In the case that the \( U(1) \) symmetry of inflaton is slightly broken, the baryon asymmetry of the Universe is produced by the decay of the inflaton through the Affleck-Dine mechanism. In addition to this, the modulation of the potential by the \( U(1) \) breaking term changes the abundance of the gravitational waves produced during the inflation. In this paper, we have studied the possibility that the sufficient baryon number and large amount of the tensor mode would be simultaneously produced by the inflaton.
I. INTRODUCTION

From the result of Planck mission [1], it is confirmed that the spectrum of the cosmic microwave background (CMB) is nearly scale invariant but slightly red tilted. In addition to this, recently BICEP2 [2] has reported the detection of primordial gravitational waves. These two results give the strong evidence for the accelerated cosmic expansion in the very early Universe (inflation), which solves lots of cosmological problems as like flatness, horizon and monopole problems.

The inflation theory, which is highly supported by the observation of the CMB is attractive to solve cosmological problems, however, accelerated cosmic expansion gives the difficulties for the explanation of the baryon asymmetry observed by Planck [1] as \( n_b/s \sim 10^{-10} \), since it dilutes the baryon asymmetry existed in the early Universe. To explain this observed asymmetry, various mechanisms of the baryogenesis have been considered as like electroweak baryogenesis [3], leptogenesis [4] and Affleck-Dine baryogenesis [5]. Among these models, especially we focus on the Affleck-Dine baryogenesis, in which the rotating scalar field in the complex field space (Affleck-Dine field) produces the \( U(1) \) charge, and then the produced charge is transformed to the baryon asymmetry through the decay of the field.

The result of BICEP2 [2] suggests that the potential of the inflaton is mainly dominated by the quadratic potential [6], but its central value of the BICEP2 suggests that the inflaton would have more steeper potential than quadratic, for instance \( V \sim m^2|\phi|^2 + \lambda |\phi|^3 \) where \( \phi \) is the inflaton. In the previous studies [7, 8], it is showed that if this higher term breaks \( U(1) \) symmetry as like \( V = m^2|\Phi|^2 + \lambda \Phi^n + h.c. \), its breaking produces the rotation of the inflaton in the field plane after the end of the inflation, and then through the decay of the inflaton conserving the baryon number, the inflaton asymmetry is transformed to the large amount of the baryon asymmetry to explain the observed value \( n_b/s \sim 10^{-10} \). In the analysis [7, 8], the dynamics of the inflation is approximated by the quadratic potential as \( V \sim m^2|\Phi|^2 \), however, the exact shape of the potential depends on the phase of the inflaton itself and the strength of the self coupling \( \lambda \), and then the tensor to scalar ratio, which is determined by the curvature of the inflaton potential and the energy scale of the inflation, depends on the phase and coupling. Thus, in the case that the \( U(1) \) symmetry of the inflaton is broken, the abundance of the baryon asymmetry and tensor to scalar ratio is correlated. In this paper, we have studied the possibility whether the inflaton can simultaneously explain the observed
tensor to scalar ratio and the baryon asymmetry for 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 to this paper is as follows. At first in Sec. II., we calculate the dependence of the tensor to scalar ratio $r$ and spectral index $n_s$ on the phase of the the inflaton $\Phi$ and the strength of the coupling $\lambda$. Then, compare the prediction of $r$ and $n_s$ with the result of BICEP2. Then, in Sec. III, we calculate the baryon asymmetry produced by the inflaton. Finally, we conclude this paper in Sec. IV.

II. INFLATION DYNAMICS

In this section, we study the dynamics of the inflaton during the inflation and then give the relation between the spectral index and tensor to scalar ratio. Here we consider the complex inflaton whose $U(1)$ symmetry is weakly broken by the cubic term as

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_p^2}{2} R + |\partial \Phi|^2 - V \right],$$

(1)

where

$$V = m^2|\Phi|^2 + \lambda(\Phi^3 + \Phi^*3) + \frac{\lambda^2}{m^2}|\Phi|^4.$$  

(2)

We have added the quartic term to insure the stability of the potential. Now we consider the regime that the $U(1)$ breaking is small as $\lambda < 10^{-2}m^2/M_p$, thus, we suppose that the dynamics of the inflation is mainly determined by the radial direction of the inflaton. In this case, rewriting the field $\Phi$ by the radial and the phase freedom as $\Phi = \phi/\sqrt{2}\exp(i\theta)$, we can obtain the e.o.m. for the radial direction as

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

(3)

where we have rescaled the coupling $\lambda$ as $\alpha \equiv \lambda M_p/(2m^2)$. We assume that the phase of the inflation $\theta$ is approximately constant during the inflation as $\theta \sim \theta_i$ where $\theta_i$ is the initial phase of the inflaton. The Hubble parameter $H$ is determined by Friedmann equation as

$$H \simeq \sqrt{\frac{1}{3M_p^2} \left[ \frac{1}{2} \dot{\phi}^2 + V \right]},$$

(4)

where

$$V = m^2 \left[ \frac{1}{2} \phi^2 + \sqrt{2}\alpha \cos(3\theta_i) \frac{\dot{\phi}^3}{M_p} + \alpha^2 \frac{\phi^4}{M_p^2} \right].$$

(5)
To constraint the parameter of the potential by observations, we predict the spectral index $n_s$ and the tensor to scalar ratio $r$. These values $n_s$ and $r$ are approximately given by slow roll parameters $\epsilon$ and $\eta$ as

$$n_s = 1 + 2\eta - 6\epsilon,$$

$$r = 16\epsilon,$$

where $\epsilon \equiv M_p^2/2(V_{\phi}/V)^2$, and $\eta \equiv M_p^2V_{\phi\phi}/V$. From (5), we can see that the $U(1)$ breaking term decreases or increases the curvature of the potential, depending on the phase of the inflaton. Thus, the spectral index $n_s$ and the tensor to scalar ratio $r$ at the pivot scale depend on the phase of the inflaton $\theta_i$ and the magnitude of the coupling $\alpha$. To compare $n_s$ and $r$ with the result of the Planck mission [1] and of the BICEP2 [2], we determine the value of $n_s$ and $r$ evaluated at $\phi = \phi(N_e)$ where $N_e$ is the e-folds number before the end of the inflation given as

$$N_e = \int_{\phi_e}^{\phi(N_e)} \frac{V}{V_{\phi}} d\phi,$$

and $\phi_e$ is the field value of the inflaton at the end of the inflation, which is given by solving the slow roll condition as

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

Numerically solving the two equations (8) and (9) where we set the e-folds number as $N_e = 60$, we can obtain the prediction for $n_s$ and $r$ depending $\theta$ and $\alpha$ showed in Fig. 1. From this Fig. 1, we can see that for the case that the self coupling of the inflaton $\alpha$ is smaller than $10^{-3}$, the prediction of $(n_s, r)$ is much the same as that of the quadratic chaotic inflation [6] regardless of the phase of the inflaton, but for the case that $\alpha$ is larger than $10^{-3}$, higher terms in the potential (5) effectively modulate the shape of the potential and then large amount of the gravitational waves is produced, which explain the result of BICEP2.

III. BARYON PRODUCTION

The potential of the inflaton has the $U(1)$ breaking term as the cubic of the inflaton itself (2). Due to this $U(1)$ breaking term, the inflaton has the angular velocity. During the inflation, this velocity for the angular direction has small effects on the dynamics of the inflation compared with that of the radial direction, however, after the end of the inflation, it makes the inflaton rotate in the complex field space and produces the $U(1)$ charge. At
the same time, since the amplitude of the inflaton decreases by the Hubble expansion, the quadratic term dominates over the cubic term, and the $U(1)$ charge of the inflaton becomes time independent. Then, after the decay of the inflaton with baryon conserving interaction, the $U(1)$ charge is transformed to the baryon charge. In this section, we calculate the $U(1)$ charge produced by the rotation of the inflaton, numerically solving the e.o.m. for the complex inflaton field.

Complex inflaton field $\Phi$ evolves as

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\partial V}{\partial \Phi^*} = 0. \quad (10)$$

$U(1)$ breaking term in the potential $V$ makes the rotation of $\Phi$, and then it produces the inflaton asymmetry $\Delta n_\phi$ as

$$\Delta n_\phi = -i(\Phi^*\dot{\Phi} - \dot{\Phi}^*\Phi). \quad (11)$$
Numerically following the evolution of the inflaton $\Phi$ from 60 e-folds before the end of the inflation up to the oscillating phase after the end of the inflation, we can determine the produced charge as showed in Fig. 2 where $A$ is rescaled $U(1)$ charge by the inflaton number as

$$A \equiv \frac{\Delta n_\phi}{n_\phi} = \frac{m}{\rho_\phi} \Delta n_\phi. \quad (12)$$

From this Fig. 2, we can see that the inflaton asymmetry $A$ becomes time independent after

![Graph showing time evolution of the U(1) charge](image)

**FIG. 2.** Time evolution of the $U(1)$ charge. The initial condition set as $\Phi_{ini} = \phi_i/\sqrt{2}\exp(i\theta_i)$ where $\phi_i = 15.4$, $\cos(3\theta_i) = -0.994$. The self coupling $\alpha = 0.001$. Inflation ends at $t \sim 20[1/m]$ in this figure.

the end of the inflation ($t > 20/m$) because of the damping of the cubic term. This inflaton asymmetry is related with the phase of the inflaton $\theta$ and coupling $\alpha$ and its dependence is showed in Fig. 3. This inflaton asymmetry is transformed into baryon number by the decay of the inflaton. Supposing that the decay takes place by the baryon conserving interaction, baryon number is determined by the inflaton asymmetry $A$ as

$$\frac{\Delta n_b}{s} = \frac{3}{4} b_\phi A \frac{T_R}{m} \quad T_R = 10^{13}\text{GeV} \quad \frac{m}{10^{4}\text{GeV}}, \quad (13)$$

$$= 7.5 \times 10^{-11} b_\phi A \frac{T_R}{0.1} \frac{10^{13}\text{GeV}}{m}.$$
FIG. 3. Time evolution of the $U(1)$ charge for $\alpha = 0.01$. The initial condition set as $\Phi_{\text{ini}} = \phi_i / \sqrt{2} \exp(i\theta_i)$ where $\phi_i = 15.4$, $\cos(3\theta_i) = -0.97$. Inflation ends at $t \sim 20[1/m]$ in this figure.

where $b_\phi$ is the baryon number assigned to the inflaton. From this relation (13) and result of the simulation in Fig. 3, we can see that when the reheating temperature is around $10^4$GeV, considerable amount of the baryon number is produced from the decay of the inflaton.

IV. CONCLUSION

In this paper, we have considered the case that the inflaton has a $U(1)$ breaking term in the potential as the cubic term (2). In this case, the curvature of the potential depends on the phase of the inflaton $\theta$ and coupling $\alpha$. Then, the prediction of the spectral index $n_s$ and tensor to scalar ratio $r$ depends on $\theta$ and $\alpha$ as showed in Fig. 1. In the case that the initial phase $\theta_i$ is set as $\cos(3\theta_i) > 0$, the potential of the inflaton becomes steeper than quadratic, which gives large amount of the tensor mode $r$ for $\alpha = 0.01$ favored by the result of BICEP2 [2].

Furthermore, $U(1)$ breaking term in the potential gives the angular velocity for the inflaton in the complex plane of the field and it produces the inflaton asymmetry. Then, after the end of the inflaton, this inflaton asymmetry is transformed into the baryon number...
through the decay of inflaton conserving the baryon number. Numerically following the
evolution of the inflaton, we have calculated the inflaton asymmetry for each initial phase
of the inflaton $\theta_i$ and coupling $\alpha$ as showed in Fig. 3. Using result Fig. 3 and the relation
for the baryon to entropy ration with the inflaton asymmetry $A$ (13), we can see that the
inflaton produces the sufficient amount of baryon asymmetry for $\alpha = 0.01$ if the reheating
temperature is $T_R \sim 10^4$GeV. Thus, in this paper, we have showed that the inflaton which
has $U(1)$ breaking term in potential as cubic of inflaton itself, simultaneously explains the
large amount of the tensor mode reported by BICEP2 [2] and observed baryon assymetry.

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