Higgs Inflaton Potential
in Higher-Dimensional SUSY Gauge Theories

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(Received March 23, 2009; Revised April 24, 2009)

We study the possibility that the Higgs and the inflaton are the same single field or
cousins arising from the extra space components of some higher-dimensional gauge field. We
take 5D supersymmetric gauge theory with a matter compactified on $S^1$ as a toy model and
evaluate the one-loop contribution to the Higgs-inflaton potential. Our gauge-Higgs-inflaton
unification picture applied to the gauge field of intermediate energy scale ($\sim 10^{13}$ GeV) can
explain the observed inflation parameters without fine-tuning.

Subject Index: 143, 172, 441, 442

Introduction Evaluation of the Higgs potential in the unified gauge theory en-
counters the fine-tuning problem in the coupling constants, so called gauge hierarchy
problem. There have been a few alternative solutions to this problem, technicolor
model, supersymmetry (SUSY) and later higher-dimensional gauge theory.1) Recently, people began to see that there
is an analogous fine-tuning problem in the evaluation of the inflaton potential,2),3) when they try to explain the cosmological
inflation parameters. Most models so far proposed have difficulty in explaining this
fine-tuning in a natural way as pointed out in 2).

Assuming that the 4D gauge theory is an effective field theory of the superstring
theory of some sort, there are only few origins of scalar fields. One is the extra space
components of higher-dimensional gauge fields in open string. We pursue the pos-
sibility that the two fine-tuning problems, one in the Higgs potential and the other
in the inflaton potential, are related and may be solved by assuming that the two
scalar fields have the same origin, i.e. the extra space components of gauge fields in
higher dimensional theory.

To study this view we take 5D $\mathcal{N} = 1$ supersymmetric $SU(2)$ gauge theory
with a matter multiplet compactified on $S^1$ as a toy model, and denote the gauge field
by $A_M$ ($M = 0, \cdots, 3, 5$). We identify the zero mode of its 5th component $A_5^{(0)}$
as the Higgs and the inflaton $\phi$. Here we take $SU(2)$ as the simplest non-Abelian
gauge group; the extension to other gauge groups should be easy. To have SUSY
breaking in 5D supersymmetric theory the Scherk-Schwarz mechanism4) is the most
economical one, which we will use and we evaluate the one-loop contribution to the
Higgs-inflaton potential. This way we also study the role of supersymmetry breaking in the two fine tuning problems. Arkani-Hamed et al. already pointed out the reliable perturbative computation of the potential in higher-dimensional gauge theories.² The same remark should apply to supersymmetric models as well.

The parameters of the model are fixed such that the conditions for inflation are met. The gauge coupling constant $g$ turns out to be as large as 0.9, being close to the realistic value of the gauge coupling constant. This gratifying result may be by chance but looks encouraging to us.

The model and one-loop effective potential We consider 5D $\mathcal{N} = 1$ $SU(2)$ super Yang-Mills (SYM) theory compactified on $S^1$. In five dimensions, the vector multiplet consists of the gauge field $A_M (M = 1, \cdots, 5)$, symplectic-Majorana spinors $\lambda_i^A (i = 1, 2)$ and a real scalar $\Sigma$. A hypermultiplet matter consists of complex scalar fields $H_i$ and a Dirac fermion $\Psi = (\Psi_L, \Psi_R)^T$. $\lambda_i^A$ and $H_i$ are doublets of the $SU(2)_R$ symmetry. The Lagrangian is given by the sum of two terms,⁵

$$
\mathcal{L}^{gauge} = \text{Tr} \left[ -\frac{1}{2} (F_{MN})^2 + (D_M \Sigma)^2 + i\bar{\lambda}_i \gamma^M D_M \lambda_i - \bar{\lambda}_i \left[ \Sigma, \lambda_i^A \right] \right],
$$

$$
\mathcal{L}^{matter} = |D_M H_i|^2 - m^2 |H_i|^2 + \bar{\Psi} (i \gamma^M D_M - m) \Psi - (i \sqrt{2} g_5 H_i \bar{\lambda}_i \Psi + \text{h.c.}) - g_5 \bar{\psi} \Sigma \psi - g_5 m H^\dagger \Sigma H_i - \frac{g_5^2}{2} \sum_{a,A} [H^\dagger (\sigma^a)^j T^A H_j]^2,
$$

where $m$ is the matter mass and $g_5$ is the 5D gauge coupling constant. The covariant derivative acting on the fundamental representation is defined as $D_M H^i \equiv \partial_M H^i - ig_5 A_M H^i$. $\sigma^a (a = 1, 2, 3)$ and $T^A (A = 1, 2, 3)$ are Pauli matrices belonging to the $SU(2)_R$ and the gauge group $SU(2)$, respectively.

After compactification on $S^1$, the 5th component $A_5^{(0)}$ of the zero modes $A_5^{(0)}$ is a 4D scalar. We denote the 5D coordinate by $x^M = (x^\mu, y)$. We identify $A_5^{(0)}$ with the inflaton field $\phi$, as will be discussed later. To have nonzero effective potential for $A_5^{(0)}$, SUSY has to be broken. A few ways of SUSY breaking are known. A natural way in the 5D theory is the Scherk-Schwarz mechanism⁴ associated with $SU(2)_R$ symmetry. We employ twisted boundary conditions for $\lambda^i$ and $H^i$ in the $S^1$ direction $y$.

$$
\lambda_i (x^\mu, y + 2\pi R) = (e^{i \beta a \sigma^a})_i^j \lambda_j (x^\mu, y) \quad \text{same for } H^\dagger.
$$

$R = L/2\pi$ is the $S^1$ radius and $\beta^a$ is the SUSY breaking parameter. We will later use $\beta = \sqrt{\beta^a \beta^a}$.

To evaluate the effective potential, we allow $A_5^{(0)}$ to have VEV of the form

$$
\langle A_5^{(0)} \rangle = \frac{1}{g_5 L} \begin{pmatrix} \theta & 0 \\ 0 & -\theta \end{pmatrix}.
$$

$\theta$ is a constant given by the Wilson line phase, $\text{diag} (\theta, -\theta) = g_5 \int_0^L dy \langle A_5^{(0)} \rangle$. We consistently set the VEV of the scalar fields $\Sigma$ and $H^i$ to zero. We study the effective
potential for $\theta$, $V(\theta)$. The one-loop terms can be easily computed in the background field method. The result is obtained in the same way as\(^6\)

$$V_{\text{gauge}}(\theta) = -\frac{8\Gamma\left(\frac{5}{2}\right)}{\pi^{5/2}} \frac{1}{L^4} \sum_{n=1}^{\infty} \frac{1}{n^{5/2}} \left(1 + \cos(2n\theta)\right)(1 - \cos(n\beta)) + \text{const}, \quad (5)$$

$$V_{\text{matter}}(\theta) = 2\sqrt{2} \frac{\pi^{5/2}}{\pi^{5/2}} \sum_{n=1}^{\infty} \left(\frac{m L}{n L}\right)^{5/2} \left(1 + \frac{3}{m L} + \frac{3}{(m L)^2}\right)\right) \left(1 - \cos(n\beta)\right) + \text{const}. \quad (6)$$

There are divergent constant terms, which we will later renormalize to the appropriate value. $V_{\text{gauge+matter}}(\theta)$ has minima at $\theta = \pi + 2\pi k$ and maxima at $\theta = \pi/2 + 2\pi k$ ($k$ = integer).

The leading term ($n = 1$) is already a good approximation in (5) (see Fig. 1) and (6).

$$V_{\text{gauge}}(\theta) \simeq -\frac{6}{\pi^2} \frac{1}{L^4} (1 + \cos(2\theta))(1 - \cos \beta) + \text{const}, \quad (7)$$

$$V_{\text{matter}}(\theta) \simeq 2\frac{1}{\pi^2} \frac{1}{L^4} \left((mL)^2 + 3mL + 3\right) e^{-mL} \cos \theta (1 - \cos \beta) + \text{const}. \quad (8)$$

The gauge and matter parts have the same $\beta$ dependence, but have different periodicity in $\theta$. They have different sign for $\theta \leq \pi/2$ and the same sign for $\pi/2 \leq \theta$. They tend to cancel each other for $\theta \leq \pi/2$. A heavy hypermultiplet $(m \gg 1/L)$ does not contribute to $V(\theta)$ due to factor $e^{-mL}$.

From now on we consider the theory near one of the potential minima $\theta_0$, and set

$$\theta(x^\mu) = \theta_0 + \omega(x^\mu). \quad (9)$$

The 4D effective Lagrangian for the field $\omega$ is

$$\mathcal{L} = \frac{1}{2} f^2(\partial_\mu \omega)^2 - V_{\text{gauge+matter}}(\omega + \theta_0). \quad (10)$$
Here \( f \) is related to the Higgs-inflaton mass (see (25)),
\[
f = \frac{1}{2\pi gR},
\]
where \( g = g_5/\sqrt{L} \) is the 4D gauge coupling constant.

**Gauge hierarchy and inflation**

We consider the possibility that the Higgs and the inflaton are the same field \( \phi \) and identify them with \( A_5^{(0)} \). We study the question of whether the fine-tuning problem in the inflaton potential may be solved in this view. We set
\[
\phi = \omega f.
\]
\( \omega \)

We begin by recapitulating the implication for the inflaton potential from the recent astrophysical data\(^7\),\(^8\)

1. We choose the renormalization of the effective potential \( V \) so that it satisfies, \( V|_{\text{min}} = 0 \), in accordance with the nearly zero cosmological constant \( \Lambda \approx 10^{-12} \text{(eV)}^4 \).
2. The slow-roll conditions
\[
\epsilon \equiv \frac{1}{2} M_P^2 \left( \frac{V''}{V} \right)^2 \ll 1, \quad \eta \equiv M_P^2 \frac{V''}{V} \ll 1,
\]
where \( M_P = 2.4 \times 10^{18} \text{ GeV} \) is the reduced Planck mass, and \( V' = dV/d\phi \).
3. The spectral index \( n_s \)
\[
n_s \equiv 1 - 6\epsilon + 2\eta, \quad 0.948 \leq n_s \leq 0.977,
\]
taking account of the latest five-year WMAP data\(^8\). This condition is satisfied if \( \epsilon, \eta \sim 0.01 \).
4. The number of e-foldings \( N \)
\[
N \equiv \int_{t_i}^{t_f} H dt \simeq \frac{1}{M_P^2} \left| \int_{\phi_i}^{\phi_f} \frac{V}{V'} d\phi \right|.
\]
The second equality holds true under the slow-roll condition. For solving the flatness and the horizon problems the observable inflation\(^*\) must occur for a sufficiently long time, namely \( N \) has to be 50 – 60. The Hubble parameter \( H \) is integrated over the observable inflation period; \( t_i \) is the time when the observable Universe leaves the horizon and is determined by the conditions (13) and (15). \( t_f \) is the time when the slow-roll condition ends, namely when \( \epsilon \) and \( \eta \) become nearly 1. \( \phi_i \) and \( \phi_f \) are the values of \( \phi \) at \( t_i \) and \( t_f \).
5. The curvature perturbation \( \delta_H \) is written in terms of \( V \) (see for instance Ref. 7)). Substituting its experimental value\(^8\) into \( \delta_H \),
\[
\delta_H = \frac{1}{5\sqrt{6\pi} M_P^2 \epsilon^{1/2}} = 1.91 \times 10^{-5}.
\]
\( \delta_H \)

\( * \) Inflation can be investigated by observations only after the observable Universe has left the horizon. This era of inflation is called the observable inflation.
6) Quantum gravity effects can be neglected if the $S^1$ compactification scale $L$ is larger than the Planck length $1/M_P$.\(^9\)

$$R \gtrsim 3 \cdot (16\pi^2 M_P)^{-1} \simeq 0.78 \times 10^{-20} \text{ GeV}^{-1}. \quad (17)$$

$V$ appearing in (16) and (14) is understood to be its value at $\phi = \phi_*$, the value of $\phi$ related to the epoch $t_*$ of horizon exit for a certain length scale, and in practice $\phi_* \simeq \phi_i$. See Ref. 7) for the precise definition of $\phi_*$.  

In our 5D model the inflaton is the Higgs $h$ itself, hence $m_{\phi}^2 = m_h^2$. We wish to see whether the two fine-tuning problems can be solved simultaneously in our view. In applying our idea to unified theories, we will see that the $m_{\phi}$ is fixed by the value of $\delta_H$ through (16).

We study whether the conditions for inflation summarized above are met for reasonable values of $g$, $R$ and $\beta$. We consider two 5D supersymmetric models, (i) model of pure SYM and (ii) model of SYM + one hypermultiplet. We take the $n = 1$ approximation (7) and (8) to $V(\phi/f)$. For the case (ii), the size of $V_{\text{matter}}$ changes slightly for different values of matter mass $m$ in the range $m \lesssim 2/L$. We will take $m = 1/L$ as its typical value. We will see that the two models yield similar results.

Before proceeding to the analysis of our model we note that the potential $V$ as a function of $\phi$ differs depending on the value of $f$. The potential in the model of pure SYM is shown for two typical values of $f$, $50 M_P$ (broken line) and $10 M_P$ (solid line) in Fig. 2. The region of observable inflation, $\phi_f \leq \phi \leq \phi_i$, is shown as the shaded area in the latter case. $\phi_i$ is determined from the condition (15), and it is $16 M_P$ and $13 M_P$ in the two cases. Note that $V \sim \phi^2$ is a good approximation for the dashed line whereas the $V \sim 1 - \cos(2\phi/f)$ should be used for the solid line.

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**Fig. 2.** The inflaton potential in the case (i) for two values of $f$. The shaded area represents the region of observable inflation.
(i) Pure SYM

In accordance with the condition 1) we set

\[ V(\phi/f) \equiv V_{\text{gauge}}(\phi/f) - V_{\text{gauge}}(0) = \frac{6}{\pi^2} \frac{1}{L^4} (1 - \cos(2\phi/f))(1 - \cos \beta). \] (18)

\( \epsilon \) and \( \eta \) are given in terms of \( \phi \) as

\[ \epsilon = 2 \left( \frac{M_P}{f} \right)^2 \frac{1 + \cos(2\phi/f)}{1 - \cos(2\phi/f)}, \quad \eta = 4 \left( \frac{M_P}{f} \right)^2 \frac{\cos(2\phi/f)}{1 - \cos(2\phi/f)} \] (19)

The conditions 2) – 4) are met if \( f^2 \gg M_P^2 \) (\( f \gg 10 M_P = 2.4 \times 10^{19} \text{ GeV} \)), and hence

\[ gR \lesssim 6.6 \times 10^{-21} \text{ GeV}^{-1}. \] (20)

The condition 5) from \( \delta_H \) gives a relation between \( R \) and \( \beta \). Then the equality is satisfied if

\[ R^2 = 4.7 \times \sqrt{1 - \cos \beta} \times \left( \frac{1 - \cos(2\phi_*/f)}{\epsilon} \right)^{1/2} \times 10^{-36} \text{ GeV}^{-2}. \] (21)

The values of \( R \) are constrained by (17) and (21).

\[ 0.8 \times 10^{-20} \text{ GeV}^{-1} \lesssim R \]

\[ = 2.2 \times (1 - \cos \beta)^{1/4} \times \left( \frac{1 - \cos(2\phi_*/f)}{\epsilon} \right)^{1/4} \times 10^{-18} \text{ GeV}^{-1}. \] (22)

Note that the lower bound is from a theoretical consideration whereas the equality on the right side is derived from the data on \( \delta_H \). Rather small values of \( \beta \) are implied in order that the inequality (22) makes sense.

\[ \cos \beta \lesssim 1 - 1.7 \times \left( \frac{\epsilon}{1 - \cos(2\phi_*/f)} \right) \times 10^{-10}. \] (23)

The allowed values of \( g \) are found by combining (17) and (20).

\[ g \lesssim 0.85. \] (24)

The parameters \( g, R \) and \( \beta \) are further related to each other so that the inflaton mass \( m_\phi \) is reproduced. We have from (18)

\[ m_\phi^2 = 6 \frac{1 - \cos \beta}{\pi^4} \frac{g^2}{R^2}. \] (25)

The Higgs-inflaton potential we have constructed from higher-dimensional gauge theories is meant to be a toy model. Nevertheless it is curious to see whether this simple inflaton model has some realistic meaning in the context of GUT or other unified models.
We first recall that the $m_\phi$ is constrained severely by the value of $\delta_H$ through (16). The $m_\phi$ turns out to differ a bit depending on whether we take the quadratic function or the exact cosine function for the potential $V$. For large values of $f$ ($f \gg 10 M_P$) the potential (18) is approximated by the quadratic term (case II). Then the model is reduced to the time-honored chaotic potential. In this case the known result can be used, $m_\phi = 1.8 \times 10^{13} \text{ GeV}$.

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Using the equality of (20), (25) and (26), we get $m_\phi = 1.3 \times 10^{13} \text{ GeV}$. The results in both the cases imply that our Higgs-inflaton may be connected to some intermediate symmetry breaking in GUT, such as $SO(10)$ model.

We now apply our Higgs-inflaton model to gauge theories for two typical values of $f$.

I) $f = 10 M_P$. The potential $V(\phi/f)$ should be treated as the cosine function. Using $m_\phi \sim 1.3 \times 10^{13} \text{ GeV}$, we have

$$\frac{1}{R^2} \sqrt{1 - \cos \beta} = 8.9 \times 10^{33} \text{ GeV}^2.$$  \hspace{1cm} (26)$$

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II) $f = 100 M_P$. The potential $V(\phi/f)$ can be approximated by the quadratic term. The same argument as (18) through (25) applies to this case. Using $m_\phi \sim 1.8 \times 10^{13} \text{ GeV}$, we find the following values of the parameters.

$g \simeq 0.9 - 0.0005, \quad R \simeq (8 \times 10^{-21} - 1 \times 10^{-17}) \text{ GeV}^{-1}, \quad \beta \simeq 8 \times 10^{-5} - 3.$  \hspace{1cm} (28)$$

It is of interest to compare the 4D gauge coupling constant $g$ with the realistic value, $g_{GUT} = 0.7$ in the SUSY $SU(5)$ GUT. Curiously, in the case I the upper value of $g$ has turned out to be close to $g_{GUT}$. On the other hand, in the case II the value of $g$ is one tenth of $g_{GUT}$.

(ii) SYM + a hypermultiplet

The sum of the gauge part and the matter part, $V(\theta) = V_{\text{gauge}} + V_{\text{matter}}$, has the periodicity $2\pi$ as shown in Fig. 3. It has a minimum at two points, $\theta_0 = 0$ and $\pi$. The latter is the true minimum. In Fig. 3, taking account of the condition 1), we have set

$$V(\phi/f) = V_{\text{gauge+matter}}(\phi/f + \pi) - V_{\text{gauge+matter}}(\pi)$$

$$= \left[ 6(1 - \cos(2\phi/f)) + 14e^{-1}(1 - \cos(\phi/f)) \right] \frac{1}{\pi^2L^4} \sqrt{1 - \cos \beta}. \hspace{1cm} (30)$$
The inflaton mass is now given by

$$m_\phi^2 = 7.3 \left(1 - \cos \beta \right) \frac{g^2}{R^2} \pi^4.$$  \hfill (31)

Note that the numerical coefficient is now 7.3 in place of 6 in (25) in the model of pure SYM. The main difference between the model of SYM + matter and the pure SYM model comes from the value of $V(\phi_*/f)$. The effect of including a matter amounts to the change of $V(\phi_*/f)$ by a factor less than 2. As a result, the estimate of the parameters $g$, $R$ and $\beta$ proceeds in the same way as in (i). We obtain almost the same results as (28) and (29) for the cases I and II. The previous comments on the physical meaning of our model applied to the Higgs of intermediate energy scale in GUT hold true.

**Discussion**

To construct an inflation model which meets the condition of slow-roll and tiny curvature perturbation without fine tuning the potential is an urgent problem in early cosmology. In higher-dimensional gauge theory small (in size) and flat potential of scalar fields arises naturally through loop corrections. It is interesting to see if the two fine-tuning problems, one in the inflaton model and the other in gauge symmetry breaking, are solved simultaneously in this view. We have studied the one-loop inflaton potential in 5D SYM theory as a toy model for this mechanism.

An inflaton potential with the desirable properties is obtained for reasonable values of the parameters of the 4D gauge theory, if we apply our picture to a gauge theory of intermediate energy scale ($m_\phi \sim 10^{13}$ GeV). Curiously, the inflaton mass is lower than $f$ ($\gtrsim M_P$) by several orders. This is due to the tiny SUSY breaking factor, $\beta \ll 1$. $m_\phi$ and $f$ are related by

$$m_\phi \sim g^2 \beta f,$$  \hfill (32)

(see (25)). Adding a small number of matter multiplets will not affect the conclusion significantly.

We note that the region of observable inflation lies in the range $|\phi| > M_P$ in Fig. 2. Many of the inflation models proposed in the past\textsuperscript{10,11} possess this
property. However their perturbative computation may not be trusted, because quantum gravity and other non-perturbative effects may upset the results. Arkani-Hamed et al.\textsuperscript{2)} have pointed out that in higher-dimensional gauge theories no higher dimensional operators containing quantum gravity and other non-perturbative effects may be generated due to the gauge invariance in higher dimensions. Our results of inflaton potential using the region of large $|\phi|$ can thus be trusted.

We may take a gauge theory in dimensions more than five. Then the Higgs and inflaton may be identified with different component of $A_M$; they are cousins rather than a single field. It is an interesting attempt to try to build a realistic model of Higgs and inflaton in this view.

An alternative to the present approach is to identify the inflaton as the extra space components of the metric $g_{MN}$ instead of that of gauge field. In the context of string, this corresponds to considering closed string instead of open string. There have been some works in this direction.\textsuperscript{12)}

Acknowledgements

It is our pleasure to thank Nobuhito Maru for a valuable discussion at many stages of this work. T. I. wishes to thank Yuji Tachikawa for directing his interest to inflation models. We wish to thank Shinji Mukohyama and Chia-Min Lin for valuable discussions. We also wish to thank Pei-Ming Ho and Wen-Yu Wen for their kind hospitality and discussions during our visit to Taiwan University. We thank the referee for pointing out the relation between the inflaton mass and $\delta H$, which has led to a significant improvement of the paper. This work is supported partially by the grants for scientific research of the Ministry of Education and Science, Kiban A, 18204024, Kiban B, 16340040 and Kiban C, 21540278 and by a Chuo University Riko-ken grant.

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