

A novel braneworld model with a bulk scalar field

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Abstract

We consider a new braneworld model with a bulk scalar field coupled to gravity. The bulk scalar action is inspired by the proposed low energy effective action around the tachyon vacuum. A class of warped geometries representing solutions of this Einstein-scalar system for a specific scalar potential is found. The geometry is non singular with a decaying warp factor and a negative Ricci curvature. The solution of the hierarchy problem is obtained using this type of warping. Though qualitatively similar to the usual Randall–Sundrum I model there are interesting quantitative differences. Additionally, in the RS II set-up the graviton zero mode as well as spin-half massless fermions are found to be localised on the brane.

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1. Introduction

The study of extra dimensions ($D > 4$) has been of considerable interest to theoretical physicists ever since Kaluza–Klein introduced them in their attempt to unify gravity with electromagnetism [1]. Over the last few decades, the notion of extra dimensions has been discussed with renewed enthusiasm in the context of string theory [2] where their presence is inevitable. More recently, attention has shifted toward the *braneworld* picture, in which our four-dimensional universe (3-brane) is viewed as an embedded hyper-

surface in a higher-dimensional bulk spacetime. In the now-popular Randall–Sundrum models (known as RS I and RS II) [3] of warped (nonfactorisable) spacetimes the extra dimensions exist, can be compact or non-compact, but the usual schemes of *compactification* are replaced by the notion of *localisation* of fields on the brane. The RS I model provides us with a solution of the gauge hierarchy problem whereas RS II shows us how the higher-dimensional gravity can still reproduce Newtonian gravity on the brane. Several problems exist with the RS models, some of which have been tackled by introducing appropriate modifications [4].

In the RS models, the bulk is essentially vacuum but with a negative (five-dimensional) cosmological constant (AdS spacetime). This leads to a problem

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of stability of the branes—a matter of concern in the two-brane (RS I) scenario. To remedy this, bulk fields are introduced, in particular, a scalar field with a potential [5]. A bulk scalar also provides us with a way of generating the braneworld as a domain wall in five dimensions—these are the so-called *thick* branes. The last few years has seen much work being carried out on diverse aspects of such braneworld models with variety of bulk field configurations [3, 6]. In the context of such newer models with bulk fields, issues such as localisation of various types of matter fields [7–9], cosmological consequences [10] and particle phenomenology in the braneworld context [11] have been addressed to some extent. Further consequences of new types of bulk matter and their resulting effects still remains an open arena of research.

Recently there has been a lot of activity on a newly proposed scalar field theory, namely, ‘tachyon matter’ arising in the context of string theory [12]. Briefly, one can say that open string tachyons (attached to D-branes and reflecting D-brane instability), residing on the unstable (tachyonic) maximum of the tachyon potential can acquire a vacuum expectation value (condensate) and roll down to a stable configuration. The energy of such a tachyon condensate has been calculated in string field theory. The effective action thus obtained is somewhat uncommon due to its special form. It is completely different from the usual scalar field action and resembles, in some sense, a Born–Infeld type action [13]. Though proposed by several authors independently [14] its physical consequences have been analysed in greater detail recently by Sen [12]. It has been shown that such a scalar field might play a role in cosmology in the context of dark matter/energy. This is because the effective energy–momentum tensor can be shown to be *equivalent* to that of noninteracting, nonrotating dust [15]. Since, currently, there is no unique, experimentally verifiable choice for bulk matter, it is surely useful to explore various possibilities [16]. This has motivated us to consider the tachyon condensate as a bulk field coupled to gravity and study its effects on the geometry. It is worth mentioning here that one might also visualise the tachyon condensate action as a new type of scalar field action without making any particular reference to string theory as such. The dynamics of this scalar field, both classical and quantum is of interest

in its own right and has been investigated from this standpoint too.

The bulk geometry is taken to be non-factorisable (warped). We first obtain an exact solution of the full set of Einstein–scalar equations with a given scalar potential. Thereafter, we address the hierarchy problem in a RS I set-up. In the subsequent section, we analyse the graviton zero mode and demonstrate its localisation in RS II set-up. Finally, we concentrate on fermion (massless) localisation and conclude with a summary of the results obtained.

2. The model and the exact solution

Let us begin with the action for the bulk scalar field [12] given by

$$S_T = \alpha_T \int d^5x \sqrt{-g} V(T) \sqrt{1 + g^{MN} \partial_M T \partial_N T}, \quad (2.1)$$

where α_T is an arbitrary constant, g_{MN} being the five-dimensional metric. The scalar field is represented by T and $V(T)$ corresponds to its potential. The constant α_T can take either positive or negative values. The energy–momentum tensor corresponding to the above action is given by:

$$T_{MN}^{(T)} = \frac{\alpha_T}{2} \left[g_{MN} V(T) \sqrt{1 + (\nabla T)^2} - \frac{V(T)}{\sqrt{1 + (\nabla T)^2}} \partial_M T \partial_N T \right]. \quad (2.2)$$

For an appropriate choice of α_T and $V(T)$ it is possible to keep the geometry, produced by the above action along with gravity, unaltered with respect to the signature change of α_T . Note the unusual form of the action, the potential, is multiplied with a square root function containing the metric and derivatives of the scalar field. This inherent novelty of the action has generated a lot of activity. The full five-dimensional action will also contain an Einstein–Hilbert term along with the contributions from the brane vacuum energies.

The action of the model is

$$S = S_G + S_T + S_B, \quad (2.3)$$

$$S_G = 2M^3 \int \sqrt{-g} R d^5x, \quad (2.4)$$

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