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Inflationary cosmology and the standard model Higgs with a small Hubble-induced mass

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ABSTRACT

We study the dynamics of the standard model Higgs field in the inflationary cosmology. Since metastability of our vacuum is indicated by the current experimental data of the Higgs boson and top quark, inflation models with a large Hubble parameter may have a problem: In such models, the Higgs field rolls down towards the unwanted true vacuum due to the large fluctuation in the inflationary background. However, this problem can be relaxed by supposing an additional mass term for the Higgs field generated during and after inflation. We point out that it does not have to be larger than the Hubble parameter if the number of *e*-folds during inflation is not too large. We demonstrate that a high reheating temperature is favored in such a relatively small mass case and it can be checked by future gravitational wave observations. Such an induced mass can be generated by, *e.g.*, a direct coupling to the inflaton field or nonminimal coupling to gravity.

1. Introduction

Recent results at the Large Hadron Collider (LHC) [1,2] are in excellent agreement with the Standard Model (SM) with a 125 GeV Higgs boson and thus far any significant deviation from the SM has not been reported. On the other hand, the current measurements of the Higgs and top quark masses [3] suggest the metastability of our vacuum [4–6] (see also Ref. [7]); the Higgs potential becomes negative typically at $h \gtrsim 10^{11}$ GeV [6]. It may be an important hint for high-energy physics.

One of the important ingredients in modern cosmology is inflation. It expands the primordial Universe at an accelerating rate. It solves the flatness and horizon problems and sows the seeds of the large scale structure of the present Universe. Within the current errors, there still remains a possibility of the SM-Higgs-driven inflation [8]. However, if the Higgs potential is negative at $h \gtrsim 10^{11}$ GeV, such Higgs inflation models cannot occur unless there is a physics beyond the SM that keeps the Higgs potential positive up to the inflationary scale because the Higgs field value during inflation is required to be larger than 10^{16-17} GeV in these models. In this paper, we assume that the electroweak vacuum is metastable and inflation is driven by a scalar field other than the SM Higgs field, called inflaton.

The current data suggests that the lifetime of the electroweak vacuum is longer than the age of the Universe [9], and there is no constraint on the reheating temperature from the thermal-fluctuation-triggered electroweak vacuum decay [4,5,10]. However, the vacuum fluctuation in the quasi-de Sitter background of the Higgs field during inflation may also push it to the unwanted Anti de Sitter (AdS) vacuum if the Hubble parameter during inflation is large, *e.g.*, as the recent BICEP2 result suggests [11].[1] Thus, it may spoil inflation or, at least, our Universe that lands in the metastable vacuum may be unlikely.[2] Therefore, low-energy scale inflation may be favored in this viewpoint, contrary to the BICEP2 result [11], as discussed in other recent literatures [15,16].[3]

As pointed out in Refs. [4,14,18], it can be avoided by supposing a coupling between inflaton and the SM Higgs field without giving any major effects on the dynamics of inflaton. This is because the coupling produces the “Hubble-induced mass” during inflation, which pushes the field value where the Higgs potential goes negative to a much larger value. In the case where the induced mass is much larger than the Hubble parameter [18] and the Higgs po-

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[1] The recent result of Planck [12] suggests that the signals that BICEP2 observed may mainly come from the dust foreground. But one cannot conclude it at least before Planck B-mode results.

[2] Note that there are still discussions whether it is catastrophe for cosmology or not [4,13,14].

[3] See also Ref. [17] for the gravitational wave background generated by the dynamics of the SM Higgs field after inflation.

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tential remains positive up to the Planck scale, the Higgs field is quickly pushed to the origin and its fluctuation is suppressed. Thus, the unwanted vacuum decay can be avoided even if the initial field value of the Higgs field is relatively large, $\sim 0.1 M_{\rm Pl}$ with $M_{\rm Pl}$ being the reduced Planck mass. Consequently, the electroweak vacuum can be naturally selected.

On the other hand, if the induced mass is smaller than the Hubble parameter, it seems to be difficult to suppress the quantum fluctuations and hence the vacuum decay cannot be avoided even if the Higgs field initially sits at the origin. In this paper, however, we point out that if the number of e-folds during inflation is not too large, we can construct a scenario with a high-scale inflation in which most part of the Universe can avoid the vacuum decay while the induced mass is not so large, as is also recently suggested in Ref. [14]. This is because the evolution of the expectation value of the Higgs field during inflation is suppressed and it can be than the field value of the potential barrier if the Hubble-induced mass m_H is large enough, $\Delta m_h^2/H_{\rm inf}^2 \gtrsim 2\times 10^{-2}$ and the number of e-folds during inflation is not too large. In addition, if the reheating temperature is high enough, the present Universe can be safely realized. Note that after inflation the Higgs field still slow-rolls and the time-dependent potential barrier may catch it up. The Higgs field will roll down towards the unwanted AdS vacuum in this case. If the Higgs field is thermalized before being caught up by the potential barrier, the Higgs field safely settles down to the electroweak vacuum. Owing to a relatively high reheating temperature, the Higgs field is thermalized earlier. Here we give a rough estimate for such a healthy scenario. We also point out that it would be possible to verify such a high reheating temperature by the future gravitational wave experiments.

2. Fluctuation of the Higgs field with a small induced mass during inflation

Let us start from the SM Higgs potential. At the large field values $h \gg v \equiv 246$ GeV, it is well described by

$$V(h) = \frac{1}{4}\lambda(h)h^4, \tag{1}$$

in the unitary gauge. The Higgs quartic coupling $\lambda(h)$ runs logarithmically with respect to h from $\lambda(M_h) \simeq 0.13$ where M_h is the Higgs mass. As is studied in Refs. [4–6,19], the Higgs quartic coupling becomes negative at $h \sim 10^{11}$ GeV. Though the uncertainties in the Higgs and top mass data lead to the uncertainty in the point where the potential goes negative ranging from 10^9 GeV to the Planck scale or higher, here we consider the case where the Higgs potential vanishes typically at 10^{11} GeV. Then, the Higgs potential has also a maximum or a "barrier" at $h = \Lambda_0 \sim 10^{11}$ GeV. If the Hubble parameter during inflation[4] $H_{\rm inf}$ is larger than Λ_0, the fluctuation of the Higgs field easily climbs up the potential barrier and rolls down to the unwanted true vacuum during inflation even when it initially sits at the origin [4,13–15]. It is claimed in Ref. [4] that the regions or the bubbles where the Higgs field falls into the unwanted true vacuum collapse due to the AdS instability and hence only the regions where the Higgs field is inside the potential barrier may remain. Consequently the metastable electroweak vacuum and high-scale inflation may be compatible.[5] However, it is not clear whether the Universe expands properly by inflation and the AdS bubble does not cause any cosmological disasters. In particular, if the AdS bubbles of the true vacuum "eat" the region where the present electroweak vacuum is selected, the existence of our Universe falls into a crisis. Therefore, we can say inflation with a relatively small Hubble parameter $H_{\rm inf} < \Lambda_0$ is safe in the light of the current data of the Higgs and top mass. It is contradictory to the recent BICEP2 result, which suggests $H_{\rm inf} \simeq 10^{14}$ GeV [11], if the observed B-mode is generated by the primordial gravitational waves.

As is pointed out in Refs. [4,14] and studied in detail in Ref. [18], the Higgs field can acquire a Hubble-induced mass due to its interaction with the inflaton ϕ. For example, the "Higgs-portal" coupling

$$\Delta V = \frac{1}{2}\kappa\phi^2 h^2 \tag{2}$$

with $\kappa > 0$ gives an effective positive mass squared $\kappa\langle\phi^2\rangle$ during and after inflation. Here the bracket represents the time average. In the case of massive chaotic inflation $V(\phi) = m^2\phi^2/2$, we have $3H_{\rm inf}^2 M_{\rm Pl}^2 = m^2\phi_{\rm inf}^2/2$ during inflation and $3\langle H^2\rangle M_{\rm Pl}^2 = m^2\langle\phi^2\rangle$ in the inflaton oscillation dominated era after inflation.[6] Thus, the effective Higgs mass squared is proportional to the Hubble squared both during and after inflation, $\Delta m_h^2 \simeq \kappa(M_{\rm Pl}/m)^2 H^2$. Note that in order for the quantum correction not to dominate the tree level potential, $\kappa \lesssim 10^{-6}$ is required [18].

A similar effect can be achieved by a non-minimal coupling of the Higgs field to gravity.[7] Suppose that the Einstein–Hilbert action is replaced by

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}\left(M_{\rm Pl}^2 + \xi h^2\right)R, \tag{3}$$

where g is the determinant of the metric, ξ is a negative parameter, and R is the scalar curvature. The effect of this term can be seen easily in the Einstein frame. By performing the conformal transformation and changing the frame to the Einstein frame, we get the effective Higgs potential as

$$\Delta V \simeq -\left(2V(\phi) - \frac{\dot\phi^2}{2}\right)\frac{\xi}{M_{\rm Pl}^2}h^2\left(1 + \mathcal{O}\left(\frac{\xi h^2}{M_{\rm Pl}^2}\right)\right). \tag{4}$$

During inflation we have $3H^2M_{\rm Pl}^2 \simeq V(\phi)$, and during inflaton oscillation dominated era after inflation we have $3H^2M_{\rm Pl}^2 = V(\phi) + \dot\phi^2/2$ with $\langle V(\phi)\rangle \simeq \langle\dot\phi^2\rangle/2$. Here we assumed that the inflaton oscillates in the quadratic potential around its potential minimum. Thus, the Higgs field acquires positive mass squared $-\gamma\xi H^2$ during and after inflation with γ being a parameter of order of $\mathcal{O}(1-10)$.

Motivated by the interactions discussed above, now we consider a simple modification of the Higgs potential during inflation,

$$\Delta V(h) = \frac{1}{2}c_{\rm inf}H_{\rm inf}^2 h^2 \tag{5}$$

with $c_{\rm inf}$ being a positive numerical parameter. Here we consider the case $c_{\rm inf} \lesssim \mathcal{O}(1)$ and study vacuum fluctuation in this potential. For $H_{\rm inf} \gg \Lambda_0$, the Hubble-induced potential overwhelms the original potential around $h \sim \Lambda_0$ and the potential barrier moves to a higher field value. In principle, we should calculate the running of the couplings to study the dynamics of the Higgs field. However, they vary only logarithmically with respect to h and hence

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[4] The subscript "inf" represents that the variable is evaluated at the inflationary era.

[5] See also the discussion in Ref. [14].

[6] Note that the kinetic energy and potential energy are equilibrated, $m^2\langle\phi^2\rangle/2 = \langle\dot\phi^2\rangle/2$, at the oscillating phase.

[7] Such a coupling is also studied recently in Ref. [16], where the running of the nonminimal coupling to gravity up to the electroweak scale is carefully studied. Since here we study the dynamics of the SM Higgs during and after inflation in detail, our study is complementary to Ref. [16].