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D-branes, SUSY breaking, and moduli stabilization

Tomasz R. Taylor[a b]

CERN Theory Division, CH-1211 Geneva 23, Switzerland

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Abstract. This is a brief introduction to the orientifold constructions leading to chiral models with partial (or complete) SUSY breaking at zero vacuum energy. The basic ingredients are D-branes and flux configurations that freeze the moduli vacuum expectation values and thus stabilize the size and shape of the compact dimensions.

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1 Introduction

In the arena of superstring compactifications, the central role is played by Calabi-Yau manifolds. They preserve supersymmetry and yield four-dimensional models with phenomenologically viable gauge groups and particle spectrum. Originally, Calabi-Yau compactifications were studied in the heterotic superstring theory; however more recently, they are also considered in a much broader context of M-theory including type II theories, eleven-dimensional supergravity, etc. Arguments based on superstring dualities indicate the importance of certain singular limits, D-branes wrapping non-trivial loops, fluxes of various fields and many other fascinating phenomena. Nevertheless, there has been very little progress achieved in understanding the basic question of what is the underlying principle favoring one compactification over another, which would select only one of millions of Calabi-Yau manifolds as Nature's ground state. Furthermore, individual compactification manifolds come in different shapes and sizes. In this talk, I will report on some recent progress in solving this "secondary" problem: given topology of a compactification manifold, what determines its shape and dimensions?

2 The moduli problem

In superstring theory, geometrical properties of the compactification manifold are determined by a priori arbitrary vacuum expectation values (VEVs) of massless moduli fields. The moduli couple to the dilaton, to p-forms and to other "bulk" fields originating from ten dimensions. Furthermore, if lower-dimensional defects like D-branes are present, the moduli also couple to their world-volumes. As long as the superpotential and the scalar potential vanish, there are no energetic constraints on the moduli VEVs. However, once such a potential appears, the continuous degeneracy of the vacuum can be lifted and a unique configuration of moduli VEVs can be selected as the true superstring ground state.

In the early investigations of heterotic superstring compactifications, non-perturbative condensation of gauginos associated with hidden non-abelian gauge groups was considered as a primary source of the scalar potential. Since, in the tree approximation, the gauge couplings are determined by the dilaton VEV, while the one-loop threshold corrections depend on compact geometry via the spectrum of Kaluza-Klein excitations, such a non-perturbative potential does indeed depend on the moduli. If the compactification space exhibits some T-duality symmetries, the moduli VEVs are naturally stabilized at the self-dual points [1,2]. Unfortunately, this mechanism is plagued by the so-called dilaton runaway problem: since the potential vanishes in the zero coupling limit, the ground state is pushed towards the infinite dilaton VEV where the theory becomes free and maximally supersymmetric.

More recently, there has been increased interest in type I and type II compactifications involving open strings and D-branes. Their main advantage as compared to the heterotic theory is a different gauge group structure and more relaxed relations between gauge coupling constants and the string coupling. This allows circumventing the dilaton runaway problem, although by sacrificing some important predictions like the gauge coupling unification. Since open strings end on D-branes, these space-time defects play a very important role in type I constructions.

[a] *Permanent address:* Department of Physics, Northeastern University, Boston, MA 02115, USA

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3 D-branes

Open string fluctuations of D-brane world-volumes give rise to gauge bosons and their supersymmetric partners. Each stack of N coinciding D-branes is capable of producing a complete $U(N)$ gauge vector supermultiplet. Furthermore, charged chiral multiplets, in representations $(N, \bar{N}')$, can appear as the fluctuations of strings stretching between two D-brane stacks intersecting at angles. They also appear on magnetized D-branes (T-dual to intersecting branes), as discussed in the following Section.

Our four-dimensional world can be shared by world-volumes of many $(4{+}n)$-dimensional D-branes. The translational symmetry of the transverse $6{-}n$ spacial dimensions is then violated and, as a result, the number of conserved supercharges is reduced (by at least one-half). Another very important property of D-branes is that they carry charges associated to the so-called Ramond-Ramond antisymmetric tensor fields: the $(4{+}n)$-dimensional world volume is "minimally" coupled to a rank $(4{+}n)$ antisymmetric tensor field, in a similar way as the electron's world-line is coupled to the electromagnetic vector potential.

Imagine extra dimensions forming one of Calabi-Yau manifolds, together with D-branes wrapped around some non-contractible loops (cycles), in the background of various fluxes of bulk fields. Can Faraday's flux lines behave like springs forcing the compactification manifold to some equilibrium shape and dimensions?

4 Magnetized branes

D-brane excitations contain $U(N)$ gauge fields which can support their own magnetic fluxes into compact directions [3]. As an example, consider $d{=}5,6$ forming a two-dimensional torus with the respective radii $R_{5,6}$. A constant field strength $F_{56} \equiv H$ (of $U(1) \subset U(N)$) is allowed provided that the magnetic field satisfies the Dirac quantization condition, $H = 2\pi/(R_5R_6) \cdot \text{integer}$. The magnetic field affects the spectrum of charged particles which form Landau levels depending on their spin. For spin 0, there is a mass gap, while for spin 1/2 there remains one massless level that corresponds to a four-dimensional chiral fermion. Thus, quite remarkably, a constant magnetic field generates chiral asymmetry, at the same time breaking the supersymmetric fermion-boson degeneration. This is certainly a step in the right direction. Now, for the purpose of illustration, imagine that the torus is placed inside a Calabi-Yau manifold so that R_5 and R_6 are dynamical VEVs of some (so-called Kähler) moduli that control the size of the manifold. The energy stored in the magnetic field gives rise to an effective four-dimensional potential. It is easy to see that it depends on the radii as $(R_5R_6)^{-1}$. Although this is a very simplistic example, it nicely illustrates the fact that magnetic D-brane fluxes give rise to chiral fermions, break supersymmetry and generate a potential for Kähler moduli.

5 Bulk fluxes

After including magnetized D-branes wrapped on the compactification manifold, we can fill the background by fluxes of the bulk fields. In particular, we can switch on field strengths of the so called NS and RR fields represented by antisymmetric tensors of rank three and higher [4,5,6,7]. It is very interesting that the fluxes, which are confined to Calabi-Yau cycles, behave very similarly to D-branes: they carry Ramond-Ramond charges and store energy which gives rise to a four-dimensional potential [4]. Now, the potential depends on the so-called complex structure moduli which control the shape of Calabi-Yau manifold. Hence, by combining D-branes with background fluxes one obtains non-trivial potentials depending on all compactification moduli.

6 Moduli stabilization and SUSY breaking

The question posed at the end of Sect. 3 can be answered by considering a simple type IIB orbifold example with a background flux configuration. The orbifold discussed in [6] has been constructed from a six-dimensional torus by identifying the points related by a $Z_2 \times Z_2$ symmetry and can be considered as a singular limit of a certain Calabi-Yau manifold. The bulk theory is $N = 2$ supersymmetric while the presence of D-branes and the so-called orientifold planes breaks it down to $N = 1$. The fluxes are localized in the compact space therefore their lines must form closes loops, without "escaping to infinity." The corresponding equations, known as the RR tadpole cancellation conditions, together with the Dirac quantization conditions, impose very stringent constraints on the allowed flux configurations. Nevertheless, it is possible to construct some interesting models with $U(N)$ gauge groups and chiral $(N, \bar{N}')$ representations. The necessary condition for the existence of a stable minimum of the scalar potential can be translated into a simple equation that ensures that the flux configurations do indeed behave as D-branes and break supersymmetry partially from $N = 2$ to $N = 1$ [8]. A complete supersymmetry breakdown is also possible. In both cases, the minimum of the potential is at zero vacuum energy, which ensures gravitational stability of the combined flux–D-brane system. The dilaton either remains undetermined or it can be forced into the weak string coupling regime by an appropriate choice of the fluxes, therefore one does not expect any significant string loop effects that could destabilize the moduli. It is not clear however, if the orbifold geometry is sensitive to a back-reaction of the self-dual five-form field.

To summarize, type II theories with D-branes and background fluxes offer a very interesting setup for superstring model-building. They certainly deserve further studies. In particular, more work is needed to understand how supersymmetry breaking is communicated to the observable spectrum of D-brane excitations.

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