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**Heterotic string model with gauge symmetry  
 $E_8 \times E_8$**

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# 1 Introduction

The Standard Model of particle physics is the theory describing three of the four known fundamental forces (the electromagnetic, weak, and strong interactions, and not including the gravitational force) in the universe, as well as classifying all known elementary particles. String theory is a candidate for theory of everything that describes all fundamental forces and forms of matter.

In this theory particles are presented by as one-dimensional object called strings. String theory describes how strings propagate through space and interact with each other. On distance scales larger than the string scale, a string will look just like an ordinary particle, with its mass, charge, and other properties determined by the vibrational state of the string. In this way, all of the different elementary particles may be viewed as vibrating strings.

Superstring theory includes supersymmetry which allows to involve into consideration also fermion strings. There are five versions of superstring theories.

The type I string has one supersymmetry in the ten-dimensional spacetime (16 supercharges). This theory is special in the spacetime that it is based on unoriented open and closed strings, while the rest of theories are based on oriented closed strings.

The type II string theories have two supersymmetries in the ten-dimensional space-time (32 supercharges). There are actually two kinds of type II strings called type IIA and type IIB. The difference between these theories is mainly that the IIA theory is non-chiral (parity conserving) while the IIB theory is chiral (parity violating).

16 or 32 supercharges refer to the number of unbroken supersymmetries. In ten dimensions the minimal spinor is Majorana–Weyl (MW) and has 16 real components, so the conserved supersymmetry charges (or “supercharges”) correspond to just one MW spinor in three cases (type I, HE, and HO). Type II superstrings have two MW supercharges, with opposite chirality in the IIA case and the same chirality in the IIB case.

The heterotic string theories are based on a peculiar hybrid of

a type I superstring and a bosonic string. There are two kinds of heterotic strings differing in their ten-dimensional gauge groups: the heterotic  $E_8 \times E_8$  string and the heterotic  $SO(32)$  string. The name heterotic  $SO(32)$  is slightly inaccurate since among the  $SO(32)$  Lie groups, string theory singles out a quotient  $Spin(32)/\mathbb{Z}_2$  that is not equivalent to  $SO(32)$  (quotient group or factor group is a mathematical group obtained by aggregating similar elements of a larger group using an equivalence relation that preserves the group structure). The dangerous Lorentz and Yang-Mills chiral anomalies cancel if and only if the gauge group of the theory is  $SO(32)$  or  $E_8 \times E'_8$ . The  $E_8 \times E'_8$  version of this theory offers the best phenomenological prospects for reproducing the real world.

## 2 Compactification and symmetry breaking

Initially, symmetry is supposed between ordinary world( $E_8$ ) and mirror world( $E'_8$ ). 26 dimensional strings are reduced to 10-dimensional gravity with the  $E_8 \times E'_8$  gauge group by compactification of 16 internal dimensions on the torus.

In order to make contact between the string theories and real world one must understand how six of the spatial dimensions compactify to a small leaving four flat dimensions, how the gauge group is broken down to a group of Standard Model. Gauge symmetry is broken by compactification into Calabi-Yau manifolds or orbifolds.

Calabi-Yau manifolds are the Kähler manifolds which admit a Ricci flat metric (so that they have  $SU(3)$  holonomy). Compactification on Calabi-Yau  $n$ -folds are important because they leave some of the original supersymmetry unbroken (if the holonomy is the full  $SU(3)$ ). These Calabi-Yau compactifications, produce for each manifold  $K$ , a consistent string vacuum, for which the gauge group is no larger than  $E_6 \times E'_8$ , and  $N = 1$  supersymmetry is preserved. In general Calabi-Yau manifolds have many free parameters (moduli – the vacuum expectation values of massless scalar fields) which determine their size and shape. This leads to the existence of a huge number of false vacuums, this problem is known as the landscape of string theory.

The quotient space  $X/\sim$  of a topological space  $X$  and an equivalence relation  $\sim$  on  $X$  is the set of equivalence classes of points in  $X$  (under the equivalence relation  $\sim$ ) together with the following topology given to subsets of  $X/\sim$ : a subset  $U$  of  $X/\sim$  is called open if and only if the union  $U_{([x] \in U)}[x] \subset X$  is open in  $X$ . Quotient spaces are also called factor spaces. Orbifold  $T_6/G$  is the quotient space of  $T_6$  (6-torus) by a finite isometry group  $G$  which acts with fixed points. We compactify on tori divided by the action of a discrete group. This allow us to break gauge group and arrive at different low-energy predictions (Orbifolds are probably special limits of Calabi Yau spaces).

The mechanism of gauge symmetry breaking as a result of compactification on Calabi – Yau manifolds or orbifolds leads to the prediction of homotopically stable solutions with a mass  $m_\alpha = r_c/\alpha'$ , where  $r_c$  – radius of compactification,  $\alpha'$  – string tension.

The homotopically stable particles are "sterile" with respect to the charges of strong, weak, and electromagnetic interactions and participate only in the gravitational interaction. Therefore the possibilities of verifying the existence of these particles are related exclusively to their cosmological manifestations.

After compactification  $E_8$  is broken to  $E_6$  and further  $E_6$  is broken to the Standard Model group.

If there exists a discrete symmetry group,  $Z$ , which acts freely on  $K$ , one can consider the smaller manifold  $K/Z$ .  $E_6$  break down to the observed low energy gauge group if  $K/Z$  is multiply connected, one can allow flux of the unbroken  $E_6$  (or of the  $E_8'$  for that matter) to run through it, with no change in the vacuum energy. The net effect is that, when we go around a hole in the manifold through which some flux runs, we must perform a nontrivial gauge transformation on the charged degrees of freedom. Such noncontractible Wilson loops act like Higgs bosons, breaking  $E_6$  down to the largest subgroup that commutes with all of them. By this mechanism one can, without generating a cosmological constant, find vacua whose unbroken low energy gauge group is, say,  $SU(3) \times SU(2) \times U(1) \times$  (typically, an extra  $U(1)$  or two). Moreover, there exists a natural reason for the existence of massless Higgs bosons which are weak isospin doublets (and could be responsible

for the electro-weak breaking at a TeV), without accompanying color triplets.

$E'_8$  remains unbroken and symmetry between "ordinary" and "mirror" world is broken, and it leads to existence of "shadow" world which interacts with ordinary matter only by gravity.

### 3 Generations of fermions

The Eulerian characteristic of the topology of compactified 6 dimensions determines the number of generations of quarks and leptons.

To calculate the number of generations predicted by the theory, we must first calculate the number of massless particles. The 10-dimensional Klein-Gordon operator:

$$\square_{10}\psi = (\square_4 + \square_6)\psi = 0$$

In general,  $\square_6$  will have eigenvalues denoted by  $m^2$ , that is,  $\square_6\psi_m = m^2\psi_m$  so that wave equation becomes

$$(\square_4 + m^2)\psi_m = 0$$

We are interested in the massless sector in four dimensions, so we want to keep only the zero eigenvalues of the  $\square_6$  operator. Thus,

$$\square_4\psi = \square_6\psi$$

It means that the four-dimensional fermions are massless. And it also means that  $\psi$  is a harmonic form in six dimensions. Therefore the number of massless modes in four dimensions will be related to the number of harmonic forms that we can write for the six dimensions manifold. Thus, topological arguments alone should give the number of generations. It is expected that the number of generations is a topological number because of the Dirac index theorem. We know that the solutions of the Dirac equation can, in general, have zero modes:

$$i\not{D}\psi = 0$$

In fact, the index of this operator is equal to the difference between the positive and negative chiralities of the zero modes:

$$Index(\not{D}) = n_+ - n_-$$

But the Dirac index is also equal to the generation number, because we will be considering only fermions of one specific chirality. Thus, the

precise relation between the generation number and the Dirac index, or the Euler number, is

$$\text{Generation number} = \frac{1}{2}|\chi(M)|$$

For example, one will consider the discrete symmetry group  $Z_5 \times Z_5$  which has 25 generators. Thus, the Euler number of this new manifold is

$$\chi(M) = \frac{-200}{25} = -8$$

which predicts four generations.

A typical construction of Calabi-Yau manifold gives a very large Euler number. Three dimensional algebraic manifold with  $c_1 = 0$  and the Euler characteristic  $\chi = 6$  was constructed by Tian and Yau.

In other case  $\text{spin}(10)$  group can arise from the spontaneous breaking of the observable sector  $E_8$  group by an  $SU(4)$  gauge instanton on an internal Calabi-Yau threefold. The  $\text{Spin}(10)$  group is then broken by a Wilson line to a gauge group containing  $SU(3)_C \times SU(2)_L \times U(1)_Y$  as a factor. To achieve this, the Calabi-Yau manifold must have, minimally, a fundamental group  $Z_3 \times Z_3$ . In this case appears three families of quarks and leptons, each with a right-handed neutrino.

Also three generation can be obtained in  $Z_3$  orbifold models with two Wilson line (constant gauge-background fields corresponding to the non-contractible loops of the torus underlying the orbifold).

## 4 Inflation

There are two different versions of string inflation. In the first version, modular inflation, the inflaton field is associated with one of the moduli, the scalar fields which are already present in the KKLT construction. In the second version, the inflaton is related to the distance between branes moving in the compactified space.

Inflation can be studied within the context of D-branes. Under certain conditions the D-brane modulus can be treated as an inflaton. The five-brane moduli can be stabilized in a non-supersymmetric anti de Sitter minimum. The potential energy has one more minimum when the five-brane coincides with the visible brane. A heterotic M-theory

vacuum can contain several five-branes wrapped on non-isolated genus zero or higher genus curves. Those which are located relatively far away from the visible brane will be stabilized. On the other hand, those which are located close enough to the visible brane will roll towards it and, eventually, collide with it.

These five-branes can be stabilized as well by balancing the supergravity potential energy against the Fayet-Iliopoulos terms induced by an anomalous  $U(1)$  gauge group in the hidden sector. It is also possible to create a positive potential satisfying the slow roll conditions and treat the five-brane translational modulus as an inflaton.

Inflation takes place when the five-brane approaches the visible brane. However, this potential has one negative feature. It has a vanishing first derivative when the five-brane coincides with the visible brane. This means that it takes infinite time for the branes to collide. This also means that the primordial fluctuations will become infinite. On the other hand, at very short distances, one cannot trust the low-energy field theory because new states are expected to become massless. The appearance of new light states in the field theory can provide escape from inflation.

After inflation, the five-brane hits the visible brane and disappears through a small instanton transition. The new system of moduli does not contain the five-brane but has extra vector bundle moduli. Unlike the five-brane modulus, these moduli can be stabilized. The new system of moduli can be stabilized in a vacuum with a positive cosmological constant which can be fine tuned to be very small and consistent with observations.

## **5 Baryogenesis. Affleck – Dine – Linde mechanism**

Baryon asymmetry can be explained by the processes with the B- and CP-violation.

Affleck – Dyne – Linde mechanism is considered in the model which is consistent supersymmetry. New hypothetical scalar fields(SUSY-partners of ordinary particles) carries the baryon(lepton) number. Through

interactions with the inflaton field  $CP$ -violating and  $B$ -violating effects can be introduced. As the scalar particles decay to fermions, the net baryon number the scalars carry can be converted into an ordinary baryon excess. The Affleck – Dine – Linde mechanism is an example of non-thermal baryogenesis.

## 6 Baryon asymmetry as a consequence of the existence of the "Shadow" world

Baryon asymmetry also may occur due to the decay of shadow particles in the early Universe under the condition unbroken  $E8'$ . Shadow hadrons arise during gluodynamic confinement, and they are nonrelativistic massive particles with a mass of the order of  $M \gg 102GeV$ , which dominate in the Universe beginning with  $t_M \sim m_p/M$  and up to the time of their decay  $t_D \sim m_p^4/M^5$ .

During this period, the ordinary particles, whose masses are negligibly small in comparison with the shadow hadrons, are ultrarelativistic; their contribution to the cosmological density falls as  $a^{-1}$  ( $a$  is the scale factor) and after the end of the shadow hadrons era is  $1/a^4 \sim (M/m_p)^2$  from the initial one. Because of this suppression at  $t > t_D$  the products of shadow hadrons decay dominate in the Universe.

Teneadrons can only decay in a gravitational way, so their lifetime is quite long. The decays of shadow particles can be gravitational (decay into gravitons and gravitino), and can also decay into ordinary particles. In the latter case, baryon asymmetry may occur due to the effects of a  $CP$ -violation in four-particle decays of shadow particles with a violation of the baryon number

$$T \rightarrow G \rightarrow q\bar{q} \rightarrow qqql, \quad \tilde{T} \rightarrow \tilde{G} \rightarrow q_s\bar{q} \rightarrow q_sqq\bar{l}$$

In this way, the observed matter originated from decays of the shadow hadrons, with the unbroken  $E8'$  group.

## 7 Dark matter

After symmetry breaking between ordinary and mirror world appears "shadow" world which consist 248 fields of matter and of interactions

which are connected with ordinary particles only by gravity. They may be candidates for the dark matter.

Contribution to the dark matter can give also 4th generation of heavy neutrino and neutralino which appears in the supersymmetry theories.

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