Ph.D. Dissertation

Study on Enhancement of Vacuum Decay in Higher-Dimensional Theory

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December, 2024

Abstract

String theory is widely regarded as a promising candidate for quantum gravity that naturally incorporates gravitational interactions. However, its vacuum structure is known to be extremely complicated. This complexity arises from the absence of a definitive guiding principle for compactifying extra dimensions in higher-dimensional theories. As a result, it has been suggested that an enormous number of vacua might emerge. In this scenario, transitions between vacua are expected to occur universally.

Many scenarios of vacuum decay are premised on the nucleation of bubbles in a homogeneous false vacuum. However, in nature, many examples are known where the presence of impurities catalyzes phase transitions. Similar phenomena have been observed in high-energy physics, where topological solitons or black holes can enhance phase transitions in the early universe. Since such impurities are expected to exist universally in realistic models involving symmetry breaking, examining the inhomogeneous nucleation of bubbles influenced by these impurities can be regarded as a more natural direction. Thus, when considering stringy vacuum decay in higher dimensions, there remains room to account for impurities and phenomena that can enhance decay. Such enhancement of decay is also intriguing from the perspective of formulating the mathematical conditions for effective theories coupled with gravity. In the bottom-up approach known as a Swampland program, various conjectures and constraints have been proposed based on empirical insights from grand unified theories and cosmology. Recent developments in the Swampland program suggest that dS vacua consistent with quantum gravity must, at least, be metastable and decay sufficiently quickly. Under this conjecture, most metastable vacua in low-energy effective theories are thought to be incompatible with quantum gravity. However, if contributions from impurities or singularities could enhance the instability of the system, it might be possible to construct UV-consistent de Sitter vacua within an effective theory. In light of these considerations, we discuss two objects, Dp-branes, and singular instantons, as potential objects for enhancing vacuum decay in higher-dimensional theories.

First, we discuss the enhancement of instability due to Dp-branes as a catalytic effect specific to string theory. Dp-branes are higher-dimensional objects in string theory, frequently utilized to construct metastable vacua. In this study, we construct a geometrically metastable vacuum by wrapping D5-branes and anti D5-branes on a higher-dimensional manifold with singularities. We also consider wrapping D3-branes in the internal space. These D3-branes dissolve into the domain wall D5-branes, forming bound states. We generalize the calculation method for the fluctuation operator and derive an exact 1-loop expression for the decay rate using the WKB approximation. Numerical calculations based on this expression confirm that, within a reliable parameter region for the approximation, increasing the number of D3-branes reduces the life-time of the metastable vacuum. Furthermore, we approximated the life-time in the limit where the potential barrier vanishes by applying results for an anharmonic oscillator and compared this with constraints imposed by the trans-Planckian censorship conjecture, one of the Swampland conjectures. As a result, we found that under reasonable assumptions about the size of the compactification space, the critical life-time can satisfy the constraints from the conjecture when the string coupling is less than $\mathcal{O}(1)$.

The second theme is the enhancement of the decay rate due to singularities in instanton solutions. Higher-dimensional vacua with compactified dimensions possess a non-perturbative decay channel where a literal "bubble of nothing," devoid of spacetime degrees of freedom, expands. The instanton solution mediating this decay corresponds to a Euclidean higher-dimensional black hole solution, which is known to exhibit a conical singularity at the location corresponding to an event horizon of the original black hole solution. In ordinary discussions, we impose a proper condition on the periodicity of the imaginary time to ensure smoothness at the horizon, resulting in an instanton spacetime without such singularities. However, since the crucial physical quantity in vacuum decay physics is the decay rate, instanton solutions with singularities may also be admissible if their contribution to the decay rate remains finite. In this study, we examine the decay mediated by singular instantons in the simplest higher-dimensional vacuum, the five dimensional Kaluza-Klein vacuum, and derive the contribution of the conical singularity to the bounce action based on the conical deficit regularization. The contribution from the singularity is negative, acting to reduce the bounce action. Our analysis demonstrates that decay mediated by singular instantons can indeed have a higher decay rate, potentially making it the dominant decay process. Additionally, we reconstruct the bounce action using thermodynamic functions and discuss the thermodynamic interpretation of how singularities in instanton solutions enhance the decay.

This thesis is based on the following papers:

- S. Tsukahara, "*Life-time of metastable vacuum in string theory and trans-Planckian censorship conjecture*," JHEP 10 (2023) 109, arXiv:2305.00781[hep-th].
- Y. Ookouchi, R. Sato and S. Tsukahara, "*Decay of Kaluza-Klein Vacuum via Singular Instanton*," arXiv:2404.13917[hep-th].

In addition, appendix also includes the study based on the following paper:

- S. Tsukahara, "*On Stabilization of Magnetically Charged Brane Shell and Over-extremality*," arXiv:2408.08798[hep-th].