Supersymmetric Standard Model Inflation in the Planck Era

M. Arai – Czech Technical University in Prague
S. Kawai – Institute for the Early Universe (IEU)
N. Okada – University of Alabama

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Supersymmetric standard model inflation in the Planck era

Masato Arai,[1] Shinsuke Kawai,[2,3] and Nobuchika Okada[4]

[1]*Institute of Experimental and Applied Physics, Czech Technical University in Prague, Horská 3a/22, 12800 Prague 2, Czech Republic*
[2]*Institute for the Early Universe (IEU), 11-1 Daehyun-dong, Seodaemun-gu, Seoul 120-750, Korea*
[3]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
[4]*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA*

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We propose a cosmological inflationary scenario based on the supergravity-embedded Standard Model supplemented by the right-handed neutrinos. We show that with an appropriate Kähler potential the L-H_u direction gives rise to successful inflation that is similar to the recently proposed gravitationally coupled Higgs inflation model but is free from the unitarity problem. The mass scale M_R of the right-handed neutrinos is subject to the seesaw relation and the present 2-σ constraint from the WMAP7 $-$ BAO $-$ H_0 data sets its lower bound $M_R \gtrsim 1$ TeV. Generation of the baryon asymmetry is naturally implemented in this model. We expect that within a few years new observational data from the Planck satellite will clearly discriminate this model from other existing inflationary models arising from the same Lagrangian, and possibly yield stringent constraints on M_R.

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I. INTRODUCTION

Today observational cosmology is a precision science. Cosmological inflation, which is supported by all observational data, is now an indispensable theoretical ingredient not only in astrophysics but also in particle phenomenology. A remaining mystery of this otherwise extremely successful paradigm is embedding it into a particle theory model. By virtue of Occam's razor, a plausible possibility may be that the fields responsible for cosmological inflation (inflatons) are those already included in the Standard Model (SM), or its (not too large) extension. The recently proposed SM Higgs inflation model [1] is an interesting idea to test this possibility. This model is attractive due to its minimalistic nature and the remarkable agreement with the present day observational data. It also relates the dynamics of inflation with the electroweak scale physics, making a prediction on the SM Higgs mass from the cosmological microwave background (CMB) data. A rather unfavorable feature of this type of model is that it requires extremely large nonminimal coupling to gravity, which could lead to violation of the unitarity bound [2]. The model also suffers from the hierarchy problem, which may be cured by supersymmetrization [3–5]. See Ref. [6] for related models.

Certainly, there are more traditional ways of embedding inflation into supersymmetric SMs. It has been known for a while that the flat directions in the minimal supersymmetric Standard Model (MSSM), lifted by soft supersymmetry breaking terms and other effects, can serve as inflatons (reviewed in Ref. [7], more recent developments include [8]). Another type of embedding is into a supersymmetric SM with right-handed neutrinos [9], in which one of the right-handed sneutrinos is identified as the inflaton. These models are phenomenologically well motivated; the hierarchy problem is solved by supersymmetry, and the models with the right-handed neutrinos are furthermore consistent with the small but nonzero neutrino masses indicated by neutrino oscillation.

In this paper we present a new scenario of inflation, inspired by these developments. Our model has the following features: (i) the scenario is based on the simplest supersymmetric extension of the SM that includes the right-handed neutrinos, naturally explaining the small neutrino masses through the seesaw mechanism [10]; (ii) the problem associated with the large nonminimal coupling that afflicts the SM Higgs inflation is alleviated; (iii) the CMB data gives predictions on the mass scale of the right-handed neutrinos through the seesaw relation; (iv) leptogenesis is naturally implemented; (v) the predicted cosmological parameters fit well in the present day observational constraint, and (vi) the model can be tested by the upcoming observational data from the Planck satellite. We discuss construction of the model and describe these features below.

II. THE SUPERSYMMETRIC SEESAW MODEL

Our model is based on the MSSM extended with the right-handed neutrinos, with the R-parity preserving superpotential

$$W = W_{\rm MSSM} + \frac{1}{2} M_R N_R^c N_R^c + y_D N_R^c L H_u, \tag{1}$$

where N_R is the right-handed neutrino superfield (having odd R-parity), M_R the mass parameter for N_R, and

$$W_{\rm MSSM} = \mu H_u H_d + y_u u^c Q H_u + y_d d^c Q H_d + y_e e^c L H_d, \tag{2}$$

is the MSSM part. Here, Q, u, d, L, e, H_u, H_d are the MSSM superfields, μ the MSSM μ-parameter, and y_D, y_u,

y_d, y_e the Yukawa couplings (the family indices are suppressed). As noted in Ref. [3], successful nonminimally coupled Higgs inflation requires at least an extra field besides those in the MSSM. Our crucial observation here is that the model (1) is already such an extension, with the L-H_u direction playing the role of inflaton. During inflation Q, u, d, e, H_d do not play any part and we shall disregard them. Parametrizing the D-flat direction along L-H_u as

$$L = \frac{1}{\sqrt{2}}\begin{pmatrix} \varphi \\ 0 \end{pmatrix}, \qquad H_u = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \varphi \end{pmatrix}, \tag{3}$$

the superpotential becomes

$$W = \frac{1}{2} M_R N_R^c N_R^c + \frac{1}{2} y_D N_R^c \varphi^2. \tag{4}$$

We assume supergravity embedding and choose

$$\Phi = 1 - \frac{1}{3}(|N_R^c|^2 + |\varphi|^2) + \frac{1}{4}\gamma(\varphi^2 + \text{c.c.}) + \frac{1}{3}\zeta|N_R^c|^4, \tag{5}$$

with γ and ζ real parameters. The Kähler potential in the superconformal framework is $K = -3\Phi$. We have included an R-parity violating term. For brevity's sake, we shall set the reduced Planck scale $M_P = 2.44 \times 10^{18}$ GeV to be unity, take y_D to be real and consider only one generation below.

We introduce real scalar fields χ, N, α_1, α_2 by $\varphi = \frac{1}{\sqrt{2}}\chi e^{i\alpha_1}$, $N_R^c = N e^{i\alpha_2}$. It can be checked that the scalar potential is stable along the real axes of φ and N_R^c; we thus assume $\alpha_1 = \alpha_2 = 0$ below. The scalar-gravity part of the Lagrangian in the Jordan frame reads (cf., Ref. [4])

$$\mathcal{L}_J = \sqrt{-g_J}\left[\frac{1}{2}\Phi R_J - \frac{1}{2}g_J^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \kappa g_J^{\mu\nu}\partial_\mu N\partial_\nu N - V_J\right], \tag{6}$$

where

$$\Phi = M^2 + \xi\chi^2, \qquad M^2 \equiv 1 - \frac{1}{3}N^2 + \frac{\zeta}{3}N^4, \qquad \xi \equiv \frac{\gamma}{4} - \frac{1}{6}. \tag{7}$$

The subscripts J indicate quantities in the Jordan frame, and $\kappa = 1 - 4\zeta N^2$ is the nontrivial component of the Kähler metric. The F-term scalar potential is computed in the standard way [11]. In the Jordan frame it reads

$$V_J = \frac{1}{2}y_D^2 N^2\chi^2 + \frac{(M_R N + \frac{1}{4}y_D\chi^2)^2}{1 - 4\zeta N^2} - \frac{N^2\{\frac{1}{2}M_R N + \frac{3}{4}\gamma y_D\chi^2 - \frac{\zeta N^2(y_D\chi^2 + 4M_R N)}{2(1-4\zeta N^2)}\}^2}{3 + \frac{\zeta N^4}{1-4\zeta N^2} + \frac{3}{4}\gamma\chi^2(\frac{3}{2}\gamma - 1)}. \tag{8}$$

The scalar potential in the Einstein frame is $V_E = \Phi^{-2}V_J$.

In this model the Dirac-Yukawa coupling y_D and the right-handed neutrino mass M_R are related by the seesaw relation [10] $m_\nu = y_D^2\langle H_u\rangle^2/M_R$, where m_ν is the mass scale of the light (left-handed) neutrinos. Using the neutrino oscillation data $m_\nu^2 \approx \Delta m_{32}^2 = 2.43 \times 10^{-3}$ eV^2 [12] and the Higgs vacuum expectation value at low energy $\langle H_u\rangle \approx$ 174 GeV, we find

$$y_D = \left(\frac{M_R}{6.14 \times 10^{14}\,\text{GeV}}\right)^{1/2}. \tag{9}$$

This puts an upper bound on M_R since $y_D \lesssim \mathcal{O}(1)$.

For large y_D (and thus large M_R) the inflationary model is very similar to the next-to-minimal supersymmetric SM [3,4] or the supersymmetric grand unified theory model [5]. These two-field inflation models in general have nontrivial inflaton trajectories that can source the isocurvature mode. While such a scenario is certainly of interest, the analysis is rather involved; we thus allow the quartic Kähler term in (5) to control the instability in the N-direction. For $M_R = 10^{13}$ GeV we find $\zeta = 100$ keeps the deviation of N from $N = 0$ negligibly small ($\sqrt{2\kappa}\Delta N/\Delta\chi \lesssim 1\%$ throughout the slow roll of $N_e = 60$

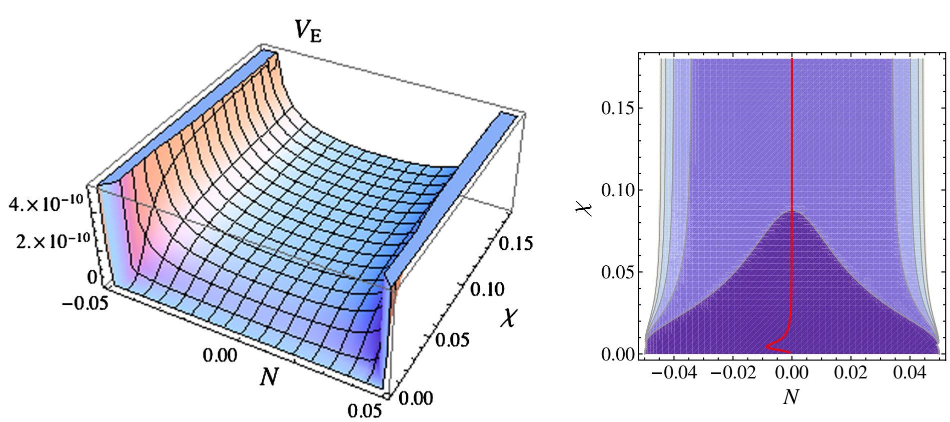

FIG. 1 (color online). The scalar potential V_E in the Einstein frame (left), and the inflaton trajectory in the contour plot of the same potential (right). The red curve is the inflaton trajectory. We have chosen $N_e = 60$, $M_R = 10^{13}$ GeV and $\zeta = 100$.

e-folds). For $M_R \leq 10^{11}$ GeV, $\zeta = 1$ is enough. In Fig. 1 we show the potential and the inflaton trajectory of our model, for $M_R = 10^{13}$ GeV, $N_e = 60$ and $\zeta = 100$ (the nonminimal coupling is fixed by CMB as below). Once the trajectory is stabilized the cosmological parameters are insensitive to the value of ζ, and as the trajectory is nearly straight the model simplifies to single field inflation with the inflaton χ. The Lagrangian then becomes

$$\mathcal{L}_{\rm J} = \sqrt{-g_{\rm J}}\left[\frac{M^2 + \xi\chi^2}{2}R_{\rm J} - \frac{1}{2}g_{\rm J}^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V_{\rm J}\right]. \quad (10)$$

III. COSMOLOGICAL SCENARIO AND THE PREDICTION

Our model provides a cosmological scenario of slow-roll inflation: the slow roll parameters ϵ, η are small during inflation, and inflation terminates when ϵ or η becomes $\mathcal{O}(1)$. The canonically normalized inflaton field $\hat{\chi}$ in the Einstein frame is related to χ by

$$d\hat{\chi} = \frac{\sqrt{M^2 + \xi\chi^2 + 6\xi^2\chi^2}}{M^2 + \xi\chi^2}d\chi, \quad (11)$$

and the slow roll parameters in the Einstein frame are

$$\epsilon = \frac{1}{2}\left(\frac{1}{V_{\rm E}}\frac{dV_{\rm E}}{d\hat{\chi}}\right)^2, \qquad \eta = \frac{1}{V_{\rm E}}\frac{d^2V_{\rm E}}{d\hat{\chi}^2}. \quad (12)$$

The inflaton value $\chi = \chi_*$ at the end of the slow roll is related to the value $\chi = \chi_k$ at the horizon exit of the comoving CMB scale k, through the e-folding number $N_e = \int_{\chi_*}^{\chi_k} d\chi V_{\rm E}(d\hat{\chi}/d\chi)/(dV_{\rm E}/d\hat{\chi})$. The potential $V_{\rm E}$ at the horizon exit is constrained by the power spectrum $\mathcal{P}_R = V_{\rm E}/24\pi^2\epsilon$ of the curvature perturbation. We used the maximum likelihood value $\Delta_R^2(k_0) = 2.42 \times 10^{-9}$ from the 7-year WMAP data [13], which is related to the power spectrum by $\Delta_R^2(k) = \frac{k^3}{2\pi^2}\mathcal{P}_R(k)$, with the normalization fixed at $k_0 = 0.002\ \text{Mpc}^{-1}$. Apart from ζ, which was introduced to keep the deviation of the trajectory from $N = 0$ small, the model contains only two parameters: ξ and y_D. The former is fixed by the curvature perturbation $\mathcal{P}_R$, and the latter is related to the right-handed neutrino mass M_R, through (9). Note that there exists a lower bound on y_D, set by the minimal coupling limit $\xi \to 0$. In this limit our model is essentially the chaotic inflation with quartic potential $V_{\rm E} = \frac{1}{16}y_D^2\chi^4$, with y_D fixed by $\mathcal{P}_R$. The corresponding value of M_R at $\xi = 0$ is 644 GeV for $N_e = 50$ and 378 GeV for $N_e = 60$.

For a given value of M_R the scalar spectral index $n_s \equiv d\ln\mathcal{P}_R/d\ln k = 1 - 6\epsilon + 2\eta$ and the tensor-to-scalar ratio $r \equiv \mathcal{P}_{\rm gw}/\mathcal{P}_{\rm R} = 16\epsilon$ can be computed. Table I shows these results, evaluated for $N_e = 50$, 60 and for several values of M_R between the upper and lower bounds [14]. We see that $\xi \lesssim \mathcal{O}(1)$ when $M_R \lesssim 10^6$ GeV. This shows that in the wide parameter region our model is free from the dangers [2] arising from the large nonminimal coupling. For small ξ, instead, a super-Planckian initial value of the inflaton field is inevitable. This feature is similar to the model studied in Ref. [15].

TABLE I. The coupling ξ, the inflaton values at the end of the slow roll (χ_*) and at the horizon exit (χ_k), the spectral index n_s, and the tensor-to-scalar ratio r for e-folding $N_e = 50$, 60 and for various values of the right-handed neutrino mass M_R. The coupling ξ is fixed by the amplitude of the curvature perturbation. We used $\zeta = 100$ for $M_R = 10^{13}$ GeV and $\zeta = 1.0$ for $M_R \leq 10^{11}$ GeV. The last lines ($N_e = 50$, $M_R = 644$ GeV and $N_e = 60$, $M_R = 378$ GeV) correspond to the minimally coupled $\lambda\phi^4$ model.

N_e	M_R (GeV)	ξ	χ_*	χ_k	n_s	r
50	10^{13}	2566	0.0212	0.167	0.962	0.004 19
	10^{11}	257	0.0671	0.527	0.962	0.004 20
	10^9	25.6	0.212	1.66	0.962	0.004 22
	10^6	0.730	1.14	8.91	0.961	0.005 15
	10^5	0.184	1.85	14.2	0.961	0.007 96
	10^4	0.0303	2.79	18.9	0.960	0.0259
	5000	0.0152	3.06	19.6	0.959	0.0448
	2000	4.97×10^{-3}	3.31	20.1	0.955	0.103
	1000	1.33×10^{-3}	3.42	20.3	0.949	0.201
	644	0	3.46	20.3	0.942	0.311
60	10^{13}	3059	0.0194	0.167	0.968	0.002 96
	10^{11}	306	0.0614	0.527	0.968	0.002 97
	10^9	30.5	0.194	1.66	0.968	0.002 98
	10^6	0.886	1.05	8.97	0.968	0.003 52
	10^5	0.232	1.73	14.6	0.968	0.005 08
	10^4	0.0421	2.63	20.1	0.967	0.0143
	5000	0.0222	2.92	21.1	0.966	0.0237
	2000	8.36×10^{-3}	3.22	21.8	0.964	0.0519
	1000	3.28×10^{-3}	3.36	22.1	0.961	0.0998
	500	6.48×10^{-4}	3.44	22.2	0.955	0.197
	378	0	3.46	22.2	0.951	0.260

After the slow roll the inflaton oscillates around the minimum at $N = \chi = 0$, and decays. The effect of nonminimal coupling on the reheating process can be important when ξ is large and the coupling between the inflaton and the matter field is small [16]. In our model, the inflaton couples directly to the SM matter fields and the coupling ξ does not have to be extremely large; we thus expect the effect of ξ on the reheating to be limited. The upper limit of the reheating temperature is estimated as $T_{\rm rh} \sim 10^7$ GeV, assuming the Higgs component decay $\varphi \to b\bar{b}$ (the slepton component decay may yield slightly higher temperature [17]). This is low enough to avoid the gravitino problem. The generation of the baryon asymmetry is due to the following mechanisms. If $T_{\rm rh} \gtrsim M_R$, the right-handed (s) neutrinos thermalize, leading to thermal leptogenesis [19] with the resonant enhancement effects [20]. If the reheating temperature is lower $T_{\rm rh} \lesssim M_R$, the mechanism of Murayama *et al.* [9,21] due to the decay of oscillating sneutrinos can be operative; with N acquiring the vacuum

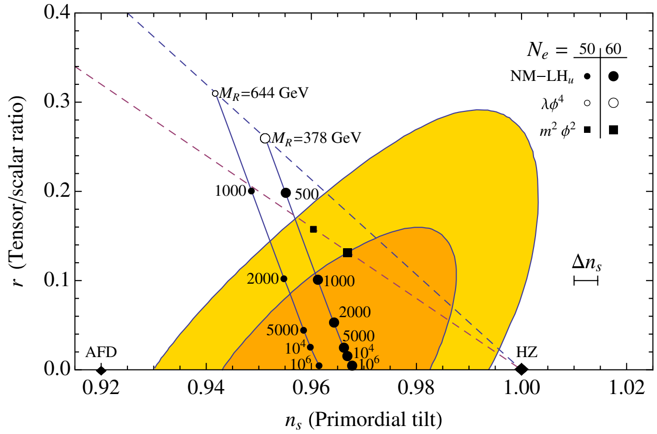

FIG. 2 (color online). The scalar spectral index n_s and the tensor-to-scalar ratio r, with the 68 and 95% confidence level contours from the WMAP7 + BAO + H_0 data [13]. The prediction of our model (NM-LH_u) is indicated by filled circles with corresponding M_R values. The predictions of the Harrison-Zel'dovich (HZ), the $\lambda\phi^4$ and $m^2\phi^2$ chaotic inflation models, as well as the A-term MSSM flat-direction (AFD) inflation models, are also shown for comparison. Δn_s is the expected Planck accuracy [23].

expectation value at the end of the slow roll, as shown in Fig. 1, the coherent oscillation in the direction of N produces lepton numbers. Interestingly, this mechanism depends on the inflaton trajectory and thus on ζ. In addition, the Affleck-Dine mechanism [22] can be operative.

The prediction of n_s and r in our model is shown in Fig. 2, along with the 68 and 95% confidence level contours from the WMAP7 + BAO + H_0 data [13]. Also indicated are the predictions of two other inflationary models arising from the same Lagrangian (1), namely the $\tilde{N}_R$ chaotic inflation model [9], marked with filled squares, and the A-term inflation models [8] marked with filled diamonds (AFD). The former is essentially the standard $m^2\phi^2$ chaotic inflation. In the latter, the inflaton is $u^c d^c d^c$, $e^c LL$, or $N_R^c LH_u$ direction in the (N_R-extended) MSSM, and its typical prediction is very small r and $n_s \approx 1$–$4/N_e$; we used $N_e = 50$ (thus $n_s = 0.92$) as the e-folding cannot be large ($N_e \lesssim 50$) in such low-scale inflation models. We see that our model fits well with the present data unless M_R is too small. The 2-σ constraints roughly give $M_R \gtrsim 1$ TeV, depending on the e-folding number (and thus on the reheating temperature). In the near future detailed data from the Planck satellite experiments [23] will be available, with the expected resolution $\Delta n_s \approx 0.0045$, also indicated in Fig. 2. With such high precision the three inflation models arising from the (N_R-extended) MSSM would clearly be discriminated. If our model turns out to be the likely scenario, the Planck data would also constrain the mass scale of the right-handed neutrinos.

IV. DISCUSSION

While the SM of particle theory is the greatest success in the twentieth century physics, it is not a complete theory. For one thing, the neutrino oscillation indicates that the right-handed neutrinos must be included. Also, in order to solve the hierarchy problem and to account for the dark matter in the universe, some extension, such as supersymmetrization, is necessary. In this paper we presented a new scenario of inflation, for which the right-handed neutrinos, supersymmetry, and the nonminimal coupling are essential. Note that all of them naturally arise in the supergravity embedding of the SM with the right-handed neutrinos. Not too large nonminimal coupling is also natural as we are dealing with quantum field theory in curved spacetime.

Our scenario is economical as it explains—apart from the standard issues that are solved by inflation—small nonvanishing neutrino masses and the origin of the baryon asymmetry. The predicted values of n_s and r are consistent with the present observation, and can be tested by the Planck satellite data. What we find particularly interesting is that it constrains the right-handed neutrino mass scale. The nature of the heavy neutrinos is mysterious; being gauge singlets, their detection in colliders is virtually impossible, nevertheless they must be present for the seesaw mechanism and leptogenesis. If our scenario turns out to be correct, CMB would provide a new window to the physics of right-handed neutrinos.

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