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ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ТЕОРИЯ

INTERSECTING D-BRANE MODELS: A BRIEF OVERVIEW

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Intersecting D-branes models are among the most promising avenues to embed the Standard Model and beyond within the string context. We present in a general way their geometrical features and discuss the possible explanation for the particle spectrum.

Нахождение точек пересечения моделей D-бран является одним из многообещающих способов включить стандартную модель и модели, выходящие за ее пределы, в рамки теории струн. В представленной работе рассматриваются в обобщенном виде их геометрические свойства и обсуждается возможное объяснение спектра частиц.

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During the last decades, there have been renovated efforts in looking for D-brane configurations with a low-energy effective theory resembling the Standard Model (SM) [1,2]. One approach which looks particularly successful is that of intersecting D-branes in oriented string models [3–6]. In such models, the basic unit of gauge invariance for oriented string models is a $U(1)$ field, so a stack of N identical D-branes gives a $U(N)$ theory with the associated $U(N)$ gauge group [2–6]. In the presence of many D-brane types, the gauge group G becomes a product form for all the gauge factors in their world-volumes $\prod_a U(N_a)$ [7], where N_a presents the number of D-branes in each stack $G = \prod_{i=a,b,\ldots} U(N_i)$. The closed string modes (gravitons and moduli) live in the entire $(9+1)$-dimensional space. The open string degrees of freedom generate the gauge theory on D6-brane world-volumes. There are different variants for ends of open strings, with both those on the same stack of branes or those connecting different stacks. The latter case is actually a chiral fermion in a bifundamental representation of $U(N_a) \times U(N_b)$ which is living at each four-dimensional intersection of two branes a and b. The topological invariant I_{ab}, that is intersection number of these two branes $\sum_{a,b} I_{ab}$ $(N_a \overline{N}_b)$ [8], in the compact space C, gives multiplicity $I_{ab} \leqslant 3$ of fermions (a modulus) and chirality (a sign).

In this paper, we present the intersecting brane worlds constructions of the SM and beyond. In particular, we consider constructions in orientifolds of type II string theory with D-branes

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wrapping certain homology cycles in a Calabi–Yau 3-fold [9–11]. For reasons of clarity, our discussion will be devoted to the intersections of D6-branes wrapping square $T^6 = \prod_{i=1}^{3} T_i^2$ and the localization of the string states corresponding to the known particle spectrum.

One of the reasons for the popularity of D-brane physics comes from the dictionary between geometry and effective field theory that exists in any D-brane model, and which is particularly simple for intersecting D6-branes in orientifold compactifications that possess many attractive features from the model building point of view. Models similar to SM can be obtained and viable constructions with $N = 1$ supersymmetry (SUSY) have been developed [12]. Since we are interested in four-dimensional string models in flat 4D Minkowski space-time, we assume that six spatial directions are described by a compact space

$$M^{1,9} = R^{1,3} \otimes C^6, \tag{1}$$

where $R^{1,3}$ is should be the 4D Minkowski space-time and the internal space C^6 should be a compact 6D manifold about which geometric assumptions for reasonable physics can be performed. The compactification can occur on a different number of C^6 varieties and for each variety there are many ways of compactifying. The simple one meeting our requirements and giving a non-trivial physics is the toroidal compactification, $C^6 = T^6/\Gamma$, a 6D torus T^6 divided by discret group Γ. Particularly the homology cycles which is easily viewable. In fact, in the T^6 manifold which can be written as a product of three 2D torus, $T^6 = \prod_{i=1}^{3} T_i^2$, taking T^2 as a square torus with the identification of the sides with their opposites, the fundamental cycles $\pi_{||}, \pi_{\perp}$ are then seen as the horizontal and vertical lines, respectively, and a general 1-cycle π general can be written as a linear combination of the fundamental cycles. In this picture, the world-volume of each D6-brane of the configuration will be given by $R^{3,1} \otimes \pi^3$ [13, 14], where π^3 is the 3-cycle in which the D6-brane is wrapped around; and because these 3-cycles are no longer 3-planes they can intersect several times. This is the nearest geometry to a flat $D(3+3)$-brane expanding a hyperplane while having n compact dimensions. These 3 extra dimensions are taken to be wrapped on an n-cycle of such T^{n-4} as

$$\left[\prod\right] = \prod_{i=1}^{3} \left(n^i \pi_{||}^i + m^i \pi_{\perp}^i\right), \quad n, m \in Z. \tag{2}$$

The n, m are the winding numbers in each homology space $H_1(T_i^2, Z)$ basis $(\pi_{||}^i + \pi_{\perp}^i)$, $i = 1, 2, 3$. Generically, these 3-cycles of different $D(3+3)$-branes involved will intersect and also possible with their corresponding orientifold images $\left[\prod^*\right] = \prod_{i=1}^{3} (n_\alpha^i - m_\alpha^i)$ in a point $p \in C^6$ [6]. In these points, chiral fermions are localized:

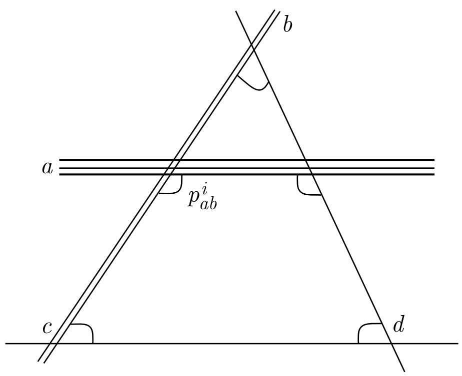
$$f \in R^{1,3} \otimes \{p\}. \tag{3}$$

The convention used is to identify left-handed fermions with a positive intersection number, whereas right-handed fermions will be identified with a negative intersection number. The number of intersections between two cycles of different two $D(3+n)$-branes a, b as well as the intersecting angle between them, the difference of their angles with the horizontal axis in each rectangular T_i^2 torus, will be given by

$$I_{ab} = \sum_{i=1}^{3} p_{ab}^i, \tag{4}$$

$$\theta_{ab}^i = \arctan\left(R_{||/\perp}^i \frac{m_a^i}{n_a^i}\right) - \arctan\left(R_{||/\perp}^i \frac{m_b^i}{n_b^i}\right), \tag{5}$$

where $R_{||/\perp}^i$ are ratios of two radii of each torus. Some intersection angles should vanish, means parallel branes, avoiding the presence of exotic physical points which are ruled out experimentally. A schematic picture is depicted in the figure.



The intersecting brane setup: $N_a = 3$, $N_b = 2$, $N_c = 1$ and $N_d = 1$

Moreover, the configuration of intersecting D-branes should satisfy the consistency conditions of the equation of motion of certain massless fields present in the theory requiring the cancellation of RR charges[1]. The orientation of the intersecting angle (5), either positive or negative, gives us the chirality of the $D = 4$ fermion, while its value gives the spectrum of light scalars. Since the latters are in general massive, such intersecting D-brane configurations generically break all space-time SUSY. This SUSY breaking manifests itself as a massive scalar ground state. Only if the intersection angles take very special values, some of the scalars become massless, and some part of space-time SUSY gets restored. Because both chiral fermions and scalars live at the intersections, concentrating in a single torus, a triplet of intersecting D6-branes a, b and c will give rise to three points p_{ab}, p_{ac} and p_{bc} in interaction, summits of a triangle. Trilinear couplings involving three such fields make up a Lorentz and gauge invariant quantity as

$$\xi_{abc}^i = g_{abc}^i(\theta_{ab}^i, \theta_{ac}^i) p_{bc}^i p_{ab}^i p_{ac}^i, \tag{6}$$

with $\theta_{ab}^i + \theta_{ac}^i + \theta_{bc}^i = \pi$. Together, the first two terms will be considered as the mass term of the corresponding fermion depending on the nature of the invloved branes a, b and c so as to let p_{ab}^i and p_{ac}^i label the two fermions of opposite chirality. The magnitude of the strength coupling function g_{abc}^i among localized open string modes can be calculated by conformal field theory technique like heterotic orbifold models. Its important part of 3-point interactions is evaluated by the classical part in terms of the triangle area A^i [15–17] on the ith torus where the string states are localized at the vertices summit boundaries consisting of a single internal

[1]Such fields arise from RR closed string sectors and, as was shown in [1], D-branes are sources of them. In general, a Dp-brane is source of a $(p+1)$-form Ramond–Ramond A_{p+1}. RR tadpoles are more dangerous and signal an inconsistency of the theory. Hence, in order to perform a consistent string-based compactification, we should require their cancellation.

dimension from each of the D6-branes. Hence, one would expect the fermion mass to be

$$m^i_{f_{bc}} = e_{bc}^{-A^i_{abc}} v^i_{bc}, \tag{7}$$

where A^i_{abc} is the corresponding triangle area and the physical point p^i_{bc} is taken to be a scalar developing a vev v^i_{bc} corresponding to the branes recombination [18, 19],

$$b + c \to bc. \tag{8}$$

Indeed, the electroweak symmetry breaking could have a geometric interpretation in terms of branes. A vev of the scalar fields p^i_{bc} corresponds to a process (8) in which branes b and c recombine into a single brane bc. Since we have started from two branes (plus orientifold mirrors) and end up with one brane and its mirror, the rank of the gauge group has been reduced. In the context, this mass formula (7) encodes the fermion masses hieararchy as well as the whole energy band where they live. This leads to negligible values when the 3 intersecting points are far away from each other but not suppressed because otherwise the branes will be parallel. This fact reveals the existence of right neutrinos in the theory since they must have masses as small as they are, while the important values belonging to small triangular areas are for heavy particles,

$$A_{abc} \geqslant A_{\text{dark}} \sim 0, \tag{9}$$

$$A_{\text{dark}} \cong p_{abc}. \tag{10}$$

The frontier dark case A_{dark}, where the 3 interacting points are very neighboring each other, makes up an invisible sector, say, dark matter sector, whose state is specified by the three involved intersecting branes.

Intersecting D-brane models have the potential to realize an SM or some of its extensions and to affect somehow its limits, namely, dark matter that could be engineered by some extra branes which are often required to cancel topological charges in other sectrors.

The intersecting brane world approach offers a rich phenomenology with convenient tools for engineering the SM and beyond with many attractive features [20–22]. Intersecting D-brane constructions provide an understanding from the string theory point of view of questions like chirality, family triplication as well as certain frontiers of the SM as dark matter sector. We have shown here that it is possible to address the very serious issue of Yukawa coupling by three point interactions in triangular worldsheets based on toroidal techniques leading to a geometrical interpretation of the mass spectrum.

It would be very interesting to explore more realistic models by incorporating the results of the model buildings based on the field theory into the framework of intersecting D-brane models.

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