We study four dimensional $Z_2 \times Z_2$ (shift)-orientifolds in presence of internal magnetic fields and NS-NS $B$-field backgrounds, describing in some detail one explicit example with $N=1$ supersymmetry. These models are related by $T$-duality to orientifolds with $D$-branes intersecting at angles and exhibit, due to the background fields, a rank reduction of the gauge group and multiple matter families. Moreover, the low-energy spectra are chiral and anomaly free if $D5$-branes are present along the magnetized directions.
1. Introduction

Within the String/M-theory picture\(^1\), the Standard Model of strong and electroweak interactions should emerge, together with a consistent quantum version of General Relativity, as a low-energy limit of some vacuum configuration in lower-dimensions. In other words, there should be a region in the moduli space of String/M-theory that is connected, possibly in a very complicated way, to our low-energy world. Unfortunately, we are able to control only a small region (actually a zero-measure region) of the moduli-space itself, and we miss the dynamical principle that should drive us to the choice of the (unique?) ground state. However, the investigation of vacua that look as close as possible to the Standard Model on the one hand can clarify the internal consistency and help to extract some model independent properties of the theory, and on the other hand can lead to some predictions of possible “experimental signatures” of the underlying String/M-theory structure. There has been a lot of effort in these directions in the last few years, both in the framework of conventional Heterotic SUSY-GUT scenarios\(^2\), and in the framework of type I models\(^3\), or more generally in the context of “Brane World” scenarios\(^4\).

An interesting way to build chiral type I models while preserving supersymmetry in the (bulk) gravity sector is the introduction of internal background magnetic fields along some compactified directions\(^5,6,7\). A magnetic field along a \(U(1)\) subgroup of the Chan-Paton gauge group affects only the boundary conditions of the (super)strings in the open sector\(^8\), providing an energy separation between states of different spins. As a consequence, supersymmetry is broken on the branes and, generically, some Nielsen-Olesen instabilities manifest themselves by the appearance of tachyonic excitations. This kind of deformation is connected by (open) T-duality to type I vacua with \(D\)-branes intersecting at angles\(^9\), and thus no longer parallel to the corresponding O-planes, and seems to be the most promising proposal to recover (some extension of) the Standard Model in the low-energy limit\(^7,10,11,12,13,14,15,16\). The introduction of a pair of aligned internal magnetic fields allows configurations with non-vanishing instanton density in the compact internal space, namely self-dual or antiself-dual field strengths\(^6\). The resulting \(D9\)-branes contributions to the tension and \(R - R\) charge can be exactly compensated by the introduction of suitable lower dimensional branes, eliminating the corresponding tachyonic instabilities and recovering supersymmetry if the BPS bound is restored, or giving rise to non-BPS configurations (models with “brane supersymmetry breaking”\(^17,18,19\)) if the fields carry \(R - R\) charges that mimic anti-\(D\)-branes. In the T-dual picture,
they correspond to vacua with branes intersecting at very special angles, the ones exactly preserving supersymmetry or their opposites. A chiral spectrum is obtained if there are massless open-string states in bifundamental representations identified by the magnetic field and the inequivalent $D5$-branes or, in other words, at the intersection of magnetized $D9$-branes and those $D5$-branes whose world-volume invades at least one of the magnetized tori.

In this talk we shall describe a class of four-dimensional freely-acting orientifolds, using as guiding example a chiral four-dimensional supersymmetric model. These models are obtained deforming the $Z_2 \times Z_2$ shift-orientifolds described in ref.\textsuperscript{20} with internal (open) background magnetic fields and will be discussed in more detail in ref.\textsuperscript{21}. Their closed oriented massless spectra are reported in Table 1 and, as can be observed analyzing the last column, they correspond to compactifications of type IIB superstrings on (singular limits of) Calabi-Yau manifolds. As shown in ref.\textsuperscript{20}, the resulting orientifolds give rise to a rich but non-chiral class of models with partial breaking of supersymmetry and interesting brane configurations. Chirality can be obtained, in some cases, introducing magnetic deformations, as we are going to discuss in the next section.

### 2. The $w_2p_3$ models

In what follows we shall consider the $w_2p_3$ model, that captures all the basic features of this class of orientifolds. The starting point is an orbifold of the type IIB superstring compactified on a six-torus taken, in a self-explanatory notation, as the product $T^{55} \times T^{67} \times T^{89}$, with complex coordinates $(Z_1, Z_2, Z_3)$, where each two-torus can be equipped with

| model $w_2p_3$ | $p_2p_3$ | $w_1p_2p_3$ | $w_1p_3$ | $w_2p_3$ | $w_1w_2$ | $w_1w_3$ | $w_2w_3$ |
|----------------|----------|-------------|----------|----------|----------|----------|----------|
| $N = 2$        | $N = 2$  | $N = 2$     | $N = 2$  | $N = 2$  | $N = 2$  | $N = 2$  | $N = 2$  |
| $1 + 3$        | $1 + 3$  | $1 + 3$     | $1 + 3$  | $1 + 3$  | $1 + 3$  | $1 + 3$  | $1 + 3$  |
| $3$            | $3$      | $3$         | $3$      | $3$      | $3$      | $3$      | $3$      |
| $16$           | $16$     | $16$        | $16$     | $16$     | $16$     | $16$     | $16$     |
| $3$            | $3$      | $3$         | $3$      | $3$      | $3$      | $3$      | $3$      |
| $8$            | $8$      | $8$         | $8$      | $8$      | $8$      | $8$      | $8$      |
| $8$            | $8$      | $8$         | $8$      | $8$      | $8$      | $8$      | $8$      |
| CY (19,19)     | CY (11,11)| CY (11,11)  | CY (11,11)| CY (3,3) | CY (3,3) | CY (3,3) | CY (3,3) |
a $NS - NS$ two-form $B_i$ of rank $r_i$ (with $r_i = 0$ or 2), quantized\textsuperscript{22,23} if the orientifold projection is to be performed. The orbifold group is the combination of the $Z_2 \times Z_2$ generated by $g = (+, -, -)$ and $h = (-, -, +)$, where the minus signs correspond to a conventional two-dimensional $Z_2$ inversion ($Z_i \rightarrow -Z_i$), with a winding shift along the 6-th (real) direction and a momentum shift along the 8-th (real) direction. As a consequence, there are no fixed points while the amplitudes corresponding to the discrete torsion orbit of the modular group are absent. The unoriented projection of the closed spectrum in Table 1, obtained by the action of the world-sheet parity operator $\Omega$, produces a Klein bottle amplitude containing $O_{9}^{+}, O_{5,1}^{-},$ and $O_{5,2}^{-}$, since the shifts lift the massless states along the $T_{89}$ direction, thus eliminating the corresponding $O_{5,3}^{+}$ present in the “plain” $Z_2 \times Z_2$ open descendants\textsuperscript{24,18,20}. The resulting truncation of the closed spectrum is displayed in Table 2. Notice that the low energy effective $N = 1$ supergrav-

| $B$ rank $r_2 + r_3$ | untwisted SUGRA | untwisted $C$ | twisted $C$ | twisted $V$ |
|---------------------|-----------------|-----------|----------|----------|
| 0                   | $N = 1$        | $1 + 3 + 3$ | $8 + 8$  | $0$       |
| 2                   | $N = 1$        | $1 + 3 + 3$ | $6 + 6$  | $2 + 2$  |
| 4                   | $N = 1$        | $1 + 3 + 3$ | $5 + 5$  | $3 + 3$  |
Table 3. Chan-Paton group: a) complex charges; b) real charges.

|   | \( U(n) \) | \( \otimes \) | \( U(d_1) \) | \( \otimes \) | \( \left( \frac{USp(d_2)}{SO(d_2)} \right) \) | \( \otimes \) | \( U(m) \) |
|---|---|---|---|---|---|---|---|
| a) | \( USp(n_1) \times USp(n_2) \) | \( \otimes \) | \( USp(d_1) \times USp(d_2) \) | \( \otimes \) | \( USp(d_3) \) | \( \otimes \) | \( USp(d_4) \) |
| b) | \( SO(n_1) \times SO(n_2) \) | \( \otimes \) | \( SO(d_1) \times SO(d_2) \) | \( \otimes \) | \( SO(d_3) \) | \( \otimes \) | \( SO(d_4) \) |

With \( n = \bar{n}, m = \bar{m} \) and \( d_1 = \bar{d}_1 \), where \( r = r_1 + r_2 + r_3 \) is the total rank of \( B \) and \( k_2 \) and \( k_3 \) are the Landau-level degeneracies along the corresponding directions. They count the numbers of zero-modes of the magnetized open strings with non-vanishing total magnetic charge. It should be stressed that the \( m \)-charges contribute to the tadpoles of the \( R - R \) ten-form and the \( R - R \) six-form. This signals the phenomenon of “brane transmutation,” connected to the Wess-Zumino-like term in the \( D \)-brane action. According to it, a magnetized \( D9 \)-brane with non-vanishing instanton number mimics the behaviour of a stack of \( k_2k_3 \) \( D5 \)-branes, thus producing both a rank reduction of the Chan-Paton group and the presence of multiple families of matter fields. It can also be interpreted as the inverse small instanton transition: the stack of \( D5 \)-branes dissolves into a \( D9 \)-brane that, being a “fat” instanton, invades the whole internal space and gives rise to a transition along some flat directions. In the T-dual language, it corresponds to a recombination of \( D6 \)-branes wrapping different intersecting cycles. The open unoriented spectra are reported in Table 4, where \( \eta_1 \) is a free sign and \( A, S \) and \( F \) stand for the antisymmetric, the symmetric and the fundamental representations of the gauge group in Table 3, respectively. Notice that, in the presence of \( D5_2 \) branes, one gets an extra-bonus, due again to the magnetic field: chirality. Chiral fermions lie at the intersection of \( D \)-branes and, as evident from Table 4, the chiral sector is exactly the one related to open strings of the \( (d_2, m) \) type thus coming from the intersection between magnetized \( D9 \)-branes and \( D5_2 \)-branes extended along one of the directions affected by the magnetic field. Of course, one could add brane-antibranes pairs and suitable combinations of Wilson lines in order to produce string vacua that exhibit low-energy spectra as close as possible to the Standard Model, both for the field content and for the phases of the
Table 4. Open spectra of \(w_2p_3\) models (complex charges).

| Mult. | Number | Reps. |
|-------|--------|-------|
| \(C\) | \((0, 2)\) | \((A + A, 1, 1)\) (1, A + A, 1, 1) (S + S, 1, 1) |
| \(C\) | \((2, 0)\) | \((A + A, 1, 1)\) (1, A + A, 1, 1) (S + S, 1, 1) |
| \(C\) | 3 | (1, 1, A, 1) or (1, 1, S, 1) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] + 2\) | \((F, 1, 1, F), (F, 1, F)\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] - 2\) | \((F, 1, 1, F), (F, 1, F)\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] + 1 + 2^{\frac{r+2}{r+1}} \eta_1 k_2 k_3\) | \((F, 1, 1, (F, F, 1, 1))\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] - 2\) | \((F, 1, 1, (F, F, 1, F))\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] + 1 + 2^{\frac{r+2}{r+1}} \eta_1 k_2 k_3\) | \((1, 1, 1, A)\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] - 2\) | \((1, 1, 1, S)\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] + 1 + 2^{\frac{r+2}{r+1}} \eta_1 k_2 k_3\) | \((1, 1, 1, A)\) |
| \(C\) | \(2^{r+2} \left[k_2 k_3\right] - 2\) | \((1, 1, 1, S)\) |
| \(C_L\) | \(2^{r+2} \left[k_2 k_3\right] + 1 + 2^{\frac{r+2}{r+1}} \eta_1 k_2 k_3\) | \((1, 1, 1, A)\) |
| \(C_L\) | \(2^{r+2} \left[k_2 k_3\right] - 2\) | \((1, 1, 1, S)\) |

various symmetries \(^7,10,11,12,13,14,15,16\). The dynamical stability of all these vacua is still an open problem, due to the presence of \(NS - NS\) tadpoles when supersymmetry is broken. The principle (if any) according to which Nature selects the right vacuum is still lacking, and its quest is probably the most important challenge in the String/M-theory research activity.

Acknowledgments

I would like to thank the Organizers of the “The First International Conference On String Phenomenology” for the kind invitation. It is a pleasure to thank M. Larosa for the enjoyable collaboration, A. Sagnotti for the many discussions and collaboration at early stages of this research and C. Angelantonj, M. Bianchi, R. Blumenhagen, G. D’Appollonio, E. Dudas, J. Mourad and Ya.S. Stanev for illuminating discussions. This work was supported in part by I.N.F.N., by the European Commission RTN programmes HPRN-CT-2000-00122 and HPRN-CT-2000-00148, by the INTAS contract 99-1-590, by the MURST-COFIN contract 2001-025492 and by the NATO contract PST.CLG.978785.

References

1. C. M. Hull and P. K. Townsend, Nucl. Phys. B 438 (1995) 109 [arXiv:hep-th/9410167]; P. K. Townsend, Phys. Lett. B 350 (1995) 184 [arXiv:hep-th/9501068]; E. Witten, Nucl. Phys. B 443 (1995) 85 [arXiv:hep-th/9503124];
1. For a review, see M. J. Duff, Int. J. Mod. Phys. A 11 (1996) 5623 [arXiv:hep-th/9608117].

2. For a review, see K. R. Dienes, Phys. Rept. 287 (1997) 447 [arXiv:hep-th/9602045].

3. A. Sagnotti, ROM2F-87-25, Talk presented at the Cargese Summer Institute on Non-Perturbative Methods in Field Theory, Cargese, France, Jul 16-30, 1987 [arXiv:hep-th/0208020]; G. Pradisi and A. Sagnotti, Phys. Lett. B 216 (1989) 59; M. Bianchi and A. Sagnotti, Phys. Lett. B 247 (1990) 517, Nucl. Phys. B 361 (1991) 519; for reviews, see E. Dudas, Class. Quant. Grav. 17 (2000) R41 [arXiv:hep-ph/0006190]; C. Angelantonj and A. Sagnotti, arXiv:hep-th/0204089.

4. N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429 (1998) 263 [arXiv:hep-ph/9803315]; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 436 (1998) 257 [arXiv:hep-ph/9804398]; L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370 [arXiv:hep-ph/9905221], Phys. Rev. Lett. 83 (1999) 4690 [arXiv:hep-th/9906064]; for reviews, see I. Antoniadis, Int. J. Mod. Phys. A 16 (2001) 866; R. Dick, Class. Quant. Grav. 18 (2001) R1 [arXiv:hep-th/0105320].

5. C. Bachas, arXiv:hep-th/9503030.

6. C. Angelantonj, I. Antoniadis, E. Dudas and A. Sagnotti, Phys. Lett. B 489 (2000) 223 [arXiv:hep-th/0007090]; C. Angelantonj and A. Sagnotti, arXiv:hep-th/0010279.

7. R. Blumenhagen, L. Goerlich, B. Kors and D. Lust, JHEP 0010 (2000) 006 [arXiv:hep-th/0007024], Fortsch. Phys. 49 (2001) 591 [arXiv:hep-th/0010198]; R. Blumenhagen, B. Kors and D. Lust, JHEP 0102 (2001) 030 [arXiv:hep-th/0012156].

8. E. S. Fradkin and A. A. Tseytlin, Phys. Lett. B 163 (1985) 123; A. Abouelsaood, C. G. Callan, C. R. Nappi and S. A. Yost, Nucl. Phys. B 280 (1987) 599;

9. M. Berkooz, M. R. Douglas and R. G. Leigh, Nucl. Phys. B 480 (1996) 265 [arXiv:hep-th/9606139].

10. M. Cvetic, G. Shiu and A. M. Uranga, Nucl. Phys. B 615 (2001) 3 [arXiv:hep-th/0107166].

11. R. Blumenhagen, B. Kors, D. Lust and T. Ott, Nucl. Phys. B 616 (2001) 3 [arXiv:hep-th/0107138]; R. Blumenhagen, V. Braun, B. Kors and D. Lust, JHEP 0207 (2002) 026 [arXiv:hep-th/0206038].

12. D. Cremades, L. E. Ibanez and F. Marchesano, JHEP 0207 (2002) 009 [arXiv:hep-th/0201205], JHEP 0207 (2002) 022 [arXiv:hep-th/0203160], arXiv:hep-th/0205074; L. E. Ibanez, F. Marchesano and R. Rabanad, JHEP 0111 (2001) 002 [arXiv:hep-th/0105155]; G. Aldazabal, S. Franco, L. E. Ibanez, R. Rabanad and A. M. Uranga, J. Math. Phys. 42 (2001) 3103 [arXiv:hep-th/0101703], JHEP 0102 (2001) 047 [arXiv:hep-ph/0011132].

13. C. Kokorelis, JHEP 0208 (2002) 036 [arXiv:hep-th/0206108], arXiv:hep-th/0207234, arXiv:hep-th/0209202.

14. M. Cvetic, P. Langacker and G. Shiu, Phys. Rev. D 66 (2002) 066004 [arXiv:hep-ph/0205252], Nucl. Phys. B 642 (2002) 139 [arXiv:hep-th/0206115]; M. Cvetic, G. Shiu and A. M. Uranga, Phys. Rev. Lett. 87
(2001) 201801 [arXiv:hep-th/0107143]; A. M. Uranga, arXiv:hep-th/0208014.
15. S. Forste, G. Honecker and R. Schreyer, Nucl. Phys. B 593 (2001) 127
[arXiv:hep-th/0008250], JHEP 0106 (2001) 004 [arXiv:hep-th/0105208].
16. D. Bailin, G. V. Kraniotis and A. Love, arXiv:hep-th/0208103, Phys. Lett.
B 530 (2002) 202 [arXiv:hep-th/0108131], arXiv:hep-th/0108127.
17. I. Antoniadis, E. Dudas and A. Sagnotti, Phys. Lett. B 464 (1999) 38
[arXiv:hep-th/9908023].
18. C. Angelantonj, I. Antoniadis, G. D’Appollonio, E. Dudas and A. Sagnotti,
Nucl. Phys. B 572 (2000) 36 [arXiv:hep-th/9911081].
19. S. Sugimoto, Prog. Theor. Phys. 102 (1999) 685 [arXiv:hep-th/9905159];
G. Aldazabal and A. M. Uranga, JHEP 9910 (1999) 024 [arXiv:hep-
th/9908072].
20. I. Antoniadis, G. D’Appollonio, E. Dudas and A. Sagnotti, Nucl. Phys. B
565 (2000) 123 [arXiv:hep-th/9907184].
21. M. Larosa and G. Pradisi, in preparation.
22. M. Bianchi, G. Pradisi and A. Sagnotti, Nucl. Phys. B 376 (1992) 365;
M. Bianchi, Nucl. Phys. B 528 (1998) 73 [arXiv:hep-th/9711201]; E. Witten,
JHEP 9802 (1998) 006 [arXiv:hep-th/9712028].
23. Z. Kakushadze, G. Shiu and S. H. Tye, Phys. Rev. D 58 (1998) 086001
[arXiv:hep-th/9803141]; C. Angelantonj, Nucl. Phys. B 566 (2000) 126
[arXiv:hep-th/9908064].
24. M. Bianchi, Ph.D. Thesis, preprint ROM2F-92/13; A. Sagnotti, arXiv:hep-
th/9302099; M. Berkooz and R. G. Leigh, Nucl. Phys. B 483 (1997) 187
[arXiv:hep-th/9605049].