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Electroweak vacuum stabilized by moduli during/after inflation

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ABSTRACT

It is known that the present electroweak vacuum is likely to be metastable and it may lead to a serious instability during/after inflation. We propose a simple solution to the problem of vacuum instability during/after inflation. If there is a moduli field which has Planck-suppressed interactions with the standard model fields, the Higgs quartic coupling in the early universe naturally takes a different value from the present one. A slight change of the quartic coupling in the early universe makes the Higgs potential absolutely stable and hence we are free from the vacuum instability during/after inflation.

1. Introduction

After the discovery of the 125 GeV Higgs boson [1,2], one of the interesting cosmological issues is the stability of the electroweak vacuum. If we take the center value of the measured top quark mass [3], the Higgs quartic coupling becomes negative at energy scale of $\sim 10^{10}$ GeV, and hence the present electroweak vacuum is metastable [4–14].[1] Although the lifetime of the present vacuum is much longer than the age of the universe, it is non-trivial whether or not the Higgs falls into unwanted deeper minimum in the early universe.

First let us suppose that there is no large effective mass term for the Higgs during inflation. During inflation, the infrared (IR) Higgs fluctuations develop. The typical amplitude of the quantum fluctuation generated during the one Hubble time is $\sim \mathscr{H}_{\rm inf}/2\pi$ with $\mathscr{H}_{\rm inf}$ being the Hubble scale during inflation. This process can be viewed as a classical random walk process [17]. As a result, after N e-foldings, the mean Higgs field value acquires

$$\sqrt{\langle h^2 \rangle} \simeq \sqrt{N}\frac{\mathscr{H}_{\rm inf}}{2\pi}, \tag{1}$$

where h is the field value of the physical Higgs boson. The classical motion overcomes this quantum noise for $h \gtrsim h_c$ where

$$h_c^2 = \frac{3\mathscr{H}_{\rm inf}^4}{8\pi^2 m_{\rm eff}^2(h_c)} \quad \leftrightarrow \quad h_c \simeq \frac{0.4\mathscr{H}_{\rm inf}}{\lambda^{\frac{1}{4}}}. \tag{2}$$

Here $m_{\rm eff}^2(h) = \lambda h^2$ is the effective mass of the Higgs with λ being the Higgs quartic coupling. This means that the natural value of the Higgs field value during inflation is

$$h \simeq \min\left[\sqrt{N}\frac{\mathscr{H}_{\rm inf}}{2\pi},\ h_c\right]. \tag{3}$$

Since the total e-folding number N must be larger than ~ 50, we can reasonably take $h \sim h_c$.

So far we have assumed that the Higgs quartic coupling λ is positive independently of the Higgs field value. However, it is actually indicated that λ becomes negative at high energy scale (which we denote by $h_{\rm max}$) due to the loop effect caused by the large top yukawa coupling.[2] It is clear that it leads to a disaster if $h_{\rm max} < h_c$: in this case the Higgs falls into the true vacuum during inflation and the present electroweak vacuum is never realized thereafter [18–24].

The vacuum instability during inflation is easily avoided by introducing a Higgs-inflaton and/or Higgs-curvature coupling like

$$V = cI^2|H|^2 \ \text{and/or}\ c'R|H|^2, \tag{4}$$

where I and R are the inflaton field and Ricci scalar, respectively and H denotes the Higgs doublet. These couplings generate large

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[1] It may be possible to make the electroweak vacuum absolutely stable by, *e.g.* introducing an additional Higgs portal singlet scalar which acquires a large vacuum expectation value. See Refs. [15,16].

[2] Later we will define $h_{\rm max}$ in a slightly different manner, but practically the precise definition is not important.

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mass terms for the Higgs field and hence the development of IR fluctuations can be suppressed. Even in this case, however, we must take care of the vacuum instability occurring *after* inflation, since these additional mass terms rapidly oscillate during the inflaton oscillation era and it leads to the resonant enhancement of the Higgs fluctuations. To avoid the catastrophe, upper bounds on these coupling constants are obtained [25–27]. Combined with the requirement of the vacuum stability during inflation, there is only a small window for the parameter region of these coupling constants.[3]

In this letter we propose a different approach for the issue of the vacuum stability during/after inflation. The crucial observation is that the Higgs quartic coupling in the early universe needs not coincide with that of the present value. In particular, it may depend on the value of some scalar field, ϕ, which we call moduli. Since the field value of moduli during/after inflation can be different from the present one, it is natural to expect that the quartic coupling in the early universe is also different from the present one. If the additional contribution to the quartic coupling is the same order as the present one, the absolute stability of the Higgs potential during/after inflation is ensured. As a specific example, we consider a moduli which has Planck-suppressed interactions with standard model (SM) fields, such as the string moduli appearing after the compactification of extra dimensions [63,64]. As we will show, even though the interactions are Planck-suppressed, they are enough to stabilize the Higgs in the very early universe successfully.

2. Electroweak vacuum stabilized by moduli

We consider a moduli field ϕ which has general Planck-suppressed interactions with SM fields. For the stability of the Higgs, the most important coupling is the moduli coupling to the Higgs:

$$V_h = \left(\lambda_0 + c_\lambda \frac{\phi - v_\phi}{M_P}\right)|H|^4, \tag{5}$$

where λ_0 is the present Higgs quartic coupling, c_λ is the coupling constant of $\mathcal{O}(1)$, v_ϕ is the present vacuum expectation value (VEV) of moduli and M_P is the reduced Planck scale. The potential of the moduli is assumed to be

$$V_\phi = \frac{1}{2}m_\phi^2(\phi - v_\phi)^2 + \frac{C_H^2}{2}\mathscr{H}^2\phi^2, \tag{6}$$

where $\mathscr{H}$ denotes the Hubble parameter, m_ϕ is the moduli mass and C_H is a coupling constant.[4] It ensures that in the early universe $\mathscr{H} \gtrsim m_\phi$, the moduli sits at $\phi \simeq m_\phi^2 v_\phi/(m_\phi^2 + C_H^2\mathscr{H}^2)$. When the moduli is displaced from the minimum v_ϕ, the effective quartic coupling is given by

$$\lambda(\phi) = \lambda_0 + c_\lambda \frac{\phi - v_\phi}{M_P}. \tag{7}$$

Here and in what follows the subscript 0 indicates that the quantity is evaluated at the present vacuum $\phi = v_\phi$. In particular, during/after inflation at which $C_H\mathscr{H} \gg m_\phi$ (and hence $|\phi| \ll v_\phi$), it is approximately given by

$$\lambda(\phi) \simeq \lambda_0 - \frac{c_\lambda v_\phi}{M_P} \equiv \lambda_0 - \xi_\lambda. \tag{8}$$

Since ξ_λ is naturally expected to be $\mathcal{O}(0.1\text{–}1)$, it significantly modifies the Higgs potential in the early universe and even the vacuum $H = 0$ can be absolutely stable.[5]

Not only the quartic coupling, but also the top yukawa coupling y_t is modified if the moduli has a coupling like

$$\mathscr{L} = \left(y_{t0} + c_y \frac{\phi - v_\phi}{M_P}\right)\overline{Q}_t \tilde{H} t_R + \text{h.c.}, \tag{9}$$

where y_{t0} is the present top yukawa coupling, Q_t is the left-handed top quark doublet, t_R is the right-handed top quark and c_y is a coupling constant of $\mathcal{O}(1)$. The effective top yukawa coupling is given by

$$y_t(\phi) = y_{t0} + c_y \frac{\phi - v_\phi}{M_P}. \tag{10}$$

Similarly to the quartic coupling, for $C_H\mathscr{H} \gg m_\phi$ it is approximately given by

$$y_t(\phi) \simeq y_{t0} - \frac{c_y v_\phi}{M_P} \equiv y_{t0} - \xi_y. \tag{11}$$

It is known that the Higgs potential is very sensitive to the top mass (or top yukawa) and even a few percent decrease of the top mass compared with the center value makes the Higgs potential absolutely stable (see *e.g.* [13]). Since ξ_y is naturally expected to be $\mathcal{O}(0.1\text{–}1)$, it can also significantly modify the Higgs potential in the early universe through the radiative correction.[6]

The gauge coupling constants can also be modified in a similar fashion by introducing the moduli couplings like

$$\mathscr{L} = -\left(1 + c_{g_i}\frac{\phi - v_\phi}{M_P}\right)\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a}. \tag{12}$$

For $\mathscr{H} \gg m_\phi$, the gauge couplings g_i, with $i = 1, 2, 3$ corresponding to the U(1), SU(2) and SU(3) gauge groups, become

$$\frac{1}{g_i^2(\phi)} \simeq \frac{1}{g_{i0}^2}\left(1 - \frac{c_{g_i} v_\phi}{M_P}\right) \equiv \frac{1}{g_{i0}^2}(1 - \xi_{g_i}). \tag{13}$$

All of these modifications of coupling constants by the moduli significantly affect the stability of electroweak vacuum in the early universe. For simplicity, below we consider non-zero ξ_λ and ξ_y only.[7]

We have calculated the effective potential of the Higgs at the one-loop order for non-zero ξ_λ and ξ_y according to Ref. [13],

$$V_h = \frac{\lambda_{\text{eff}}(h)}{4}h^4. \tag{14}$$

We have imposed the boundary condition (8) and (11) at the Planck scale and define $h_{\max}$ by $(\partial V_h/\partial h)_{h=h_{\max}} = 0$. We have cho-

[3] In addition, even if the resonant Higgs production does not cause the decay of the electroweak vacuum during the preheating stage, it could happen *afterwards*. This is because the cosmic expansion reduces the effective mass term induced by the Higgs-inflaton and/or Higgs-curvature coupling so that the Higgs fluctuations may eventually overcome the potential barrier. Thermalized population of other SM particles might save this situation, but it strongly depends on thermalization processes and further studies are required.

[4] Without loss of generality, we can shift the moduli field such that the Hubble mass term takes the form of $\sim \mathscr{H}^2\phi^2$ and the coupling constants coincide with the present values at the potential minimum $\phi = v_\phi$. We take this convention.

[5] We regard the potential as "absolutely stable" if the potential remains positive up to $h \simeq M_P$. See also Refs. [28,29] for possible effects of higher-dimensional Planck-suppressed operators on the vacuum stability.

[6] Flavor symmetry may suppress the coupling of the moduli to other SM quarks and leptons so that they are less important than the top yukawa coupling for the vacuum stability.

[7] The moduli may also couple to the Higgs kinetic term. However, such a coupling is translated into Eqs. (7) and (9) after canonically normalizing the Higgs for constant ϕ. Hence we neglect it here.