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Brane-induced decay of the Kaluza-Klein vacuum

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Abstract: The enhancement in the decay rate of the Kaluza-Klein vacuum due to the presence of a brane is studied, both in the test brane approximation and beyond it. Spontaneous brane materialization in the Kaluza-Klein vacuum is also described.

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Contents

1. Introduction

It was shown long time ago that the Kaluza-Klein theory is non-perturbatively unstable [1]. In the simplest case, $R^4 \times S^1$ space can decay via the formation of the, so called, "bubbles of nothing". The bounce solution describing the decay was shown to be the euclidean 5d black hole. Later on, this process was generalized to the Melvin type Kaluza-Klein vacuum with magnetic flux [2]. The vacuum decays via the mediation of the euclidean 5d Kerr solution, which is the corresponding bounce configuration in this case.

Such manifold decay processes have been discussed in the context of string/M theory [3, 4], as well as in the study of the stability of brane scenarios of the Universe [5]. The whole subject has become quite popular recently, partially because of the interest in string dynamics in time-dependent backgrounds [6]–[8].

The aim of the present paper is to study the induced decay of Kaluza-Klein vacuum, that is, the decay caused by the presence of a heavy object (particle, cosmic string, 2-brane) in the initial state. It is natural to expect that the presence of a heavy object in the initial state enhances the decay rate. A qualitative explanation of this effect for the case of particle induced decay was given in [9]: the worldline of the inducing particle in some circumstances happens to be "shorter" in the presence of the bounce than in its absence and this leads to the enhancement factor e^{2Rm} for the decay rate where R is the radius of the bounce. In fact, as explained in [9], for a sufficiently heavy particle one should take into account the back reaction of the particle onto the bounce. The resulting distortion of the latter gives rise to an even stronger enhancement. These ideas were further developed to describe the nonperturbative instability of neutral branes in external fields [10], or the spontaneous creation of the so-called Brane-World [11].

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The present paper is organized in six sections, of which this introduction is the first. In section 2 we briefly review the case of spontaneous decay of the Kaluza-Klein $R^4 \times S^1$ vacuum.

In section 3 we compute the enhancement of this decay rate, due to the presence of a 2-brane (codimension 1), a 1-brane (codimension 2) or a 0-brane (codimension 3) in the, so-called, test brane approximation. In this approximation the back reaction of the external object onto the background geometry is not taken into account and it is easy to treat. Essentially, one has to compare areas of worldsheets of the inducing brane in the presence and the absence of bounce. Inducing branes of arbitrary codimension are discussed. Actually, codimension 1 case happens to be degenerate - the brane gives an ill-defined boundary dependent contribution to the decay rate. We attribute this to the fact that codimension 1 brane beyond the test brane approximation does not exist in the asymptotically locally flat space. The cases of codimension 2 and 3 are unambiguous.

In section 4 we go beyond the test brane approximation, but only for the case of the codimension 2 brane. A "bubble of nothing" is formed, which breaks the brane and expands to fill out the whole space. The bounce configuration relevant to this case and the computation of the enhancement factor of the vacuum decay rate are presented here. It so happens that the enhancement factor coincides with the one obtained in the test brane approximation. The process discussed here is different from those considered in [12]–[16], where the external string breaks and two black holes are formed.

However, we have been unable to go beyond the test brane approximation in the codimension 3 case, essentially because we could not find a solution of the Einstein-Nambu-Goto equations, which is a deformation of the bubble of nothing due to the presence of the brane.

Somewhat outside the main theme of this paper, in section 5 we consider not induced but spontaneous decay of the Kaluza-Klein vacuum via a channel with a 2-brane in the final state. A minor modification of Witten's construction allows to describe spontaneous decay of the vacuum into a bubble of nothing with a codimension 2 brane on its boundary.

Section 6 contains our conclusions.

2. Spontaneous decay of $R^4 \times S^1$

Let us consider the locally flat manifold $R^4 \times S^1$ with metric

$$ds^2 = dr^2 + r^2 d\Omega_3^2 + d\tau^2 \tag{2.1}$$

where $d\Omega_3^2$ is the metric on S_3 and τ runs over the circle,

$$\tau \sim \tau + 2\pi R\,. \tag{2.2}$$

This manifold was shown to decay [1], the corresponding bounce being described by the metric

$$ds^2 = \left(1 - \frac{\alpha}{r^2}\right)^{-1} dr^2 + r^2 d\Omega_3^2 + \left(1 - \frac{\alpha}{r^2}\right) d\tau^2\,. \tag{2.3}$$

This metric is nothing but the 5d Schwarschild metric analytically continued to euclidean space. The coordinate τ runs over the same circle (2.2), while r runs from $\sqrt{\alpha}$ to ∞. This does not mean, that $r = \sqrt{\alpha}$ is a boundary of the manifold (2.3). In fact, $r = \sqrt{\alpha}$ defines a codimension 2 subspace (because S^1 spanned by τ shrinks to a point on this subspace). Geometrically it is an S_3. Generically, this S_3 is a locus of conical singularity unless α and R are related by

$$\alpha = R^2 \,. \tag{2.4}$$

The surface

$$r = \sqrt{\alpha} \tag{2.5}$$

as well as the whole geometry described by (2.3) is sometimes called "bubble of nothing". It is interpreted as a bounce, since it has one negative mode in the spectrum of small fluctuations around it [1].

As usual in the semiclassical approximation, the decay rate is with exponential accuracy estimated as $\exp(-\Delta S)$ where $\Delta S \equiv S - S_0$, S being the euclidean action of the relevant bounce and S_0 the action of the reference background $R^4 \times S^1$ with metric (2.1), the natural reference space for the discussion of spontaneous decay of the Kaluza-Klein vacuum. The euclidean action is

$$S = -\frac{1}{16\pi G_5}\int \sqrt{g}R - \frac{1}{8\pi G_5}\oint \sqrt{h}K \,, \tag{2.6}$$

where the first term is the Einstein-Hilbert term, and the second is the integral over the boundary of the trace K of the extrinsic curvature of the boundary surface, with the measure constructed from the induced metric h. In non-compact spaces this action is infinite. However, one needs only the difference $\Delta S \equiv S - S_0$ which, being properly defined, is finite. An important point here is that in the computation of S_0 one has to consider a boundary with the same intrinsic geometry as in the computation of S. Given the metric (2.3), it is convenient to take the boundary

$$r = r_0 \,, \tag{2.7}$$

where r_0 is large compared to all physical length scales. Restricting metric (2.3) to the surface (2.7) gives the induced metric h on the boundary,

$$h_{ij}dx^i dx^j = r_0^2 d\Omega_3^2 + (1 - \frac{\alpha}{r_0^2})d\tau^2 \,. \tag{2.8}$$

Then, to find in the reference space a boundary surface with the same intrinsic geometry (2.8), one should take in $R^4 \times S^1$ the same surface (2.7) and - what is more subtle - tune the period of τ, so that

$$\tau \sim \tau + 2\pi R\sqrt{1 - \frac{\alpha}{r_0^2}} \,. \tag{2.9}$$

The rest of the calculation is straightforward. The curvature term does not contribute because both metrics (2.3) and (2.1) are Ricci flat. The trace of the extrinsic curvature can be computed using the identity

$$K\sqrt{h} = n\sqrt{h} \,, \tag{2.10}$$

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where h is the determinant of the induced metric (2.8) on the boundary,

$$\sqrt{h} = r_0^3 \sqrt{1 - \frac{\alpha}{r_0^2}} \sin^2\theta_1 |\sin\theta_2| \tag{2.11}$$

(on S_3 we use the standard spherical coordinates (3.2) below), and n is the unit normal

$$n = \sqrt{1 - \frac{\alpha}{r_0^2}} \frac{\partial}{\partial r_0} . \tag{2.12}$$

This way we obtain the boundary term in the "bubble" space

$$K\sqrt{h} = 3r_0^3 \left(1 - \frac{2}{3}\frac{\alpha}{r_0^2}\right) \sin^2\theta_1 |\sin\theta_2| . \tag{2.13}$$

The simplest way to evaluate the trace of the extrinsic curvature K_0 of the boundary (2.7) in the reference space $R^4 \times S^1$, is to note that it is equal to the sum of principal curvatures of S_3 of radius r_0 i.e. $K_0 = 3/r_0$. The measure $\sqrt{h}$ is of course the same on the boundary in the reference space and is given by (2.11), since the boundaries were tuned to have the same intrinsic geometry.

Finally, the difference of the boundary integrals gives

$$\Delta S = -\frac{1}{8\pi G_5} \int (K - K_0)\sqrt{h} = \frac{\pi R^2}{8G_4} , \tag{2.14}$$

where $G_4 = 2\pi R G_5$.

We conclude that in the exponential approximation the probability per unit time and per unit volume of formation of a critical bubble is equal to

$$\Gamma_0/V \sim G_4^{-2} e^{-\frac{\pi R^2}{8G_4}} . \tag{2.15}$$

In fact, the evaluation of the prefactor requires the computation of a functional determinant, usually a formidable task [17]. In the problem at hand, however, the prefactor is G_4^{-2} times a function of the dimensionless ratio R^2/G_4. We arbitrarily, but consistently with the exponential approximation discussed here, took this function equal to one. The probability of formation of such a critical bubble in the volume of the observable Universe and within its age is, as it should be, much smaller than unity, as long as the size R of the extra dimension is greater than or about $40M_{Pl}^{-1}$. Thus, the spontaneous decay of the Kaluza-Klein vacuum does not imply a severe constraint on the size of the internal dimension.

3. Induced decay in the test brane approximation

We now turn to the computation of the enhancement of the vacuum decay rate due to the presence of a test brane. We shall treat the codimension 1, 2 and 3 cases separately. In the next section we shall deal with the full problem, including back reaction on the background metric due to the brane. The dynamics of the brane is described by the Nambu-Goto action, which for a p-brane has the form

$$S_{NG} = T_p \int d^{p+1}\xi \sqrt{\det g_{\rm ind}}\,, \tag{3.1}$$

where T_p is the brane tension, a positive constant with dimensions of (mass)$^{p+1}$. A natural assumption, implicit in the discussion of test branes in the Kaluza-Klein vacuum, is that the presence of the branes does not remove the negative mode from the spectrum of small fluctuations around the bounce configuration, responsible for the instability of the pure vacuum. Their only effect in the exponential approximation is to modify the decay rate by a term in the exponent linear in the brane tension.

3.1 Codimension 1 test brane

The application of the test brane approximation is questionable in this case, because a codimension 1 brane is not compatible with asymptotic flatness [18]. Nevertheless, we would like to discuss it just to demonstrate in a simple example the method we shall be using and to see what exactly will go wrong with our approximation.

Let us consider the same $R^4 \times S^1$ space (2.1) and a 3-brane with tension T_3 located, say, at $x = 0$, where x is one of the cartesian coordinates in R^4, and wrapped around S^1. In the context of the test brane approximation we ignore the backreaction of the brane on the geometry of the background, which is assumed to be the flat space (2.1). The brane dynamics is described by the Nambu-Goto action (3.1) with $p = 3$ and the enhancement factor to leading order is the exponential of the difference of the actions of the brane in the bounce (2.3) and in the flat geometry (2.1). Thus, to describe the influence of the brane on the vacuum decay rate, we have to find the minimal surface in the bounce geometry (2.3), which coincides asymptotically with the worldsheet of the brane in flat space. This is easiest in the spherical coordinates $0 \le \theta_1, \theta_2 \le \pi$ and $0 \le \theta_3 \le 2\pi$, in terms of which the $d\Omega_3^2$ term in (2.1) and (2.3) takes the standard form

$$d\Omega_3^2 = d\theta_1^2 + \sin^2\theta_1 d\theta_2^2 + \sin^2\theta_1 \sin^2\theta_2 d\theta_3^2\,. \tag{3.2}$$

Consider the surfaces

$$\theta_1 = \frac{\pi}{2} \tag{3.3}$$

in the spaces (2.1) and (2.3). By symmetry these are minimal surfaces. These surfaces coincide asymptotically $r \to \infty$ and are asymptotically of the required type. Thus (3.3) describes the worldsheet of the inducing brane.

Let us clarify the geometry of the brane near the bubble. The brane intersects the 3-sphere (2.5) along an equatorial S_2. Since the S^1 spanned by τ shrinks to a point on this sphere, we conclude that there is a bubble of nothing inside the brane too.

It remains only to compute the difference of the Nambu-Goto actions of the brane in the presence and in the absence of the bubble. Note that the worldsheet volumes are infinite in both cases, so we have to use a boundary as it was discussed in the previous section.

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Notice that the $1 - \alpha/r^2$ factors cancel out in the determinant, so that the difference in the actions is simply

$$\Delta S_{NG} = 4\pi T_3 2\pi R \left(\int_{\sqrt{\alpha}}^{r_0} r^2 dr - \sqrt{1 - \frac{\alpha}{r_0^2}} \int_0^{r_0} r^2 dr \right) \sim \frac{4}{3}\pi^2 T_3 R \alpha r_0 \,. \qquad (3.4)$$

The factor in front of the second integral is due to the period rescalling (2.9) of τ in flat space. Notice, that ΔS_{NG} in (3.4) diverges linearly when $r_0 \to \infty$. One would be tempted to conclude at this point that the presence of the brane stabilizes the flat Kaluza-Klein space-time. However, ΔS_{NG} obtained above is ill-defined, being boundary dependent and divergent. This behaviour is a manifestation of the fact mentioned in the beginning that the presence of a codimension 1 brane affects drastically the asymptotic behaviour of the background, which changes into AdS.

3.2 Codimension 2 test brane

Consideration of this case is quite similar to the previous one apart from some technical details. The inducing brane is of codimension 2 in the R^4 component and is wrapped around the S^1 spanned by τ. In this case, a convenient coordinate system to use on S_3 is

$$d\Omega_3^2 = \sin^2\theta d\psi^2 + d\theta^2 + \cos^2\theta d\phi^2, \qquad (3.5)$$

where θ runs from 0 to $\pi/2$, while ψ and ϕ run from 0 to 2π. Consider the surfaces

$$\theta = 0 \qquad (3.6)$$

in spaces (2.1) and (2.3). The S^1 spanned by ψ shrinks to a point on these surfaces, which consequently have codimension 2. By symmetry they are minimal surfaces. In addition, these surfaces again coincide asymptotically and are asymptotically of the required type. Thus (3.6) describes the worldsheet of the inducing brane. Similarly to the codimension 1 case above, in the presence of the bubble of nothing in the space, there is a "hole" of nothing on the inducing brane too. After its formation the critical bubble and with it the hole on the brane expands, eliminating the brane and pushing space to infinity.

The computation of the enhancement factor is the same as in the codimension 1 case. The difference of the Nambu-Goto actions is

$$\Delta S_{NG} = 2\pi T_2 2\pi R \left(\int_{\sqrt{\alpha}}^{r_0} r dr - \sqrt{1 - \frac{\alpha}{r_0^2}} \int_0^{r_0} r dr \right) \sim -\pi^2 \alpha^{3/2} T_2 \,, \qquad (3.7)$$

so that the enhancement factor is equal to

$$\frac{\Gamma}{\Gamma_0} = e^{\pi^2 \alpha^{3/2} T_2} \,, \qquad (3.8)$$

where T_2 is the tension of the inducing brane. In terms of R satisfying (2.4) and the "macroscopic" tension $\mu_2 \equiv 2\pi R T_2$ of the brane, i.e. the energy of the brane per unit of non-compact volume, the enhancement factor takes the form:

$$\frac{\Gamma}{\Gamma_0} = e^{\frac{1}{2}\pi R^2 \mu_2} \,. \qquad (3.9)$$

3.3 Codimension 3 test brane

In the case of codimension 3 the decay is induced by a 1-brane, a string wrapped around the compact dimension. In this case instead of (3.7) we obtain

$$\Delta S = 2T_1 2\pi R \left(\int_{\sqrt{\alpha}}^{r_0} dr - \sqrt{1 - \frac{\alpha}{r_0^2}} \int_0^{r_0} dr \right) . \tag{3.10}$$

The factor $\sqrt{1 - \frac{\alpha}{r_0^2}}$ does not contribute in this case, and we end-up with

$$\frac{\Gamma}{\Gamma_0} = e^{4\pi\alpha T_1} . \tag{3.11}$$

Defining $\mu_1 \equiv 2\pi R T_1$ and using equation (2.4) one arrives at

$$\frac{\Gamma}{\Gamma_0} = e^{2R\mu_1} . \tag{3.12}$$

4. Beyond the test brane approximation

To go beyond the test brane approximation of the previous section, one needs to find a solution of the Einstein-Nambu-Goto equations, which is a deformation of the bubble of nothing metric (2.3) due to the presence of the brane. We shall consider here only the case of codimension 2 brane. Other cases will be considered elsewhere.

The metric describing a codimension 2 brane in $R^4 \times S^1$ is characterized by the so-called deficit angle:

$$ds^2 = dr^2 + r^2 \left(\nu^2 \sin^2\theta d\psi^2 + d\theta^2 + \cos^2\theta d\phi^2 \right) + d\tau^2 , \tag{4.1}$$

where, as discussed above, θ runs from 0 to $\pi/2$, ψ and ϕ run from 0 to 2π and ν is a constant less than 1. The metric in equation (4.1) is singular at $\theta = 0$. This is where the brane is located. In the orthogonal plane, $\theta = \pi/2$, there is a deficit angle equal to $\Delta = 2\pi(1-\nu)$. It is well known [18] that the deficit angle is related to the brane tension T_2 according to

$$\nu = 1 - 4G_5 T_2 = 1 - 4G_4 \mu_2 . \tag{4.2}$$

Strictly speaking, only the string case, that is, codimension 2 brane in 3+1-dimensions, is considered in [18], but it is only codimension that matters.

Consider the metric

$$ds^2 = \left(1 - \frac{\alpha}{r^2}\right)^{-1} dr^2 + r^2 \left(\nu^2 \sin^2\theta d\psi^2 + d\theta^2 + \cos^2\theta d\phi^2 \right) + \left(1 - \frac{\alpha}{r^2}\right) d\tau^2 . \tag{4.3}$$

It is a solution of the Einstein-Nambu-Goto field equations, and represents a generalization of (4.1) describing both the bubble and the string and which coincides with (4.1) asymptotically as $r \to \infty$. It is, of course, singular along the locus of the brane, and since we do not want any other singularity, we require the parameter α to be related to the Kaluza-Klein radius by (2.4).

The geometry of the brane near the bubble is the same as in the test brane case: there is a bubble of nothing inside the brane which is an intersection of the brane with the bubble of nothing in the total space.

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It remains to estimate the induced decay rate which with exponential accuracy is equal to the exponential of $-\Delta S$, the difference of actions of the metrics (4.3) and (4.1). The action (2.6) is now modified to include the Nambu-Goto term

$$S = -\frac{1}{16\pi G_5}\int \sqrt{g}R + T_2 \oint \sqrt{g_{\rm ind}} - \frac{1}{8\pi G_5}\oint \sqrt{h}K\,. \tag{4.4}$$

Note that because of the conical singularity the R-term is not zero, rather it gives a contribution similar to the Nambu-Goto term. We now would like to argue that the first two terms cancel each other in the case of the codimension 2 brane. One way to show this is to smoothen-out the brane in the transverse directions, to solve Einstein equations and to see explicitly that the contributions cancel. This was performed in [18] for the case of a straight string. Contributions due to non-straightness of the string should arise only for a string with finite thickness. Actually, cancellation of the first two terms is equivalent to nothing but the relation (4.2).

Thus we are left with the difference of the boundary terms. The computation then follows the lines reviewed in section 2. The parameter ν enters only in h; K is ν-independent. Thus, the final answer for ΔS differs from (2.14) just by a factor of ν:

$$\Delta S = \nu\frac{\pi R^2}{8G_4}\,. \tag{4.5}$$

We conclude that the probability per unit of space-time volume V of the formation of a critical bubble in the Kaluza-Klein state in the presence of the codimension 2 brane is equal to

$$\Gamma/V \sim e^{-\nu\frac{\pi R^2}{8G_4}}\,. \tag{4.6}$$

Notice that upon substitution of ν in terms of the brane tension from (4.2) we recover the result (3.9), obtained in the test brane approximation.

5. Spontaneous vacuum decay with a brane in the final state

As a byproduct of the previous discussion, in this section we shall describe a new channel of spontaneous decay of the Kaluza-Klein vacuum. It is characterized by the existence of a brane in the final state. Consideration of this subsection is inspired by the previous section, where the metric with a conical singularity was used to describe the inducing codimension 2 brane. Now recall that the metric (2.3) has a conical singularity at $r = \sqrt{\alpha}$ when the parameter α is not tuned according to equation (2.4). Indeed, changing in (2.3) the coordinates so that $r \equiv \sqrt{\alpha} + \rho^2/2\sqrt{\alpha}$ we arrive in the vicinity of $\rho = 0$ to the metric

$$ds^2 = d\rho^2 + \frac{\rho^2}{\alpha}d\tau^2 + \alpha d\Omega_3^2\,. \tag{5.1}$$

Thus, in view of (2.2), the deficit angle parameter ν is given by

$$\nu = \frac{R}{\sqrt{\alpha}}\,. \tag{5.2}$$

The presence of the conical singularity represents a codimension 2 brane, and equation (4.2) relates the parameter α, the Kaluza-Klein radius R and the tension of this brane T_2 by

$$\frac{R}{\sqrt{\alpha}} = 1 - 4G_5 T_2 \,. \tag{5.3}$$

The brane is located at $r = \sqrt{\alpha}$ and its euclidean signature world-sheet is S^3 with induced metric

$$ds^2_{\text{ind}} = \alpha d\Omega_3^2 \,. \tag{5.4}$$

According to [1], the critical bubble is the $\theta = \pi/2$ section of the bounce. Thus, at "time" $\theta = \pi/2$ a brane with the geometry of S^2 materializes in space and starts expanding.

So, if in the "spectrum" of the theory under consideration there exist codimension 2 branes with tension T_2, the Kaluza-Klein vacuum can decay not only via the bounce (2.3) with α obeying (2.4), but also via bounce (2.3) with α obeying (5.3). This is an additional channel of spontaneous decay. We should point out here, that there is no problem with energy conservation. The discussion of [1] applies to our case as well. Both the initial and the final states have zero energy, since asymptotically the departure of the metric from flat space does not contain $1/r$ terms.

To estimate the rate of spontaneous decay in this channel, we follow the steps reviewed in section 2. In fact, one only has to distinguish between α and R^2. The result is

$$\Gamma/V \sim e^{-\frac{\pi R^2}{8G_4(1-8\pi R G_4 T_2)^2}} \,. \tag{5.5}$$

Note that this result is compatible with the test brane approximation of the same process. Indeed, in this approximation the correction in the exponent of Γ would be the Nambu-Goto action of the test brane with tension T_2 located at $r = \sqrt{\alpha}$ in the manifold (2.3). The Nambu-Goto action of the induced metric on the world-sheet of the brane (5.4) is $2\pi^2 R^3 T_2$. This is identical to the linear in $G_5 T_2$ term in the expansion of the exponent of (5.5).

6. Conclusion

We studied how the Kaluza-Klein vacuum - that is the space-time of the type $R^4 \times S^1$ - decays in the presence of branes. As it is natural to expect, the presence of branes generically facilitates the decay. The enhancement factor was computed, to exponential accuracy, first in the test brane approximation (when one neglects back reaction of the brane onto the gravity), as well as beyond the test brane approximation in the case of codimension 2 brane only. We also considered the possibility of having a codimension 2 brane (membrane) in the final state of the spontaneous decay of the Kaluza-Klein vacuum and estimated the rate of decay in this channel.

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