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TeV scale seesaw from supersymmetric Higgs-lepton inflation and BICEP2

Shinsuke Kawai [a,*], Nobuchika Okada [b]

[a] Department of Physics, Sungkyunkwan University, Suwon 440-746, Republic of Korea
[b] Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA

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ABSTRACT

We discuss the physics resulting from the supersymmetric Higgs-lepton inflation model and the recent CMB B-mode observation by the BICEP2 experiment. The tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$ of the primordial fluctuations indicated by the CMB B-mode polarization is consistent with the prediction of this inflationary model for natural parameter values. A salient feature of the model is that it predicts the seesaw mass scale M from the amplitude of the tensor mode fluctuations. It is found that the 68% (95%) confidence level (CL) constraints from the BICEP2 experiment give 927 GeV $< M <$ 1.62 TeV (751 GeV $< M <$ 2.37 TeV) for 50 e-foldings and 391 GeV $< M <$ 795 GeV (355 GeV $< M <$ 1.10 TeV) for 60 e-foldings. In the type I seesaw case, the right-handed neutrinos in this mass range are elusive in collider experiments due to the small mixing angle. In the type III seesaw, in contrast, the heavy leptons will be within the reach of future experiments. We point out that a significant portion of the parameter region corresponding to the 68% CL of the BICEP2 experiment will be covered by the Large Hadron Collider experiments at 14 TeV.

1. Introduction

The discovery of the cosmic microwave background (CMB) B-mode polarization by the BICEP2 experiment [1] is truly remarkable as the existence of the tensor mode in the primordial fluctuations provides a direct evidence for inflation in the early Universe.[1] It has a significant impact on inflation model building. In the past decade models producing small tensor mode fluctuations were considered favourable since, for example, the Planck data in 2013 [2] constrained the tensor-to-scalar ratio $r < 0.11$ at 95% confidence level (CL). The models of inflation producing such small r include the Higgs inflation model [3,4], supersymmetric Higgs inflation-type models [5–9], the hill-top inflation model [10], and the R^2 inflation model [11]. Among these, the Higgs inflation model is a particularly simple and concrete particle physics realization of inflation that also provides predictions in low-energy particle physics. These models are in tension with the finding of the BICEP2 experiment. See Refs. [12–14] for the updated status of various models.

In the present paper we point out that the prediction of the inflationary scenario which we call the Higgs-lepton inflation (HLI) [15,16] fits extremely well with the new data for natural choice of parameters. The HLI scenario is realized in the supersymmetric seesaw model, which is the simplest extension of the minimal supersymmetric Standard Model (MSSM) to include the right-handed neutrinos. The model incorporates the type I [17] or type III seesaw mechanism [18] by which the small nonzero neutrino masses that are evidenced by the neutrino oscillations are naturally explained. It also includes possibility for generating baryon asymmetry through leptogenesis or the Affleck–Dine mechanism. As a feature of the model, HLI directly associates the spectrum of the CMB with the mass scale of the right-handed neutrinos. We will see that the new data from the BICEP2 experiments constrains this mass scale to be between a few hundred GeV and a few TeV. These constraints are potentially useful since the right-handed (s)neutrinos may also be searched in colliders.

2. Higgs-lepton inflation in the supersymmetric seesaw model

The HLI model [15,16] is an “all-in” phenomenological model of inflation that includes the seesaw mechanism [17], the origin of the baryon asymmetry, the origin of the dark matter, as well as

* Corresponding author.
E-mail addresses: kawai@skku.edu (S. Kawai), okadan@ua.edu (N. Okada).

[1] The BICEP2 experiment uses 150 GHz single wavelength bolometers. In order to conclude that the gravitational waves causing the polarization are undeniably of inflationary origin, the results need to be confirmed also at other wavelengths.

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the Standard Model of particle physics. It is based on the seesaw-extended MSSM. The superpotential in the type I seesaw case is

$$W = W_{\mathrm{MSSM}} + \frac{1}{2} M N^c N^c + y_D N^c L H_u, \tag{1}$$

where W_{MSSM} is the MSSM superpotential and N^c, L, H_u are the right-handed neutrino singlet, the lepton doublet, and the up-type Higgs doublet superfields, respectively (the family indices are suppressed). In the type III case, the superpotential is

$$W = W_{\mathrm{MSSM}} + \frac{1}{2} M \operatorname{Tr}\left(T^c T^c\right) + y_D L T^c H_u, \tag{2}$$

where

$$T^c = \frac{1}{2} \begin{pmatrix} N^0 & \sqrt{2} N^+ \\ \sqrt{2} N^- & -N^0 \end{pmatrix} \tag{3}$$

is the right-handed neutrino triplet superfield. With odd R-parity assigned to N^c or T^c, the superpotential preserves the R-parity in both cases. The Majorana masses of the right-handed neutrinos M and the Dirac Yukawa coupling y_D are related by the seesaw relation

$$m_\nu = m_D^T M^{-1} m_D, \tag{4}$$

where $m_D = y_D \langle H_u^0 \rangle$ and $\langle H_u^0 \rangle \simeq 174$ GeV for moderate $\tan\beta$. While realistic seesaw requires at least two families of the right-handed neutrinos, we will be interested mainly in the outcome of inflation and consider a simplified one family case.[2] Since the inflationary model is essentially the same for both type I and type III seesaw, we will describe in the case of the type I model below. Estimating the mass scale of the light (left-handed) neutrinos as $m_\nu^2 \approx \Delta_{32}^2 = 2.32 \times 10^{-3}$ eV^2 where the data of [19] is used, the seesaw relation (4) reads

$$y_D = \left(\frac{M}{6.29 \times 10^{14}\,\mathrm{GeV}} \right)^{1/2}. \tag{5}$$

Inflation is assumed to take place along one of the D-flat directions L–H_u, which is parametrized by a field φ so that

$$L = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi \\ 0 \end{pmatrix}, \qquad H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}. \tag{6}$$

We consider supergravity embedding with slightly noncanonical Kähler potential $K = -3\Phi$, where

$$\Phi = 1 - \frac{1}{3}\left(\left|N^c\right|^2 + |\varphi|^2 \right) + \frac{\gamma}{4}\left(\varphi^2 + \mathrm{c.c.}\right) + \frac{\zeta}{3}\left|N^c\right|^4. \tag{7}$$

Here γ and ζ are real parameters. The third term on the right hand side violates the R-parity; the consequence of this will be discussed in Section 3. We will use the unit in which the reduced Planck scale $M_{\mathrm{P}} = (8\pi G)^{-1/2} = 2.44 \times 10^{18}$ GeV is set to unity. During inflation only the fields N^c and φ are important and the superpotential simplifies to

$$W_{\mathrm{inf}} = \frac{1}{2} M N^c N^c + \frac{1}{2} y_D N^c \varphi^2. \tag{8}$$

From (7) and (8) the Lagrangian of the model can be obtained following the standard supergravity computations [15,16].

The dynamics of the resulting system is complicated in general, with a nontrivial inflaton trajectory in multidimensional field space. It can be shown however that with mild assumptions the model simplifies to give single-field slow roll inflation [15,16]. This is due to the non-zero quartic term in (7), which makes the N^c field massive, ensuring the inflaton trajectory to lie along the φ direction. Furthermore, the scalar potential can be shown to be stable along the real axis of the φ field so that the phase direction of φ does not participate in the inflationary dynamics. The model then involves only one real scalar field and the Lagrangian becomes

$$\mathcal{L}_{\mathrm{J}} = \sqrt{-g_{\mathrm{J}}} \left\{ \frac{1}{2} \Phi R_{\mathrm{J}} - \frac{1}{2} g_{\mathrm{J}}^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - V_{\mathrm{J}} \right\}, \tag{9}$$

where the subscript J stands for the Jordan frame and

$$\chi = \sqrt{2}\,\mathrm{Re}\,\varphi, \qquad V_{\mathrm{J}} = \frac{|y_D|^2}{16} \chi^4. \tag{10}$$

Here the field is understood to represent the scalar component. Note that Φ of (7) is now written as

$$\Phi = 1 + \xi \chi^2, \qquad \xi = \frac{\gamma}{4} - \frac{1}{6}. \tag{11}$$

This is the nonminimally coupled $\lambda\phi^4$ model [20]. The Higgs inflation model [3,4] also has the same structure. An essential feature of the HLI model here is that the inflaton self coupling is the square of the Yukawa coupling y_D which is determined by the seesaw relation (4). In this supersymmetric model the effects of renormalization on the Yukawa coupling y_D and the nonminimal curvature coupling ξ are negligibly small [15,16].

The dynamics of inflation and the prediction of the model can be studied conveniently in the Einstein frame, by Weyl-rescaling the metric $g_{\mu\nu}^{\mathrm{E}} = \Phi g_{\mu\nu}^{\mathrm{J}}$ and redefining the field χ into the canonically normalized one $\hat{\chi}$ in the Einstein frame,

$$d\hat{\chi} = \frac{\sqrt{1 + \xi\chi^2 + 6\xi^2\chi^2}}{1 + \xi\chi^2} d\chi. \tag{12}$$

The Lagrangian in the Einstein frame is then

$$\mathcal{L}_{\mathrm{E}} = \sqrt{-g_{\mathrm{E}}} \left\{ \frac{1}{2} R_{\mathrm{E}} - \frac{1}{2} g_{\mathrm{E}}^{\mu\nu} \partial_\mu \hat{\chi} \partial_\nu \hat{\chi} - V_{\mathrm{E}} \right\}, \tag{13}$$

where the scalar potential is

$$V_{\mathrm{E}} = \frac{V_{\mathrm{J}}}{\Phi^2}. \tag{14}$$

The slow roll parameters are defined in the usual way,

$$\epsilon = \frac{1}{2} \left(\frac{1}{V_{\mathrm{E}}} \frac{dV_{\mathrm{E}}}{d\hat{\chi}} \right)^2, \qquad \eta = \frac{1}{V_{\mathrm{E}}} \frac{d^2 V_{\mathrm{E}}}{d\hat{\chi}^2}. \tag{15}$$

The model contains two tuneable parameters y_D and ξ, which are related to M and γ through (5) and (11). The value of ξ will be fixed by the amplitude of the CMB power spectrum as follows. The end of the slow roll is characterized by the condition that either of the slow roll parameters are not small anymore; we use $\max(\epsilon, |\eta|) = 1$ and denote the value of the inflaton obtained from this condition as χ_*. We then follow the inflaton trajectory backward in time for N_e e-foldings, and identify the inflaton value χ_k that corresponds to the horizon exit of the comoving CMB scale k, using the relation $N_e = \int_{\chi_*}^{\chi_k} d\chi\, V_{\mathrm{E}} (d\hat{\chi}/d\chi)/(dV_{\mathrm{E}}/d\hat{\chi})$. Then the power spectrum of the curvature perturbation $P_R = V_{\mathrm{E}}/24\pi^2\epsilon$ at the CMB scale $\chi = \chi_k$ is obtained for a given set of N_e, y_D, ξ. To compare this with the observed CMB amplitude, we use for definiteness the value $A_s(k_0) = 2.215 \times 10^{-9}$ from the Planck satellite experiment [2], with the pivot scale at $k_0 = 0.05$ Mpc^{-1}. Here, $A_s(k) = \frac{k^3}{2\pi^2} P_R(k)$ and $P_R(k)$ is the Fourier transform of P_R. Fixing

[2] See [16] for a detailed description of the HLI with two families (the minimal seesaw case) in type I seesaw.