Electroweak inflation and reheating in the NMSSM

Takeshi Fukuyama†, Tatsuru Kikuchi‡ and Wade Naylor†
Department of Physics, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan
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A low reheating temperature is now well motivated by the recently reconsidered gravitino problem, if we incorporate supergravity. In this article, we propose a model which naturally realizes a low reheating temperature. The model is based on the next to minimal supersymmetric standard model (NMSSM) by identifying a singlet scalar field as the inflaton. This entertains the possibility that the inflaton may be detected at future colliders, such as the LHC.

Keywords: Beyond the Standard Model, Inflation

I. INTRODUCTION

The supersymmetric (SUSY) extension of the standard model (the MSSM) is one of the most promising ways to solve the gauge hierarchy problem in the standard model [1]. Though introducing supersymmetry into the Standard Model solves a lot of problems which could not be solved in the Standard Model, some still remain some. In confrontation with cosmology we have unnecessary thermal relics: the moduli, gravitino, and so on. These would ruin a successful prediction of the photon number density at the recombination era in the standard Big Bang cosmology.

However, if thermalization occurs at a sufficiently low scale we have no such unnecessary thermal relics. Hence, we are driven to construct a model with a low reheat temperature. Though there have been some studies on low reheat temperature models [2] the reheat temperature was just put in by hand. However, in this letter we shall attempt to realize it by using a non-perturbative mechanism, instant preheating [3].

On the other hand, there is another problem in the MSSM: the so called $\mu$ problem, arising from SUSY preserving mass terms for the Higgs fields in the superpotential, $\mu H_u H_d$ [4]. If the MSSM is viable at the (reduced) Planck scale, $M_P \simeq 2.4 \times 10^{18}$ GeV, the $\mu$ parameter is naturally expected to lie at the Planck scale. However, the $\mu$ parameter should be at the electroweak scale to provide the correct mass scale for the gauge bosons. This may be solved by adding an additional singlet to the MSSM: the next to minimal supersymmetric standard model (NMSSM) [3, 5, 6].

In this letter, we shall discuss inflation in the NMSSM, especially with regard to realising a low reheating temperature. For some related work in the $\phi$NMSSM model, see [7].

II. THE NMSSM

This model uses the following set of Higgs fields having the indicated $SU(2)_L \times U(1)_Y$ charges,

$$H_d = \begin{pmatrix} H^0_d \\ H^+ \end{pmatrix} \sim (2, 1), \quad H_u = \begin{pmatrix} H^+ u \\ H^0_u \end{pmatrix} \sim (2, -1),$$

$S \sim (1, 0)$

and we use the following superpotential for the Higgs fields to describe the effective theory below the Planck scale

$$W = \lambda_S H_u \cdot H_d + \frac{1}{3} \kappa_S S^3,$$

where the product of the $SU(2)$ doublets are defined by, e.g.

$$H_u \cdot H_d \equiv H^+_u H^- - H^0_u H^0_d.$$

For the soft SUSY breaking terms for the Higgs fields we take

$$- \mathcal{L}_{\text{soft}} = m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2 + m^2_S |S|^2 + \lambda A_S S H_u \cdot H_d + \frac{1}{3} \kappa_A S^3 + h.c.$$  

It is a well known fact that the superpotential [2] has a discrete $Z_3$ symmetry, which would be at odds with cosmology by producing unwanted topological defects if this $Z_3$ symmetry is local and spontaneously broken. However, here we shall assume it just a global symmetry.

After developing a vacuum expectation value (VEV) for $S$, we obtain a natural explanation for the electroweak scale $\mu$-term,

$$\mu_{\text{eff}} \equiv \lambda \langle S \rangle \sim M_Z.$$  

From the Higgs part of the superpotential [2] and taking the $D$-term contributions into account, we obtain the following Higgs potential,
The VEV of the singlet $\lambda$ contains the soft SUSY breaking terms. To obtain the vacuum condition, we take the Higgs fields at the potential minimum to be

$$\langle H_d \rangle = \begin{pmatrix} v \cos \beta \\ 0 \end{pmatrix}, \quad \langle H_u \rangle = \begin{pmatrix} 0 \\ v \sin \beta \end{pmatrix}, \quad \langle S \rangle = s,$$

where $v = 174$ [GeV].

From this vacuum condition, we obtain three relations, linking the three soft mass parameters to the three VEV’s of the Higgs fields.

$$m_{H_u}^2 = \begin{pmatrix} \frac{g^2 + g^2}{4} v^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta \\ (A_\lambda + \kappa s) \lambda s \cot \beta - \lambda^2 s^2 \end{pmatrix},$$

$$m_{H_d}^2 = \begin{pmatrix} \frac{g^2 + g^2}{4} v^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta \\ (A_\lambda + \kappa s) \lambda s \cot \beta - \lambda^2 s^2 \end{pmatrix},$$

$$m_S^2 = -2\kappa^2 s^2 - \lambda^2 v^2 + \kappa \lambda v^2 \sin 2\beta + \lambda A_\lambda \frac{v^2 \sin 2\beta}{s} - \kappa A_\lambda s.$$

The VEV of the singlet $S$ in the exact SUSY limit can easily found by setting $m_S = 0$ with $A_\kappa = A_\lambda = 0$:

$$s^2 = \frac{\lambda v^2}{2\kappa^2} (-\lambda + \kappa \sin 2\beta)$$

and hence,

$$\mu_{\text{eff}} = \frac{\lambda^3 v^2}{2\kappa^2} (-\lambda + \kappa \sin 2\beta)^{1/2} \sim v.$$

So, if we have both parameters $\lambda$ and $\kappa$ of order one, $\lambda \sim \kappa \sim 1$, we can find a solution to the $\mu$ problem.

The mass matrices of the Higgs fields can be read off from the above potential by expanding the Higgs fields around their minima. For the charged Higgs fields, we have

$$H^{-} = H^{-} \sin \beta - G^{-} \cos \beta, \quad H^{+} = H^{+} \cos \beta + G^{+} \sin \beta,$$

where $G^{\pm}$ become would-be Goldstone bosons. For the neutral Higgs fields, we have

$$\Im(H'd) = \frac{1}{\sqrt{2}} (P_1 \sin \beta - G^0 \cos \beta),$$

$$\Im(S) = \frac{P_2}{\sqrt{2}}.$$

where $G^0$ becomes a would-be Goldstone boson, and

$$\Re(H'd) = v \cos \beta + \frac{1}{\sqrt{2}} (-S_1 \sin \beta + S_2 \cos \beta),$$

$$\Re(H'u) = v \sin \beta + \frac{1}{\sqrt{2}} (S_1 \cos \beta + S_2 \sin \beta),$$

$$\Re(S) = s + \frac{\sigma}{\sqrt{2}}.$$

Then, the charged Higgs mass spectra can explicitly be written since they are already in their mass eigenstates.

$$M_{H^\pm}^2 = M_A^2 + M_Z^2 - \frac{1}{2} (\lambda v)^2,$$

$$M_A^2 = \frac{\lambda s}{\sin 2\beta} (\kappa s + \sqrt{2} A_\lambda).$$

The neutral Higgs fields $P_1$, $P_2$ and $S_i$ ($i = 1, 2, 3$) are not in their mass eigenstates. Their mass matrices are given as follows. For the Higgs fields $P_1$, $P_2$,

$$(M_P^2)_{11} = M_A^2,$$

$$(M_P^2)_{12} = \frac{1}{2} (M_A^2 \sin 2\beta - 3\lambda \kappa s^2) \left(\frac{v}{s}\right),$$

$$(M_P^2)_{22} = \frac{1}{4} (M_A^2 \sin 2\beta + 3\lambda \kappa s^2) \left(\frac{v}{s}\right)^2 \sin 2\beta - \frac{3}{\sqrt{2}} \kappa s A_\kappa,$$

and for the Higgs fields $S_i$ ($i = 1, 2, 3$),

$$(M_S^2)_{11} = M_A^2 + \left(M_Z^2 - \frac{1}{2} (\lambda v)^2\right) \sin 2\beta,$$

$$(M_S^2)_{12} = -\frac{1}{2} \left(M_Z^2 - \frac{1}{2} (\lambda v)^2\right) \sin 4\beta,$$

$$(M_S^2)_{13} = -\frac{1}{2} \left(M_A^2 \sin 2\beta - \kappa \lambda s^2\right) \left(\frac{v}{s}\right) \cos 2\beta,$$

$$(M_S^2)_{22} = M_Z^2 \cos 2\beta + \frac{1}{2} (\lambda v)^2 \sin 2\beta,$$

$$(M_S^2)_{23} = \frac{1}{2} \left(2\lambda^2 s^2 - M_A^2 \sin 2\beta - \kappa \lambda s^2 \sin 2\beta\right) \left(\frac{v}{s}\right),$$

$$(M_S^2)_{33} = \frac{1}{4} M_A^2 \sin 2\beta \left(\frac{v}{s}\right)^2 + \kappa \lambda s^2 + \frac{1}{\sqrt{2}} \kappa s A_\kappa - \frac{1}{4} \lambda \kappa v^2 \sin 2\beta.$$

From here, we see that the lightest (neutral) Higgs boson mass is bounded by

$$m_h^2 \lesssim M_Z^2 \cos^2 2\beta + (\lambda v)^2 \sin^2 2\beta,$$

which relaxes the tree level MSSM upper bound, $m_h^2 \lesssim M_Z^2 \cos^2 2\beta$. For a detailed calculation tool for all the Higgs mass spectra in the NMSSM open source code can be found in [8].
III. INFLATION AT THE ELECTROWEAK SCALE

We shall now consider how to construct an electroweak scale inflation model, which can avoid the gravitino problem in local SUSY models [10]. For previous works on such model building, see [10, 11, 12, 13, 14, 15, 16].

Our model of low scale inflation is based on the NMSSM, and hereafter, we regard \( S \) as a Higgs field, providing a natural explanation for the \( \mu \) term, as the inflaton field. One major reason being that “inflaton-Higgs mixing” [16] occurs in this model and thus, the inflaton itself might be detectable at a collider, e.g. the LHC.

Let us remind the reader that the scalar potential for inflation, the so called flatness and the slow-roll conditions. These can be illustrated by defining

\[
\epsilon \equiv \frac{M_P^2}{2} \left( \frac{\langle V' \rangle}{\langle V \rangle} \right)^2, \quad \eta \equiv M_P^2 \left| \frac{\langle V'' \rangle}{\langle V \rangle} \right|,
\]

where \( ' \) represents the derivative with respect to the inflaton field, \( \sigma \). Clearly, the necessary conditions are

\[
\epsilon \ll 1, \quad \eta \ll 1.
\]

To evaluate the parameter \( \eta \), we need to calculate \( V'' \) from the potential given by [18]:

\[
\langle V'' \rangle = \left[ -\lambda(-\lambda + \kappa \sin 2\beta) v^2 + 6\kappa^2 s^2 + m_S^2 + \kappa A_s \right].
\]

Then the required condition for the \( \eta \) parameter becomes

\[
\eta = \frac{M_P^2}{\langle V \rangle} \left[ -\lambda(-\lambda + \kappa \sin 2\beta) v^2 + 6\kappa^2 s^2 + m_S^2 + \kappa A_s \right].
\]

To keep an inflationary era for long enough, the number of e-foldings for the inflaton field should be \( N > 60 \). The field value \( \sigma_N \) with \( N \) e-foldings is given by

\[
N = \frac{1}{M_P} \int_{\sigma_{\text{end}}}^{\sigma_N} d\sigma \frac{V}{\langle V \rangle},
\]

where \( \sigma_{\text{end}} \) is the value of the field at which the inflation ends. In hybrid inflation models, it is also useful to define the parameter

\[
\eta_H \equiv M_P^2 \left( \frac{M_P^2}{\langle V \rangle} \right) \approx 10^{32}.
\]

Then, the CMB anisotropy in low scale inflation models requires the coupling constant, \( \lambda \), to satisfy [14]

\[
\lambda^2 = 3 \times 10^{-7} \eta_H^2 \eta_H \approx 3 \times 10^{25} \eta^2.
\]
In order to realize instant preheating effectively (see the next section), we need a marginal coupling constant \( \lambda \sim 1 \), hence the parameter \( \eta \) should be \( \eta \sim 10^{-25} \). This requires the potential to be very flat in the inflaton field direction:

\[
\langle V'' \rangle \simeq 10^{-40} \text{ GeV}^2.
\] (26)

In the first order approximation this reduces to the following condition

\[-\lambda(-\lambda + \kappa \sin 2\beta)v^2 + 6\kappa^2 s^2 + m_S^2 + \kappa A_\kappa s = 0.\] (27)

Putting the vacuum condition \( \langle V'' \rangle \) into this equation gives a very simple form:

\[4\kappa^2 s^2 + \lambda A_\lambda v^2 \sin 2\beta = 0.\] (28)

Here we assume the parameter \( \kappa \) to be of order one, then the above equation determines the parameter \( A_\lambda \) as

\[A_\lambda = \frac{-4\kappa^2 s^2}{\lambda v^2 \sin 2\beta} \sim -\frac{4v}{\sin 2\beta}.\] (29)

In such a case we obtain electroweak inflation which explains the density perturbations and also gives a viable mechanism for instant preheating, which is discussed in the next section.

IV. INSTANT PREHEATING

The instant preheating mechanism requires the particle decay channel \( \sigma \to H \to f\bar{f} \), where \( H \) is one of the CP-even Higgs bosons, which can have a mass much heavier than \( \sigma \) due to preheating, and \( f \) denotes a fermion with mass lighter than \( H \). This leads to a very natural explanation for a low reheating temperature

\[T_R \simeq 0.05 M_{\text{H}} \lesssim 50 \text{ [GeV]}.\] (30)

Importantly, this also satisfies the gravitino constraint on the reheating temperature \( \lesssim 100 \text{ [TeV]} \)

\[T_R \lesssim 100 \text{ [TeV]}\] (31)

for the TeV scale gravitino \( m_{3/2} \approx 1 \text{ [TeV]} \).

The key ingredient for obtaining the relation \( T_R \sim M_{\text{H}} \) was given in 13. Given an inflationary model, we can investigate the effects of preheating to generate a large decay rate for the inflaton, which can be achieved by using the instant preheating mechanism. In this case the inflaton oscillates about the minimum of the potential only once and it is possible to show that

\[n_k = \exp \left( -\frac{\pi(k^2/a^2 + M_{\text{H}}^2)}{\lambda s M_{\text{H}}} \right).\] (32)

As discussed in 3, \( s M_{\text{H}} \) can be replaced by \( |\dot{\sigma}(t)| \), which leads to

\[n_k = \exp \left( -\frac{\pi(k^2/a^2 + M_{\text{H}}^2)}{\lambda |\dot{\sigma}(t)|} \right).\] (33)

This can then be integrated to give the number density for the Higgs field,

\[n_H = \frac{1}{2\pi^2} \int_0^\infty dk k^2 n_k \exp \left( -\frac{\pi M_{\text{H}}^2}{\lambda |\dot{\sigma}(t)|} \right) = \frac{(\lambda s M_{\text{H}})^{3/2}}{8\pi^3} \exp \left( -\frac{\pi M_{\text{H}}}{\lambda s} \right) \simeq \frac{M_{\text{H}}^3}{8\pi^3} e^{-\pi}.\] (34)

As argued in 3, if the couplings are of order \( \lambda \sim 1 \) then there need not be an exponential suppression of the number density. Interestingly, this fact has recently been used in a model of non-thermal leptogenesis. Whence, the resultant reheating temperature is found to be

\[T_R = \left( \frac{30}{g_\ast \pi^2} \cdot M_{\text{H}} \cdot n_H \right)^{1/4} \simeq \left( \frac{15}{4\pi^2 g_\ast} \right)^{1/4} M_{\text{H}} e^{-\pi/4} \simeq 0.05 \times M_{\text{H}}.\] (35)

It should be stressed that the reheating temperature above, obtained from the preheating mechanism, is proportional to the mass of the decayed particle, the Higgs boson mass \( T_R \lesssim M_{\text{H}} \) and does not depend on the inflaton mass.

V. DISCUSSION

Although there are various problems in the MSSM, we have shown that the simplest extension of it, the NMSSM, has interesting consequences for cosmology. In particular, by assuming that the extra singlet in the NMSSM, has interesting consequences for cosmology. In particular, by assuming that the extra singlet in the NMSSM is the inflaton field we can naturally realize inflation and a low reheat temperature which is not in conflict with the gravitino relic abundance bound.

As far as electroweak baryogenesis is concerned, even in such a low reheat temperature model, the NMSSM should naturally incorporate a strongly first order phase transition with less stringent bounds than in the MSSM.

Moreover, although we require a fine tuning in the slow-roll conditions, such a fine tuning only affects the soft SUSY breaking terms in the Lagrangian, which are themselves put in by hand. This feature might be considered as a relaxation of the fine tuning problem, that is, we are only tuning the soft SUSY breaking terms.

Finally, given that we are considering an NMSSM model, where the scalar-singlet is identified as the inflaton, we might be led to believe that the inflaton could be detected at future colliders, such as the LHC.

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