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Graviton resonances on two-field thick branes

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ABSTRACT

This work presents new results about the graviton massive spectrum in two-field thick branes. Analyzing the massive spectra with a relative probability method we have firstly showed the presence of resonance structures and obtained a connection between the thickness of the defect and the lifetimes of such resonances. We obtain another interesting result considering the degenerate Bloch brane solutions. In these thick brane models, we have the emergence of a splitting effect controlled by a degeneracy parameter. When the degeneracy constant tends to a critical value, we have found massive resonances to the gravitational field indicating the existence of modes highly coupled to the brane. We also discussed the influence of the brane splitting effect over the resonance lifetimes.

1. Introduction

Recently, much attention has been given to the study of topological defects in the context of brane-world models, due to its property of allowing the localization of several different types of fields. As extended defects in field theory, the domain walls have been used in high-energy physics to represent brane scenarios with extra dimensions [1,2]. The Bloch walls, which could be seen as chiral interfaces [3], are used in the context of extra dimensions to construct a $(4,1)$D model of two scalar fields coupled with gravity, the so-called Bloch brane [4].

The Bloch brane model is generated dynamically and has internal structure. The asymptotic bulk metric is a slice of a five-dimensional anti-de Sitter (AdS) spacetime, denoted by AdS_5. Such scenario may be used to mimic a brane-world containing internal structure [5], which have implications on the density of matter-energy along the extra dimension [6]. The appearance of the internal structure could be also observed by a splitting effect on the curvature invariant.

On the other hand, Dutra et al. have showed that the Bloch brane scenario addressed in [4] holds more general soliton solutions [7–9]. The brane configurations obtained from these new solutions were named by the authors as *degenerate Bloch branes* due to the existence of a degeneracy parameter that is not present in the Lagrangian density. Such defects present more details as the appearing of two-kink solutions. These additional features were interpreted as the formation of a double wall structure. When the degeneracy parameter approaches a critical value, the brane splits in two and its separation becomes larger. This effect will contribute to the emergence of massive graviton resonances. The phenomenon of two separate interfaces on the defect is known in condensed matter physics as complete wetting [10,11]. Moreover, the same behavior was considered as a critical phenomenon of phase transition on thick branes in warped geometries [12].

In the above scenarios some authors have investigated the localization of several types of bulk fields. Namely, fermion fields [9,13–15], gauge fields [16,17] and graviton zero mode [4,8]. However, the study of the graviton massive spectrum has not been properly studied. It is worthwhile to mention that the search for resonances in warped spacetimes [14,16,18–26] has received attention because they give us important information about the interaction of Kaluza–Klein (KK) massive spectrum with the four-dimensional brane. Specifically in the study of gravity localization, the presence of a resonance at zero energy is related to the existence of a large-distance region on which the 4D laws of gravity are valid [26,27]. Therefore, if the resonance width becomes very large, it results in nonphysical effects.

To the best of our knowledge the first work about localization of graviton zero mode on the Bloch brane was the work of Bazeia and Gomes [4]. Their results were also confirmed on the degenerate Bloch branes by Dutra et al. [8]. However, the important issues concerning the analysis of the massive spectrum and the search for resonances in these scenarios have not been addressed.

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Therefore, in the present work we propose to study the graviton massive spectrum and search for resonant states on the two field thick brane scenarios described above. Additionally, we intend to verify the relation between the brane thickness and the internal structure over possible detected resonances.

We organized this work as follows. In Section 2, we review the Bloch brane scenario and search for new resonant structures in this model in Section 3. We addressed the degenerate Bloch brane solutions in the beginning of Section 4 and we search for new graviton resonances in this more general setup. Finally, we present our results and conclusions in Section 5.

2. Brane setup

The two-field thick brane scenario that we consider is composed by two fields ϕ and χ coupled to gravity which depend only on the extra dimension y. Such model was previously studied in Refs. [4,13,14,16]. Their action is given as follows:

$$S=\int d^5x\sqrt{-G}\left[-\frac{1}{4}R+\frac{1}{2}(\partial\phi)^2+\frac{1}{2}(\partial\chi)^2-V(\phi,\chi)\right], \qquad (1)$$

where R is the scalar curvature and the spacetime is an AdS $D=5$ with metric

$$ds^2=e^{2A(y)}\eta_{\mu\nu}\,dx^\mu\,dx^\nu-dy^2. \qquad (2)$$

The Minkowski spacetime metric is $\eta_{\mu\nu}$ with signature $(-,+,+,+)$ and the indices μ, ν run over 1 to 4.

The corresponding equations of motion are

$$\phi'^2+\chi'^2-2V(\phi,\chi)=6A'^2,$$
$$\phi'^2+\chi'^2+2V(\phi,\chi)=-6A'^2-3A'',$$
$$\xi''+4A'\xi'=\partial_\xi V,\quad \xi=\phi,\chi, \qquad (3)$$

where prime stands for derivative with respect to y.

A method for solving the coupled differential equations system (3) has been developed in the context of thick branes [28–33]. It consists of a appropriate redefinition of the potential $V(\phi,\xi)$ as

$$V(\phi,\chi)=\frac{1}{8}\left[\left(\frac{\partial W}{\partial\phi}\right)^2+\left(\frac{\partial W}{\partial\chi}\right)^2\right]-\frac{1}{3}W^2 \qquad (4)$$

in terms of a superpotential

$$W(\phi,\chi)=2\phi-\frac{2}{3}\phi^3-2r\phi\chi^2. \qquad (5)$$

This implies that the resulting first-order equations can be written as $\phi'=\frac{1}{2}\frac{\partial W}{\partial\phi}$, $\chi'=\frac{1}{2}\frac{\partial W}{\partial\chi}$ and $A'=-\frac{1}{3}W$, from which we find the solutions that describe our brane model, namely

$$\phi(y)=\tanh(2ry), \qquad (6)$$

$$\chi(y)=\sqrt{\left(\frac{1}{r}-2\right)}\operatorname{sech}(2ry), \qquad (7)$$

and

$$A(y)=\frac{1}{9r}\left[(1-3r)\tanh^2(2ry)-2\ln\cosh(2ry)\right]. \qquad (8)$$

From Eq. (7), we can see that for the limit $r=0.5$ the one-field scenario is recovered. For certain values of the coupling parameter r that controls the brane thickness, we have a splitting of the defect and the appearance of an internal structure. This characteristic is also evident on the curvature invariant. For this geometry, for instance, we obtain

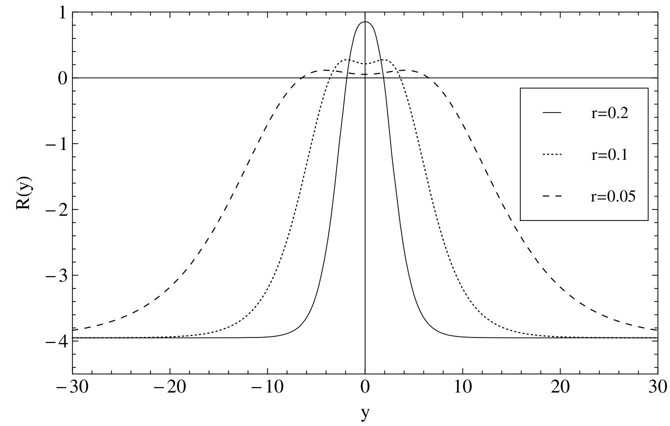

Fig. 1. Plots of the curvature invariant $R(y)$ with $r=0.2$, 0.1 and 0.05.

$$R=-\left[8A''+20\left(A'\right)^2\right]. \qquad (9)$$

The Ricci scalar is finite, which we can observe through Fig. 1. For $0.5>r>r_c$, with $r_c\approx 0.17$ there is a maximum at $y=0$. When r arrives to the interval $r_c>r>0$, the maximum splits into two separate maxima, which indicates the presence of the internal structure. These effects will influence the behavior of the massive modes, which will be investigated in the following section.

3. Massive spectrum and resonances

The seminal work of Bazeia and Gomes [4] considering the Bloch brane model performed an analysis in the zero modes of the graviton but have not confirmed the existence of resonant modes. From now, we will take this scenario again focusing our attention in the massive spectrum and seeking resonant modes for the graviton. In order to search for resonances in the massive spectrum we must obtain a Schrödinger-like equation to the graviton on the fifth dimension. Initially, we perform a metric perturbation using $ds^2=e^{2A(y)}(\eta_{\mu\nu}+\epsilon h_{\mu\nu})\,dx^\mu\,dx^\nu-dy^2$, where $h_{\mu\nu}=h_{\mu\nu}(x,y)$ represents the graviton with the axial gauge $h_{5N}=0$. When we set the metric fluctuation as transverse and traceless (TT), namely $\bar{h}_{\mu\nu}$, its equations of motion take the simplified form [18,34,35]:

$$\bar{h}''_{\mu\nu}+4A'\bar{h}'_{\mu\nu}=e^{-2A}\partial^2\bar{h}'_{\mu\nu}, \qquad (10)$$

where ∂^2 is the four-dimensional wave operator. Using the transformation $dz=e^{-A(y)}\,dy$ and choosing an ansatz containing a bulk wave function times a space plane wave, $\bar{h}_{\mu\nu}(x,z)=e^{ip\cdot x}e^{-\frac{3}{2}A(z)}\psi_{\mu\nu}(z)$, we can rewrite Eq. (10) as a Schrödinger-like equation given by

$$-\frac{d^2\psi(z)}{dz^2}+V(z)\psi(z)=m^2\psi(z), \qquad (11)$$

with the potential $V(z)=\frac{3}{2}A''(z)+\frac{9}{4}A'^2(z)$. Eq. (11) leads to no tachyonic states and owns a normalizable zero mode solution as was showed in Ref. [4].

When $m^2\gg V_{max}$, the potential represents only a small perturbation and the solutions will acquire plane wave structure. In Fig. 2 we plot the potential $V(z)$ varying r. As in the curvature scalar (Fig. 1) we note the appearance of a splitting effect due to the thickness of the defect. The minimum of the potential separates in two as we reduce r, acquiring the shape of a double-well-type potential. Similar feature was also found in the potential of the Schrödinger equation for the TT sector of the metric perturbations in a thick brane scenario generated by one scalar field [12].

For some specific energies, the solutions of Eq. (11) could exhibit large amplitudes inside the brane in comparison with its