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Inflatonic baryogenesis with large tensor mode

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ABSTRACT

We consider a complex inflaton field with a CP asymmetric term for its potential. This CP asymmetric term produces the global charge of the inflaton after inflation. With the assignment of the baryon number to the inflaton, the baryon asymmetry of the universe is produced by inflaton's decay. In addition to this, the $U(1)$ breaking term modulates the curvature of the inflaton radial direction depending on its phase, which affects the tensor-to-scalar ratio. In this paper, we have studied the relation between the baryon asymmetry and the tensor-to-scalar ratio, then verified that the future CMB observation could test this baryogenesis scenario with large tensor modes.

1. Introduction

Inflation theory is attractive to solve the cosmological problems such as the flatness, horizon and monopole problems. Furthermore, inflaton's quantum fluctuations give the seeds of the large scale structures, and they are imprinted on the cosmic microwave background (CMB). Observations of the CMB such as the Planck mission [1] have verified that the spectral index of the scalar perturbation deviates from the flat spectrum with more than 5σ, which strongly suggests the realization of the inflation. By the detection of the tensor mode in the near future, this inflation theory and its energy scale will be confirmed.

The domination of the inflaon's energy over the universe induces the cosmic accelerating expansion, which dilutes the other matter contents and their asymmetry presented before inflation. On the other hand, by the observation of CMB [2] and by the measurements of the primordial abundances of the light elements [3], the abundance of the baryon asymmetry after the Big Bang Nucleosynthesis is confirmed as $n_s/s \simeq 10^{-10}$. To explain this asymmetry, various production mechanisms have been proposed such as the electroweak baryogenesis [4], the leptogenesis [5] and the Affleck–Dine baryogenesis [6]. In this paper, we focus on the Affleck–Dine baryogenesis, in which the rotating complex scalar field (AD field) on the field space with the baryon number produces the $U(1)_B$ charge, and then by the decay of the AD field into baryon, the baryon asymmetry is produced. We assign the baryon number on the inflaton, and investigate the baryon production by the inflaton's AD mechanism.

Suppose the quadratic chaotic inflation [7], the constraint for the abundance of the tensor mode by Planck mission [1] suggests that the potential takes some suppression by the higher terms such as a cubic one $V \sim m^2\phi^2 - \lambda\phi^3$. In the previous studies [8–10], it is shown that if this higher term breaks $U(1)$ symmetry such as $V = m^2|\Phi|^2 + \lambda\Phi^n + h.c.$, its breaking gives the variation of the inflaton for the phase direction after the inflation and then the asymmetry of the inflaton is produced. Furthermore, [8–10] have shown that by the decay of the inflaton assigned baryon number, the large amount of the baryon asymmetry is produced to explain the observed one $n_s/s \sim 10^{-10}$.

As shown in [8,9], the abundance of the tensor mode for this model is mainly determined by the quadratic term $V \sim m^2|\Phi|^2$, however, the higher terms $V \ni \lambda\Phi^n$ would also gives the sizable modulation of the tensor mode. This higher term is also the source of the inflaton's asymmetry, which thus means that the tensor mode is correlated with the inflaton's asymmetry, and then with the baryon asymmetry. In this paper, we have investigated the relation between the prediction for the tensor mode and the abundance of the baryon asymmetry produced by the inflaton, supposing the polynomial inflation where $U(1)$ symmetry is broken by the cubic term as $V = m^2|\Phi|^2 + (\lambda\Phi^3 + h.c.) + \lambda^2/m^2|\Phi|^4$.

The organization of this paper is as follows. At first, in Section 2, we briefly explain the dynamics of this inflation model, and then calculate the prediction for tensor-to-scalar ratio r and spectral index n_s for each initial phase of the inflaton and for the typical strength of the coupling λ. Then, in Section 3, we calculate the inflaton's asymmetry produced in this model, and then discuss its decay into baryons. Finally, we conclude this paper in Section 4.

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2. Inflation dynamics

In this section, we show the model and briefly explain its dynamics. Then, we investigate the prediction for CMB observations r and n_s.

We consider the complex scalar inflaton Φ, whose action is given as

$$S = \int d^4x \sqrt{-\det(g_{\mu\nu})} \left[\frac{M_p^2}{2} R + |\partial_\mu \Phi|^2 - V(\Phi) \right], \tag{1}$$

where R is the Ricci scalar. We give the inflaton's potential within the renormalizability as

$$V = m^2 |\Phi|^2 + \lambda(\Phi^3 + \Phi^{*3}) + g|\Phi|^4, \tag{2}$$

where m is the mass, λ is the dimension one constant, and g is the dimensionless coupling, and we have supposed a CP asymmetric cubic term in the potential. For the simplicity, we set the coupling g by the dimension one parameter λ as $g = \lambda^2/m^2$.[1] Separating variable of the inflaton into the radial and phase parts as $\Phi = (\phi/\sqrt{2}) \exp(i\theta)$, we can reduce the potential (2) as

$$V = m^2 \left[\frac{\phi^2}{2} + \sqrt{2}\alpha \cos(3\theta) \frac{\phi^3}{M_p} + \alpha^2 \frac{\phi^4}{M_p^2} \right], \tag{3}$$

where we have defined the dimensionless parameter as $\alpha \equiv \lambda M_p/(2m^2)$. For this potential, the radial part ϕ follows bellow equation as

$$\ddot{\phi} + 3H\dot{\phi} + m^2 \left[1 + 3\sqrt{2}\alpha \cos(3\theta) \frac{\phi}{M_p} + 4\alpha^2 \frac{\phi^2}{M_p^2} \right] \phi = 0, \tag{4}$$

where the over dot means the cosmic time derivative and H means the Hubble parameter and we have neglected the spatial derivative of the inflaton. In the case of the quadratic chaotic inflation model $V_{\rm chao} = (m^2/2)\phi^2$, the field value at 60 e-folds number is $\sqrt{60} M_p$. We suppose that the strength of the asymmetric term is small so that the modulation of the cubic term for the quadratic term is small at 60 e-folds as $\alpha < 10^{-2}$. In this section, we neglect the dynamical variation of the inflaton's phase during inflation, and set the phase by the constant one as $\theta \simeq \theta_i$. Then, the Hubble parameter is approximated by the homogeneous mode of the inflaton's radial direction as $H \simeq \sqrt{(1/3M_p^2)\left[(1/2)\dot{\phi}^2 + V\right]}$.

The curvature perturbations produced by inflaton and the graviton's fluctuations are imprinted on CMB as the scalar and the tensor mode. The scale dependence of the scalar mode is given by the spectral index n_s, and the abundance of the tensor mode is given by the tensor-to-scalar ratio r. Taking the slow roll approximation, we can give n_s and r by the slow roll parameters ϵ and η as

$$n_s = 1 + 2\eta - 6\epsilon, \tag{5}$$

$$r = 16\epsilon, \tag{6}$$

where $\epsilon \equiv M_p^2/2\left(V_\phi/V\right)^2$, and $\eta \equiv M_p^2 V_{\phi\phi}/V$. From these definitions, we can see that n_s and r depend on the gradient or the curvature of the inflaton's potential, which are determined by the coupling of the *CP* asymmetric term α and inflaton's initial phase θ_i. Thus, by the determination of n_s and r, we can constrain α and θ_i. Remaining of this section, we calculate the n_s and r at the pivot scale, where we suppose 60 e-folding number. Then, compare the prediction by the present constraint by Planck mission [1].

The e-folding number from the pivot scale t_i to the end of the inflation t_e is given as

$$N_e = \int_{t_i}^{t_e} H dt \simeq \int_{\phi_e}^{\phi_i} \frac{1}{M_p^2} \frac{V}{V_\phi} d\phi, \tag{7}$$

where $\phi_e(\phi_i)$ is the field value of ϕ at $t_e(t_i)$, and we have used the slow roll approximation. ϕ_e is given by the one at the breaking of the slow roll condition as

$$\max\{\epsilon, \eta\} = 1. \tag{8}$$

In this paper we numerically solve the two equations (7) and (8) for $N_e = 60$, then substituting the obtained value of ϕ_i into the equations (5) and (6), we evaluate the predictions of n_s and r at the pivot scale. The results of the simulations are summarized in Fig. 1. From the top left panel of Fig. 1, we can see that the spectral index depends on initial phase of the inflaton referred as $C \equiv \cos(3\theta_i)$ and its modulation is larger for more larger α. For the negative value of C, the potential is suppressed by the cubic term, then the tensor-to-scalar ratio becomes smaller showed on the top right panel of Fig. 1. Our model converges to the quadratic chaotic inflation model for the limit of the small coupling $\alpha \to 0$ [7]. We can see this behavior for n_s–r relation on the bottom panel of Fig. 1. For the smaller couplings $\alpha = 10^{-3}, 10^{-4}$, the n_s–r relation is the point like one regardless of the initial phase, which is the same pint as the chaotic inflation predicts. However, for the larger one $\alpha = 10^{-2}$, due to the cubic term modulation, the prediction for the tensor-to-scalar ratio depends on the initial phase of the inflaton,[2] which will be tested in the future observation of the CMB. This initial phase of the inflaton also relates to the amount of the inflaton's asymmetry, then finally to the baryon asymmetry, which is described in the next section.

3. Inflaton asymmetry and its decay into Baryon

During the inflation, the variation for the phase direction is negligible due to the Hubble friction, and after the inflation it stars to roll down to the minimum $\theta_{\rm min} = n\pi/3$, $(n \in \mathcal{N})$. This rotation for the phase direction produces $U(1)$ charge of the inflaton. At the same time, the Hubble expansion decreases the amplitude of the radial direction, which suppresses the cubic term and then the $U(1)$ charge becomes time independent. By the decay of inflaton into other particles, the $U(1)$ charge is transferred to the baryon asymmetry. In this section, we evaluate the $U(1)$ charge by numerically solving the equation of motion including the dynamical variation of the phase direction.

The equation of motion of the complex inflaton field Φ is given as

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\partial V}{\partial \Phi^*} = 0, \tag{9}$$

where the derivative of the potential is given as

$$\frac{\partial V}{\partial \Phi^*} = m^2 \left[\Phi + 6\alpha \frac{\Phi^{*2}}{M_p} + 8\alpha^2 \frac{|\Phi|^2}{M_p^2} \Phi \right]. \tag{10}$$

[1] This relation between λ and g as $g = \lambda^2/m^2$ is established for the supersymmetric polynomial inflation model [11].

[2] We have checked the effect of the phase direction's dynamical variation on the e-folding number by the numerical simulation. Even including the dynamical variation of the phase direction, the deviation of the total e-folding number is smaller than one.