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Bubble Collision in Curved Spacetime

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Abstract

We study vacuum bubble collisions in curved spacetime, in which vacuum bubbles were nucleated in the initial metastable vacuum state by quantum tunneling. The bubbles materialize randomly at different times and then start to grow. It is known that the percolation by true vacuum bubbles is not possible due to the exponential expansion of the space among the bubbles. In this paper, we consider two bubbles of the same size with a preferred axis and assume that two bubbles form very near each other to collide. The two bubbles have the same field value. When the bubbles collide, the collided region oscillates back-and-forth and then the collided region eventually decays and disappears. We discuss radiation and gravitational wave resulting from the collision of two bubbles.

Keywords: Vacuum Bubble, Collision, Curved Spacetime

1. Introduction

The expanding bubble as our expanding universe was first introduced in Ref. [1], in which the bubbles were defined regions between which no causal influence can ever pass, i.e. they are causally disconnected. One in a bubble can not see any other bubbles unless they collide.

The very first picture of an inflationary multiverse scenario [2] was proposed to get our universe without the cosmological singularity problem [3] using an interesting feature of self-reproducting or regenerating exponential expansion of the universe. However, the inflationary spacetimes have a fatal flaw, the spacetime cannot be made complete in the past direction [4], even though the universe is eternal into the future. Thus if we want to understand the origin of our universe we should make a mechanism for the universe with completion in the past direction and with a configuration of low entropy or the universe described as quantum tunneling from nothing [5, 6]. One can also consider a self-creating universe coming from the spacetime with a closed time loop [7].

The eternal inflationary scenario [8, 9, 10, 11] and the string theory landscape scenario [12, 13] were also combined with the multiverse scenario. The eternal inflationary scenario is related to the expanding sea of false vacuum with a positive cosmological constant. The region with the false vacuum state is continuously expanding, even the inflation is ended in one region. This means that the universe can be eternal into the future. The landscape has a huge number of stable or metastable vacua [14] originated from different choices of Calabi-Yau manifolds and generalized magnetic fluxes, in which each local minimum may correspond to the vacuum of a possible stable or metastable universe with different laws of low energy physics. All these above independent scenarios seem to succeed to our ambition of understanding the origin of our universe described in Ref. [1].

The nucleation process of a vacuum bubble has been studied for a long time. The process was first investigated in Ref. [15], developed in both flat [16] and curved spacetime [17, 18]. Other type of transition describing the scalar field jumping simultaneously onto the top of

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the potential barrier was investigated by Hawking and Moss [19] and later in Ref. [20]. As a special case of the true vacuum bubble, a vacuum bubble with a finite-sized background after nucleation was studied in Ref. [21]. The decay of false monopoles with a gauge group was also studied using the thin-wall approximation [22]. The bubble or brane resulting from flux tunneling was studied in a six-dimensional Einstein-Maxwell theory [23].

The mechanism for nucleation of a false vacuum bubble in a true vacuum background has also been studied within various contexts. Nucleation of a large false vacuum bubble in dS space was obtained in Ref. [24] and nucleation with a global monopole in Ref. [25]. The mechanism for nucleation of a small false vacuum bubble was obtained in the Einstein gravity with a nonminimally coupled scalar field [26] with the correction of an error term [27], with Gauss-Bonnet term in Ref. [28], and using Brans-Dicke type theory [29]. The classification of vacuum bubbles including false vacuum bubbles in the dS background in the Einstein gravity was obtained in Ref. [30], in which the transition rate and the size of the instanton solution were evaluated in the space, as the limiting case of large true vacuum bubble or large false vacuum bubble.

The collision of two vacuum bubbles in flat spacetime was discussed using analytic methods or numerical methods in Ref. [31]. One of the interesting points of colliding bubbles is that the colliding bubble may induce a vacuum transition [32] or a production of particles [33] using the colliding energy. Second, including gravitation, it is highly non-trivial to study the dynamics. We may use the thin-wall approximation [34][35]. In the study of Freivogel, Horowitz, and Shenker [36] (for more advanced review, see [37]), they discussed two colliding true vacuum bubbles in the de Sitter background: one is flat and the other is anti de Sitter. The analysis in itself is very concise and important, but this may not be able to describe the dynamics of fields on the colliding walls. For example, this cannot describe the vacuum transition behaviors. Hence, we may need further numerical studies.

There were some numerical studies of bubble collisions with gravitation. Very recently, Johnson, Peiris, and Lehner [38] succeeded in studying bubble collisions with gravitation beyond the thin-wall approximation. They assumed hyperbolic symmetry from the Birkhoff-like theorem of colliding bubbles and assumed initial data from the Coleman-DeLuccia type solutions. They could solve Einstein and field equations numerically and observe and report on symmetric/asymmetric bubble collisions and vacuum transitions. Soon after, the authors could do the numerical calculations of bubble collisions with gravity [39], by using double-null formalism [40], where we already applied this method to study general bubble dynamics [41] including semiclassical effects [42].

When the bubbles collide, the collided region oscillates back-and-forth and then the collided region eventually decays and disappears. We expect that radiations and gravitational waves are produced from the collision of two bubbles. The amount of gravitational radiation resulting from the collision of two true vacuum bubbles was numerically computed in Ref. [43] and the envelope approximation to calculate the gravitational radiation was introduced in Ref. [44].

The outline of this paper is as follows: In Sec. 2 we review the nucleation process of a vacuum bubble and the evolution after its materialization in flat Minkowski spacetime. In Sec. 3 we review the collision of two bubbles in the absence of gravity. In Sec. 4 we study bubble collision in the presence of gravity. We summarize and discuss our results in Sec. 5.

2. The Nucleation of a Vacuum Bubble and Evolution in Flat Minkowski Spacetime

In this work, we study the system with a scalar field governed by an asymmetric double-well potential. Thus the potential has two non-degenerate minima with lower minima at Φ_T, a true vacuum state, and higher minima at Φ_F, a false vacuum state. We assume that a system is initially in the false vacuum state $\Phi = \Phi_F$, i.e. the system has the energy density of the homogeneous and static scalar field everywhere in space. However, the field can inhomogeneously tunnel via the barrier separating the two vacua. That means the initial state is an unstable state, i.e. one whose energy has an imaginary part. The decay rate of the background vacuum state per unit volume and unit time has the form $\Gamma/V \simeq Ae^{-B}$. The prefactor A is evaluated from the Gaussian integral over fluctuations around the background classical solution and the leading semiclassical exponent $B = S^{cs} - S^{bg}$ is the difference between the Euclidean action corresponding to the classical solution S^{cs} and the background action S^{bg}.

We take Euclidean $O(4)$ symmetry($\eta^2 = \tau^2 + r^2$) for both Φ and the spacetime metric $g_{\mu\nu}$. The solution with the minimum Euclidean action is assumed to have the highest symmetry [45].

For the flat space the metric with $O(4)$ symmetry has the form

$$ds^2 = d\eta^2 + \eta^2[d\chi^2 + \sin^2\chi(d\theta^2 + \sin^2\theta d\phi^2)], \quad (1)$$