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Properties of vacuum and brane spectrum of Type IIB string theory

T.V. Obikhod

Abstract F-theory has been receiving more attention in the past few years because its rich structure allows to solve many problems of the Standard Model and Grand Unification Theory. This theory is also important because of the necessity to solve the problem of vacuum stability. A simpler solution of F-theory is used to describe the Type IIB string theory. For the classification of D-brane charges in superstring theory of Type IIB is applied K-theory. This approach provides an access to gauge fields connected with vector bundles, classified by K-theory. This technique implements the resolution of issues related to the structure of scales and hierarchies, the gauge group and charged matter content.

Keywords F-theory · Vacuum stability · Type IIB string theory · gauge fields · K-theory

УДК 539.12

1 Introduction

One of the most pressing issues of modern theoretical high energy physics is the question of the origin of the Universe and the subsequent adequate treatment of problems of the physics of elementary particles in the light of recent experimental data at the LHC. Most modern theoretical studies tend to come from Big Bang as a mechanism for further formation of our universe when all four of the known interactions were merged into one in the early stages. But we deal with the cosmological constant problem, or more accurately with the vacuum energy problem, because energy density of vacuum receives a nonzero contribution from symmetry breaking: the scale Λ would be typically of the order of 100 GeV in the case of the electroweak (EW) gauge symmetry breaking or 1 TeV in the case of supersymmetry breaking, but from [1] we have

$$\Lambda \leq 10^{-30} m_p \sim 10^{-3}\text{eV}.$$

Therefore, the solution of this problem could be connected with the inclusion of gravity and supersymmetry in the theory of supergravity. The "gap" between the weak scale and the Planck scale, that is presented in Fig.1, is one of the major motivating factors behind trying to search for a quantum gravity theory in general, and string theory in particular as natural extensions of the Standard Model which solve the hierarchy problem. Many physicists would like a single theory that could be applied at all scales.

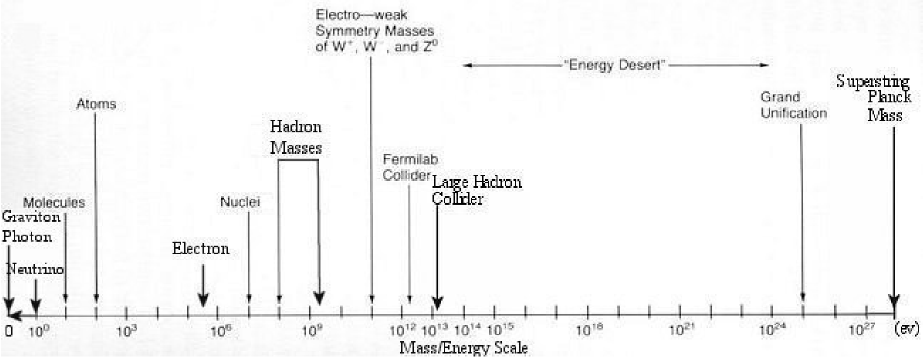


Fig.1. Energy scale of four interactions

The theory, which implements these ideas is F-theory. F-theory description is 12-dimensional theory, because in addition to three space dimensions plus one time, we have eight small dimensions. This is an example of a common theme in the development of string theory; more and more of the theory's details, such as what particles exist and how they interact, or what branes live where, can be described simply in terms of the geometry of the extra dimensions. F-theory has been receiving more attention in the past few years because its rich structure allows solutions that reproduce many of the phenomena of the Standard Model (SM) and Grand Unification Theory (GUT).

2 F-theory and effective potential of unstable vacuum

Vafa noticed that certain complicated solutions of Type IIB string theory [2] could be described in terms of a simpler solution of F-theory with 12 dimensions, up from the 10 dimensions of superstrings or the 11 dimensions of M-theory. One no longer spoke of different theories, but rather different solutions of some master theory. The space of these solutions is called the Moduli Space of Supersymmetric Vacua. String/M theory appears to describe a very large number of four dimensional vacua with inequivalent physics, most of which clearly do not describe our universe. However the continuum of solutions in the supermoduli–space are all supersymmetric with vanishing cosmological constant. Furthermore they all have massless scalar particles, the moduli themselves. May be none of these vacua can be our world. As the expansion of the Universe is accelerating, the simplest explanation is a small but non–zero cosmological constant. Evidently we have to expand our thinking about vacua to include states with non–zero vacuum energy. If we call the space of all string theory vacua the landscape, the supermoduli–space is a special part of the landscape where the vacua are supersymmetric and the potential V(Φ) is exactly zero. These vacua are marginally stable and can be excited by giving the moduli arbitrarily small time derivatives. Once we move off the plain, supersymmetry is broken [3]. There is the picture with such vacua in Fig.2. The de Sitter vacuum occurs at the point $\Phi = \Phi_0$. However, the absolute minimum of the potential occurs not at Φ_0 but at $\Phi = \infty$.

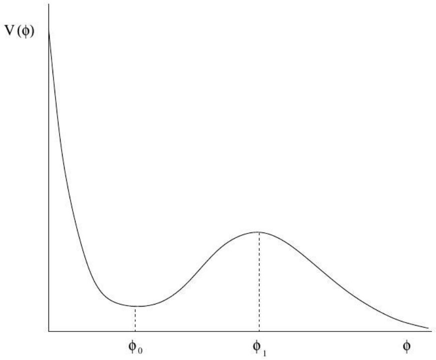


Fig.2. Effective potential of unstable vacuum with respect to tunneling to other vacua.

3 Minimization of Type IIB string potential

In [5] was emphasized that for Type IIB theories, the corresponding vacua are realized as compactifications of F-theory on Calabi-Yau fourfolds. When Type IIB strings are compactified on a Calabi-Yau manifold, under the assumption that the special Kähler moduli space of complex structures of the Calabi-Yau has a symplectic basis, it was shown that the potential could be minimized [4]. It should be noted that the N = 0 supersymmetric minima are below the N = 2 minima. So we can talk about the particle spectrum of the string Type IIB and about the instability of the vacuum associated with this string. As explained in [6], realizing the primary ingredients of GUT models requires, that the singularity type, connected with the compactification of Type IIB string theory, should correspond to a subgroup of the exceptional group E_8 . Because the Standard Model gauge group has rank four, SU(5) is the only available GUT group. After implementation of a higher-dimensional breaking mechanism to obtain four-dimensional models, we can receive the minimal four-dimensional supersymmetric SU(5) Grand Unification Theory with standard Higgs content [7].

The unification of gauge coupling constants, which takes place in SUSY models at high energies [8], allows the SM gauge group to be embedded into GUTs [9]. Such GUTs gauge groups are SU(5), SO(10) or E_6 . Theories with flat extra spatial dimensions, the simplest of which are fivedimensional theories [10]

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

and warped extra spatial dimensions [11]

$$ds^2 = \frac{1}{k^2 y^2}(dy^2 + \eta_{\mu\nu} dx^\mu dx^\nu)$$

(where k is some constant and η has "-+++" metric signature) also allow one to explain the hierarchy between the EW and Planck scales, providing new insights into gauge coupling unification [12] and the cosmological constant problem [13]. However, in the presence of a non-factorizable geometry, the Planck scale is determined by the higher dimensional curvature. The relation between the M_{Pl} in our 4 dimensions and the fundamental unification scale $M_{Pl(4+n)}$ is the following

$$M_{Pl}^2 = M_{Pl(4+n)}^{n+2} R^n,$$

where n are extra dimensions and R is the size of the extra dimensions. For the model described by Randall and Sundrum (RS1) the 5-d Planck scale is related to the geometry of the extra dimensions and the observed Planck scale by the formula

$$M_{Pl}^2 = \frac{M_{Pl5}^3}{k}[1 - e^{-2kr_c\pi}].$$

Randall and Sundrum also discovered that Λ_5, the fivedimensional cosmological constant (vacuum energy) of the bulk, is negative $\Lambda_5 = -24M_{Pl5}^3 k^2$.

4 Phase transitions of SUGRA model and electroweak vacuum stability

The SUGRA, which is one of the variety of GUT, demonstrates, that in N = 1 supergravity there might be a mechanism which ensures the vanishing of vacuum energy density in the physical vacuum [14]. This mechanism may also lead to a set of degenerate vacua with broken and unbroken supersymmetry. The higher-dimensional breaking mechanism which is associated with four-dimensional GUT Higgs multiplets and symmetry breaking higgs mechanism is presented in [7]. Thus, after the breaking of supersymmetry, we are dealing with a Higgs boson. However, at this stage of supersymmetry breaking it is not all smooth. Recent data on the top quark mass, make it possible to assert about the metastability of the electroweak vacuum and the possibility of transition to a new state of the Universe. Therefore, we have a number of successive minima of vacuum.

In quantum field theory, a false vacuum is a metastable sector of space that appears to be a perturbative vacuum, but is unstable due to instanton effects that may tunnel to a lower energy state. The false vacuum is a local minimum, but not the lowest energy state, even though it may remain stable for some time. The Standard Model of particle physics opens the possibility of calculating from the masses of the Higgs boson and the top quark, whether the Universe's present electroweak vacuum state is likely to be stable or merely long-lived. A 125–127 GeV Higgs mass seems to be extremely close to the boundary for stability but a definitive answer requires much more precise measurements of the top quark's pole mass. Vacuum stability up to Planck scale put constraint for the mass of the Higgs boson

$$m_H[GeV] > 129.5 + 1.4\left(\frac{m_t[GeV] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right).$$

Complexity emerges when another local minimum at large field is the same or deeper than the EW. Then quantum tunneling effects from the EW vacuum to the deeper one could make vacuum decay. At present therefore, there are "too large uncertainties which do not allow to draw a firm conclusion on the important question whether the electroweak vacuum is indeed stable or not". Fig.3 reflects the essence of the problem.

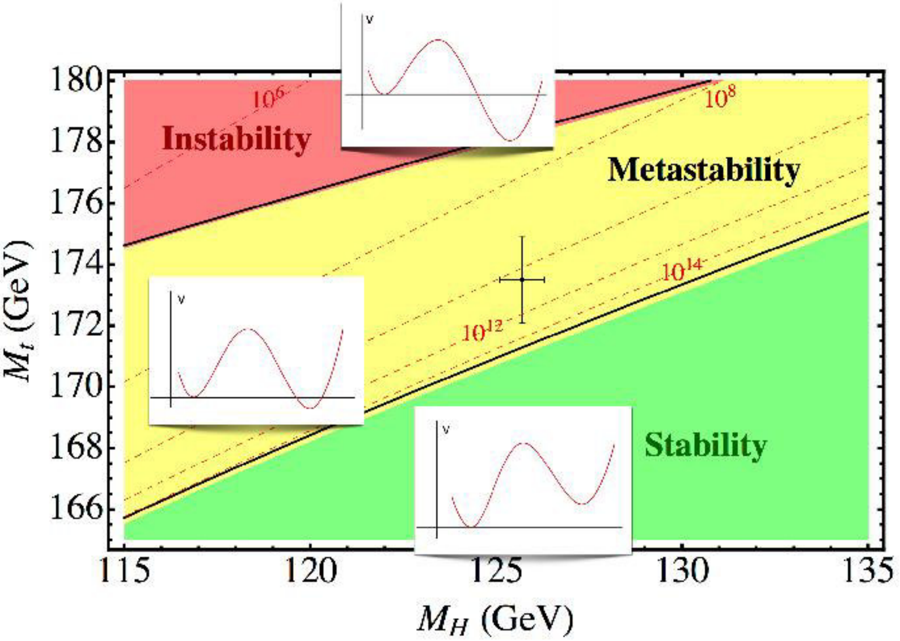
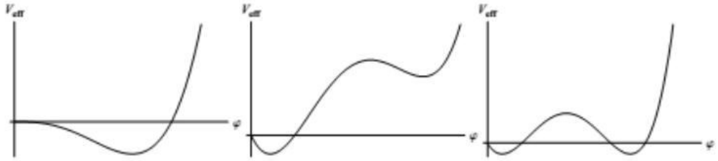


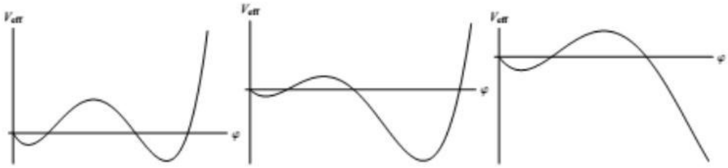
Fig.3. Top quark mass dependence of the mass of the Higgs boson, showing a metastable vacuum

Scientific models of our Universe have included the possibility that it exists as a long-lived, but not completely stable, sector of space, which could potentially at some time be destroyed upon 'toppling' into a more stable vacuum state. This catastrophic bubble of "true vacuum" could theoretically occur at any time or place in the Universe, which means (because the bubble of "true vacuum" will expand at the speed of light) the end of such a false vacuum could occur at any time [15].

Various configurations of the effective potential of vacuum are presented in Fig.4. If the life time is larger than the age of our Universe, then the vacuum is metastable (c and d). If not, we have an unstable vacuum (e).



(a) stable (b) stable (c) metastable



(d) metastable (e) unstable (f) unstable

Fig.3. Various configurations of the effective potential

5 The classification of D-brane charges in superstring theory of Type IIB

We can try to develop techniques to realize that the standard questions are motivated directly by comparison with experiment, such as the structure of scales and hierarchies, the gauge group and charged matter content. It would be interesting to consider the D-brain charges in terms of the K-theory of spacetime. As soon as D-branes carry Ramond-Ramond charge which are cohomology classes, we deel with K-theory which involves vector bundles and gauge fields. In the brane spectrum of Type IIB one has unitary gauge groups and this fact explained the proposal that D-brane charge takes value in K(X). We apply the K-theory to the classification of charges of D-branes in superstring theory of Type IIB [16]. We begin by considering the Type IIB theory, where superstring closed and oriented. RR-charge of D-branes of Type IIB is measured by K-group of transversal space to the manifold X, i.e $\overline{K}(S^n)$ classifies (9-n) branes in string theory of Type IIB. Conformity of K-group is determined by the homotopy theory:

$$\overline{K}(S^n) = \pi_{n-1}(U(k)), \quad k > n/2.$$

Since

$$\pi_n(\bigcup_k U(k) = U(\infty)) = \pi_{n+2}(U(\infty)),$$

then

$$\overline{K}(S^n) = \overline{K}(S^{n+2}).$$

I.e one can see Bott periodicity in the brane spectrum of Type IIB. From this and relations

$$\overline{K}(S^0) = Z, \quad \overline{K}(S^1) = 0$$

we get Table 1, which reflects the fact that the theory of Type IIB has stable Dp-branes only for p – odd.

Table 1. *Topological charges of Dp-branes for $\overline{K}(S^p)$ group*

Dp	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0	D(-1)
S^p	S^0	S^1	S^2	S^3	S^4	S^5	S^6	S^7	S^8	S^9	S^{10}
$\overline{K}(S^p)$	Z	0	Z	0	Z	0	Z	0	Z	0	Z

It is clear from the table, that D3-brane charge takes an integer value and this fact indicates the possible existence of solitonic object in our fourdimensional world (3+1) with the energy values or RR charges belonging to the group of integers. As soon as we deel with K-theory, we can speak about vector bundles and gauge fields connected with this bundles. It should be noted that in [17] is calculated the total number of vacua with cosmological constant $|\Lambda| < \Lambda_{max}$ and compactification volume $V_M < V^{>}$. The predictivity of string/M theory leads to the conjecture that the number of consistent flux vacua

$$N_{fluxvac}(\Lambda_{max}, V^{>}, [B]) \in Z$$

is finite.

6 Conclusions

Thus, within the Big Bang framework it is assumed that the Universe expands. During this process the Universe passes through some characteristic energy scales of phase transitions. These transitions are connected with symmetry breakings, each of which leaves the vacuum state less symmetric than before. A more symmetric vacuum state undergoing a chain of symmetry breakings producing a less symmetric vacuum state at present. A chain of symmetry breakings could be illustrated as follows:

$$\cdots \xrightarrow[\sim 10^{14} GeV]{} \begin{pmatrix} \text{GUT} \\ \text{symmetry} \\ \text{breaking} \end{pmatrix} \xrightarrow[\sim 10^{2} GeV]{} \begin{pmatrix} \text{Electroweak} \\ \text{symmetry} \\ \text{breaking} \end{pmatrix} \xrightarrow[\sim 10^{-1} GeV]{} \begin{pmatrix} \text{QCD} \\ \text{symmetry} \\ \text{breaking} \end{pmatrix} \cdots$$

The physics of the phase transitions depend on the theory of particle physics which is implemented to model of the Universe. The new vacua described as F-theory and discovered by Vafa [18], allowed string theorists to construct new realistic vacua, that is shown for Type IIB string theory in this article. Thus, the particle spectrum of Type IIB string theory is the most adequate representation of the nature of elementary particle physics taking into account recent experimental data and theoretical developments.

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Свойства вакуума и спектр бран струнной теории Типа IIB

В последние несколько лет Ф-теория привлекает большее внимание благодаря ее богатой структуре, позволяющей решить многие проблемы Стандартной Модели и Теории Великого Объединения. Эта теория также важна из-за необходимости решить проблему стабильности вакуума. Более простая реализация Ф-теории используется для описания струнной теории типа IIB. Для классификации зарядов D-бран в суперструнной теории типа IIB применяется K-теория. Этот подход обеспечивает выход на калибровочные поля, связанные с векторными расслоениями, классифицированными K-теорией. Эта техника реализует решение вопросов, связанных со структурой масштабов и иерархий, калибровочной группой и составом заряженных полей.