucial moduli, which is flat at tree level, have been computed at one loop, showing a good behavior, at least for the model based on the \mathbf{Z}_2 orbifold.

1 The Scherk-Schwarz mechanism in string theory

The Scherk-Schwarz mechanism was introduced in models where some compact extra dimension is present. Given a symmetric theory under a group G it is possible to break the symmetry by fixing different boundary conditions for fields in the same multiplet. If we consider a SUSY theory with fields ϕ_F defined on the compact dimension $x \sim x + 2\pi R$, where F labels the fermionic or bosonic nature of each field, the procedure of SUSY breaking is encoded in the twisted boundary conditions

$$\phi_F(x + 2\pi R) = g(F)\phi_F(x), \quad (1)$$

where $g(F)$ is, for example, a phase that takes different values for bosons and fermions. In a compact formalism, introducing P as a translation along the compact dimension,

$$\phi_F = g(F)P\phi_F. \quad (2)$$

In string theory this is realized through an orbifold projection with an operator obtained by joining a SUSY-breaking operator g with a translation along a compact dimension.

The key feature is that the translation shifts the tachyon masses that usually arise when orbifolding with g only. The shift is proportional to R^2 , R being the radius of the compact direction where the translation acts, so that, for R sufficiently big the model is tachyon free. Moreover the scale of SUSY breaking is proportional to R .

We demand that g and P commute, and so we also need the two operators to have order N_g and N_P such that $nN_g = N_P$ for some $n \in \mathbb{N}$. This is due to the fact that modular invariance requires, in the closed sector, the introduction of sector twisted by $(gP)^q$, with $q \in \{0, 1, \dots, N_{gP} - 1\}$, so that if the above relation is not fulfilled there exists at least one sector twisted only by g that contains tachyons. In the next sections we shall introduce an order-two and an order-three operator and apply them to $d = 4$, $N = 1$ string models.

2 The $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ model

The $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ orientifold of [11] is obtained by applying a SUSY-breaking \mathbf{Z}'_2 projection to the SUSY \mathbf{Z}'_6 model of [16]. The \mathbf{Z}'_6 group is generated by θ acting as rotations of angles $2\pi v_i^\theta$ in the three internal tori T_i^2 ($i = 1, 2, 3$), with $v_i^\theta = 1/6(1, -3, 2)$. The \mathbf{Z}'_2 group is instead generated by β acting as a translation of length πR along one of the radii of T_2^2 (that we shall call SS direction in the following), combined with a sign $(-)^F$, where F is the 4D space-time fermion number. Beside the $O9$ -plane, the model contains $O5$ -planes at $y = 0$ and $y = \pi R$ (as the corresponding SUSY model [16]) and $\bar{O}5$ -planes at $y = \pi R/2$ and $y = 3\pi R/2$ along the SS direction (see Fig. 1), corresponding to the two order-2 elements θ^3 and $\theta^3\beta$. In order to cancel both NSNS and RR massless tadpoles, $D9$, $D5$ and $\bar{D}5$ -branes must be introduced.

2.1 Spectrum

The main features of the closed string spectrum of the $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ model can be deduced from those of the \mathbf{Z}'_6 model, that can be found in [16]. The spectrum is summarized in Table 1.

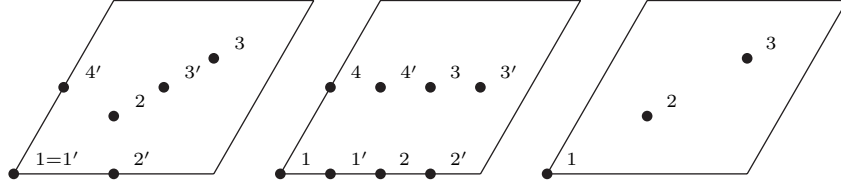


Figure 1: The fixed-points structure in the $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ model. We label the 12 θ -fixed points with P_{1bc} and the 12 $\theta\beta$ -fixed points with $P_{1bc'}$, each index referring to a T^2 , ordered as in the figure. Similarly, we denote with $P_{a\bullet c}$ the 9 θ^2 -fixed planes filling the second T^2 , and respectively with $P_{a'b\bullet}$ and $P_{a'b'\bullet}$ the 16 θ^3 -fixed and $\theta^3\beta$ -fixed planes filling the third T^2 . The 32 $D5$ -branes and the 32 $\bar{D}5$ -branes are located at the point 1 in the first T^2 , fill the third T^2 , and sit at the points 1 and 1' respectively in the second T^2 .

Sector	$\mathbf{Z}'_6 \times \mathbf{Z}'_2$	$\mathbf{Z}_3 \times \mathbf{Z}'_3$
Untwisted	1 graviton, 5 scalars	1 graviton, 11 scalars, 1+1 spinors
θ twisted	6 chiral multiplets	6 hypermultiplets
θ^2 twisted	18 scalars	—
θ^3 twisted	6 chiral multiplets	—
$\theta\beta$ twisted	6 chiral	9 chiral
$\theta^3\beta$ twisted	6 chiral	—
$\theta\beta^2$ twisted	—	9 chiral

Table 1: Massless closed string spectrum for $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ and $\mathbf{Z}_3 \times \mathbf{Z}'_3$ models. We used θ as the generator of \mathbf{Z}'_6 (\mathbf{Z}_3) and β as the generator of \mathbf{Z}'_2 (\mathbf{Z}'_3). Hypermultiplets are multiplets of $N=1$ SUSY in 6D, while chiral multiplets are multiplets of $N=1$ SUSY in 4D. The SUSY generators are different in the different sectors as explained in the text. The two spinors in the untwisted sector of $\mathbf{Z}_3 \times \mathbf{Z}'_3$ have opposite chirality.

The open spectrum sectors are defined by tadpole cancellation, that requires the presence of $D9$, $D5$ and $\bar{D}5$ branes. Tadpole cancellation leaves a certain freedom in the choice of the gauge group, for simplicity we consider the case of maximal unbroken gauge symmetry where all $D5$ and $\bar{D}5$ branes are located respectively at $P_{11\bullet}$ and $P_{11'\bullet}$ (see Fig. 1 and its caption). The \mathbf{Z}'_2 projection requires then that an equal number of image branes are located respectively at $P_{12\bullet}$ and $P_{12'\bullet}$. We do not consider the case in which branes and anti-branes coincide also along the SS direction because this configuration is unstable even classically, due to the presence of open string tachyons. On the other hand, fixing the branes at antipodal points along the SS direction allows a metastable configuration without open string tachyons for sufficiently large SS radius. The massless open string spectrum can now be easily derived, and is summarized in Table 2.

3 A $\mathbf{Z}_3 \times \mathbf{Z}'_3$ model

It has been shown in [5] that SS symmetry breaking can be obtained also in \mathbf{Z}_3 models through a suitable freely-acting and SUSY-breaking \mathbf{Z}'_3 projection. In this section, we will construct a new $\mathbf{Z}_3 \times \mathbf{Z}'_3$ model, based on this structure, that will prove to be much simpler than the $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ one.

The $\mathbf{Z}_3 \times \mathbf{Z}'_3$ orbifold group is defined in the following way [5]. The \mathbf{Z}_3 generator α acts as a SUSY-preserving rotation with twist $v_i^\alpha = 1/3(1, 1, 0)$, while the \mathbf{Z}'_3 generator β acts as a SUSY-breaking rotation with $v_i^\beta = 1/3(0, 0, 2)$ and an order-three diagonal translation δ in T_1^2 .

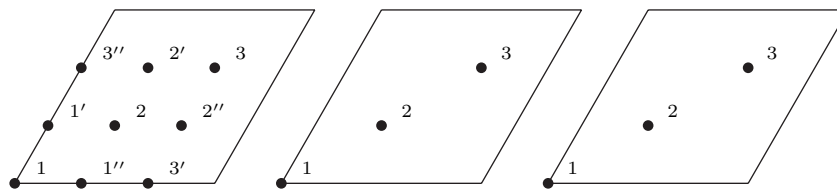


Figure 2: The fixed-point structure in the $\mathbf{Z}_3 \times \mathbf{Z}'_3$ model. We label the 9 α -fixed planes with $P_{ab\bullet}$, the 27 $\alpha\beta$ -fixed points with $P_{a'bc}$, the 27 $\alpha\beta^2$ -fixed points with $P_{a''bc}$, and the 3 β -fixed planes with $P_{\bullet\bullet c}$.

3.1 Spectrum

The closed string spectrum is summarized in Table 1. The open spectrum contains only a sector from strings stretching between $D9$ -branes. The maximal gauge group is $SO(8) \times U(8) \times U(4)$. The $U(8) \times U(4)$ factor comes from the $U(12)$ gauge factor of the 4D $N=1$ \mathbf{Z}_3 model, which is further broken by the \mathbf{Z}'_3 projection. As in the previous model, this can be interpreted as a Wilson line symmetry breaking. Notice that all the gauginos have a mass $\sim 1/R_1$. The spectrum of charged massless states is easily obtained and reported in Table 2.

4 Discussion

The Scherk-Schwarz SUSY breaking mechanism has been introduced in open string theory and applied to two $d = 4$, $N = 1$ models. We obtained two non-SUSY tachyon-free chiral models, whose stability has been discussed in [6], where the potential V for the relevant modulus R defined in the first section has been studied. V is flat at tree level but gets corrections from loop amplitudes. We considered the one-loop amplitudes for various models, in the odd-order orbifolds a quantum instability is found in every case, while in the Z_2 case V shows a minimum. This stability has also been studied considering more than a modulus, and it seems that the presence of a general minimum is not guaranteed, but in this case we think that a deeper analysis is needed.

In [18] we have also studied the local anomaly cancellation in the two models. All pure gauge and mixed gauge-gravitational anomalies cancel, thanks to a generalized GS mechanism that involves also twisted RR 4-forms, necessary to cancel localized irreducible

	$\mathbf{Z}'_6 \times \mathbf{Z}'_2$	$\mathbf{Z}_3 \times \mathbf{Z}'_3$
$G_9 :$ $G_5 = G_{\bar{5}} :$	$U(4)^2 \times U(8)$ $U(2)^2 \times U(4)$	$SO(8) \times U(8) \times U(4)$ —
99 scalars	$(4, 4, 1), (\bar{4}, \bar{4}, 1), (1, 1, 28),$ $(1, 1, \bar{28}), (6, 1, 1), (1, 4, \bar{8}),$ $(\bar{4}, 1, 8), (1, \bar{6}, 1), (\bar{4}, 4, 1),$ $(4, 1, 8), (1, \bar{4}, \bar{8})$	$2(8, 8, 1), 2(1, \bar{28}, 1),$ $(8, 1, 4), (1, 1, \bar{6})$
99 fermions	—	$2(8, 1, 4), 2(1, 1, \bar{6}),$ $(1, \bar{8}, 4), (1, \bar{8}, \bar{4})$
55 chiral mult.	$(2, 2, 1), (\bar{2}, \bar{2}, 1), (1, 1, 6),$ $(1, 1, \bar{6}), (1_A, 1, 1), (1, 2, \bar{4}),$ $(\bar{2}, 1, 4), (1, \bar{1}_A, 1), (\bar{2}, 2, 1),$ $(2, 1, 4), (1, \bar{2}, \bar{4})$	—
95 chiral mult.	$(\bar{4}, 1, 1; \bar{2}, 1, 1), (1, 4, 1; 1, 2, 1),$ $(4, 1, 1; 1, 1, \bar{4}), (1, 1, \bar{8}; 2, 1, 1),$ $(1, \bar{4}, 1; 1, 1, 4), (1, 1, 8; 1, \bar{2}, 1)$	—

Table 2: Massless open string spectrum for $\mathbf{Z}'_6 \times \mathbf{Z}'_2$ and $\mathbf{Z}_3 \times \mathbf{Z}'_3$ models. In the 55 sector chiral multiplets in the representation of G_5 are reported. The matter content of the $\bar{5}\bar{5}$ sector is the same of the 55 sector but in conjugate representations of $G_{\bar{5}} = G_5$. In the 95 sectors chiral multiplets are present in representations of $G_9 \times G_5$ respectively. Again, the matter content in the $\bar{9}\bar{5}$ sector is obtained from that in the 95 sector by conjugation.

6-form terms in the anomaly polynomial, which vanish only globally. The 4D remnant of this mechanism is a local Chern–Simons term. The local (and global) cancellation of reducible anomalies is instead ensured by twisted RR axions. In the latter case, even $U(1)$ gauge fields affected by anomalies that vanish only globally in 4D are spontaneously broken by the GS mechanism. Such $U(1)$'s do not appear in the corresponding SUSY \mathbf{Z}'_6 and \mathbf{Z}_3 4D orientifolds.

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References

- [1] J. Scherk and J. H. Schwarz, *Phys. Lett. B* **82** (1979) 60; *Nucl. Phys. B* **153** (1979) 61.
- [2] L. J. Dixon, J. A. Harvey, C. Vafa, and E. Witten, *Nucl. Phys. B* **261** (1985) 678; *Nucl. Phys. B* **274** (1986) 285.
- [3] C. Kounnas and M. Porrati, *Nucl. Phys. B* **310** (1988) 355;
S. Ferrara, C. Kounnas, M. Porrati, and F. Zwirner, *Nucl.Phys.B***318** (1989) 75;
- [4] R. Rohm, *Nucl. Phys. B* **237** (1984) 553;
C. Kounnas and B. Rostand, *Nucl. Phys. B* **341** (1990) 641;
E. Kiritsis and C. Kounnas, *Nucl. Phys. B* **503** (1997) 117 [hep-th/9703059].
- [5] C. A. Scrucca and M. Serone, *JHEP* **0110** (2001) 017 [hep-th/0107159].
- [6] M. Borunda, M. Serone, and M. Trapletti, arXiv:hep-th/0210075.
- [7] I. Antoniadis, *Phys. Lett. B* **246** (1990) 377.
- [8] I. Antoniadis, C. Munoz, and M. Quiros, *Nucl. Phys. B* **397** (1993) 515 [hep-ph/9211309];
I. Antoniadis and K. Benakli, *Phys. Lett. B* **326** (1994) 69 [hep-th/9310151].
- [9] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, *Phys. Lett. B* **436** (1998) 257 [hep-ph/9804398].
- [10] I. Antoniadis, E. Dudas, and A. Sagnotti, *Nucl. Phys. B* **544** (1999) 469 [hep-th/9807011].
- [11] I. Antoniadis, G. D'Appollonio, E. Dudas, and A. Sagnotti, *Nucl. Phys. B* **553** (1999) 133 [hep-th/9812118]; *Nucl. Phys. B* **565** (2000) 123 [hep-th/9907184].
- [12] A. L. Cotrone, *Mod. Phys. Lett. A* **14** (1999) 2487 [hep-th/9909116].
- [13] A. Pomarol and M. Quiros, *Phys. Lett. B* **438** (1998) 255 [hep-ph/9806263];
I. Antoniadis, S. Dimopoulos, A. Pomarol, and M. Quiros, *Nucl. Phys. B* **544** (1999) 503 [hep-ph/9810410];
A. Delgado, A. Pomarol and M. Quiros, *Phys. Rev. D* **60** (1999) 095008 [hep-ph/9812489].
- [14] R. Barbieri, L. J. Hall, and Y. Nomura, *Phys. Rev. D* **63** (2001) 105007 [hep-ph/0011311].
- [15] C. Angelantonj, M. Bianchi, G. Pradisi, A. Sagnotti, and Y. S. Stanev, *Phys. Lett. B* **385** (1996) 96 [hep-th/9606169].
- [16] G. Aldazabal, A. Font, L. E. Ibanez, and G. Violero, *Nucl. Phys. B* **536** (1998) 29 [hep-th/9804026].
- [17] I. Antoniadis, K. Benakli, and A. Laugier, [hep-th/0111209].
- [18] C. A. Scrucca, M. Serone, and M. Trapletti, *Nucl. Phys. B* **635** (2002) 33 [arXiv:hep-th/0203190].