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SFC BARYOGENESIS MODEL, INFLATIONARY SCENARIOS AND REHEATING IN THE UNIVERSE

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Abstract. We discuss Scalar Field Baryogenesis Model and its capability to produce the observed baryon asymmetry of the Universe in different inflationary scenarios and for different types of reheating. Interestingly enough among the preferred by SFC baryogenesis models are the Starobinsky inflation model and quintessential inflation model, which are also among the preferred ones by the recent Planck data.

1. INTRODUCTION

Locally, up to galaxy cluster scales our Universe is made of matter. Observational data from cosmic rays and gamma rays point that no significant quantities of antimatter exist up to scales of 10-20 Mpc. (see e.g. Steigman 1976, 2008, Stecker 1985, Ballmoos 2014, Dolgov 2015). It is usually assumed that globally our Universe is also baryon-antibaryon asymmetric. The baryon asymmetry is given by:

$$\beta = (N_b - N_{\bar{b}})/N_\gamma, \tag{1}$$

where N_b is the number of baryons,N_γ - the number of photons. This is to a good approximation $\beta \sim N_b/N_\gamma = \eta$, where η is the baryon-to-photon ratio. η is precisely measured today at two epochs, at BBN and CMB epochs. Namely, η measured by BBN theory and D observations is (see e.g. Pettini, Cooke 2012):

$$\eta_D = 6 \pm 0.3 \times 10^{-10} \text{at } 95\% \text{ C.L.},$$

while η measured by CMB anisotropy data (see e.g. Planck Collab. 2016) is:

$$\eta_{CMB} = 6.11 \pm 0.04 \times 10^{-10} \text{at } 68\% \text{ C.L.}$$

Baryogenesis models have to answer the question how and when in the Universe history this net baryon number has been generated. Alas, at present there are many baryogenesis models, which can successfully produce this number at different epochs in the period after inflation and before BBN. Just to mention the most popular ones: GUT baryogenesis (see e.g. Sakharov 1967, Kuzmin, Rubakov, Shaposhnikov 1985), SUSY baryogenesis, baryogenesis through leptogenesis (see e.g. Fukugita, Yanagida 1986), Afleck and Dine baryogenesis (see e.g. Affleck, Dine 1985), Scalar Field Condensate baryogenesis (SFC) (see e.g. Dolgov, Kirilova 1990, 1991), etc.

In what follows we discuss SFC baryogenesis model in different inflationary models and for different reheating scenarios. In the next section the SFC baryogenesis model is briefly described. The second section discusses several inflationary models and the popular reheating scenarios. The third section provides the results concerning the baryon asymmetry generation in different inflationary models by SFC baryogenesis and is mainly based on our recent work (Kirilova, Panayotova, 2020b).

2. SFC BARYOGENESIS MODEL

SFC baryogenesis model was first proposed and analytically studied in refs. (see e.g. Dolgov, Kirilova 1990, 1991). The model was appropriate to explain the very large scale structure in the universe and the quasi-periodicity found at very large scales with typical period of 128 h^{-2} Mpc (see the semi-analytical SFC model in e.g. Chizhov, Kirilova 1996, 2000, Kirilova 2003).

Particle creation processes play important role for the determination of the baryon asymmetry produced in that model (see e.g. Dolgov, Kirilova 1990). Precision numerical account for particle creation processes and their role in baryogenesis was provided in refs (see e.g. Kirilova, Panayotova 2014, 2015; Panayotova, Kirilova 2016).

According to the SFC baryogenesis model a complex scalar field φ exists at the inflationary stage, besides the inflaton ψ. Due to quantum fluctuations baryon excess is generated at the inflationary stage and is contained in the condensate of the field $< \varphi >$, namely $B \sim H_I^3$, where B is the baryon charge density and H_I is the value of Hubble parameter at the inflationary stage.

The potential of φ is chosen of the type:

$$U(\varphi) = m^2\varphi^2 + \frac{\lambda_1}{2}|\varphi|^4 + \frac{\lambda_2}{4}(\varphi^4 + \varphi^{*4}) + \frac{\lambda_3}{4}|\varphi|^2(\varphi^2 + \varphi^{*2}). \tag{2}$$

where the mass parameters of the potential $m \ll H_I$, the self-coupling constants λ_i are with values similar to the gauge coupling constant α_{GUT}. The energy density of φ at the inflationary stage is H_I^4, hence

$$\varphi_o^{max} \sim H_I \lambda^{-1/4}, \quad \dot{\varphi}_o = (H_I)^2. \tag{3}$$

As is obvious, this potential contains B-violating terms at large field amplitudes. At later epoch, these terms become negligible, and when φ decays it transfers the B-charge contained in it to the matter particles.

The evolution of $\varphi(t)$ and B(t) from the end of inflation until the decay of $\varphi(t)$ is described by:

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{1}{4}\Gamma_\varphi\dot{\varphi} + U'_\varphi = 0, \tag{4}$$

$$B = -i(\dot{\varphi}^*\varphi - \dot{\varphi}\varphi^*) \tag{5}$$

where $H = \dot{a}/a$ is the Hubble parameter, $a(t)$ is the scale factor. $\Gamma_\varphi = \alpha\Omega$ is the rate of particle creation, where $\Omega = 2\pi/T$ and T is the period of the field oscillations.

As far as the analytical approach for particle creation process was shown to give up to 2 orders of magnitudes higher values for B in comparison with the exact numerical approach, we have provided numerical account for the particle creation processes. We studied numerically the evolution of $\varphi(t)$ and B(t) in the period after inflation until the B-conservation (BC) epoch developing and executing a computer program in Fortran 77 using Runge-Kutta 4th order method. The system of ordinary differential equations, corresponding to the equation of motion for the real and imaginary part of φ and B contained in it was solved calculating Ω at each step.

We have provided numerical analysis for the evolution of the real and the imaginary components of $\varphi = x + iy$ and for B(t). The parameter range studied was: $H_I = 10^7 - 10^{12}$ GeV, $m = 100 - 1000$ GeV, $\alpha = 10^{-3} - 5 \times 10^{-2}$, $\lambda_1 = 10^{-3} - 5 \times 10^{-2}$, $\lambda_{2,3} = 10^{-4} - 5 \times 10^{-2}$.

In ref.(e.g. Kirilova, Panayotova 2015) we have analyzed over 70 sets of parameters of the model, and for each set we have calculated the final B contained in the condensate $\varphi(t)$ before its decay. The dependence of the produced B on the parameters of the models (namely m, H_I, λ_i and α) were revealed. Namely:

- It was found that B evolution and the final B value decrease with the increase of H_I which is expected since the bigger H_I is, the decrease of β due to particle creation is more efficient.
- The analysis of B dependence on α showed that with increasing α, B evolution becomes shorter and the final B decreases.
- For the dependence on m, we found that B decreases with the increase of the value of m and for big values of H_I this is more clearly expressed.
- B evolution becomes shorter and final B value decreases with increasing λ_1. Possible change of the final B value is within an order of magnitude.
- It was found also that even for small changes of λ_2 and λ_3 the final value of B may differ up to 3 orders of magnitude.

It can be shown that the produced baryon asymmetry in SFC baryogenesis model depends on the baryon excess B, the reheating temperature T_R and the value of the Hubble parameter at the end of inflation H_I. The latter depend on the concrete considered model of inflation and reheating. In the next section we list several popular inflationary models and reheating scenarios.

3. MODELS OF INFLATION AND REHEATING

According to the contemporary cosmological model the universe has experienced a rapid acceleration phase (inflation), followed by reheating, which lead to the standard cosmology radiation dominated phase.

3. 1. INFLATIONARY MODELS

There exist hundreds different models of inflation. Chronologically, the first more semi-realistic inflationary model was proposed by Starobinsky (see e.g. Starobinsky 1980), when he found the solution of Einstein's equations in the presence of curvature squared terms. In case the curvatures are large, it leads to an effective cosmological constant Λ. The *Starobinsky R^2 inflation model* has a potential as follows:

$$V(\psi) = \Lambda^4 \left(1 - e^{-\sqrt{2/3}\psi/M_{\rm pl}}\right)^2 \tag{6}$$

This model is in agreement with Planck18 data (see e.g. Planck Collab. 2020).

New inflation model or slow-roll inflation model, according to which inflation occurred during the scalar field rolling down a potential energy hill, instead of tunneling out of a false vacuum state, was independently proposed by Linde (see e.g. Linde 1982) and Albrecht and Steinhardt (see e.g. Albrecht, Steinhardt 1982) in 1982.

Chaotic inflationary model was proposed in 1983 (see e.g. Linde 1983, 1985). For its realization neither initial thermal equilibrium nor supercooling and tunneling from the false vacuum is required. This inflationary model is characterized by a single monomial potential

$$V(\psi) = \lambda M_{\rm pl}^4 \left(\frac{\psi}{M_{\rm pl}}\right)^p , \tag{7}$$

where inflation proceeds for $\psi > M_{\rm pl}$. Potentials with $p \geq 2$ are disfavored by the Planck18 data but models with simple linear potentials $p = 1$ or $p = 2/3$ and fractional power monomials are allowed.

One of the most elegant and interesting inflationary models is the model of *quintessential inflation* of Peebles and Vilenkin (see e.g. Peebles, Vilenkin 1999). Using a single scalar field potential:

$$V = \lambda(\psi^4 + M^4), \quad \psi < 0, \tag{8}$$

$$V = \frac{\lambda M^8}{\psi^4 + M^4}, \quad \psi \geq 0. \tag{9}$$

the model provides a unified description for the inflation and the current acceleration stage of the Universe. At $-\psi \gg M$ this is a "chaotic" inflation potential (see e.g. Linde 1983, 1985), at $\psi \gg M$ it is a "quintessence" form, $\lambda = 1 \times 10^{-14}$.

There exist the *hybrid models of inflation* in spontaneously broken supersymmetric (SUSY) grand unified theories described by the potential

$$V(\psi) = \Lambda^4 \left[1 + \alpha_h \log\left(\psi/M_{\rm pl}\right)\right], \tag{10}$$

where $\alpha_h > 0$ is a dimensionless parameter. Planck18 data strongly disfavors these inflationary models.

Here we discuss SFC baryogenesis model in the following inflationary models: new inflation (see e.g. Linde 1982, Albrecht, Steinhardt 1982), chaotic inflation (see e.g. Linde 1983), chaotic inflation in SUGRA (see e.g. Nanopoulos, Olive, Srednicki 1983), Shafi-Vilenkin chaotic inflation (see e.g. Shafi, Vilenkin 1984), Starobinsky inflation (see e.g. Starobinsky 1980) and quintessential inflation (see e.g. Peebles, Vilenkin 1999). Preliminary results, for several of these models, were provided recently in ref. (see e.g. Kirilova, Panayotova 2019, Kirilova, Panayotova 2020). Here we present also the results from ref. (Kirilova, Panayotova 2020b).

3. 2. REHEATING

Different scenarios of reheating process are considered in literature. Historically the first scenario of reheating discussed the perturbative decay of the inflaton ψ to fermions (see e.g. Dolgov, Kirilova 1990, Traschen, Brandenberger 1990).

In case this decay is followed by instantaneous reheating, i.e. an instantaneous conversion of the inflaton energy at the end of inflation into radiation and furthermore efficient thermalization of the decay products, it is easy to estimate the reheating temperature T_R.

$$T_R = (90/32\pi^3 g_*)^{1/4}(M_{Pl}\Gamma)^{1/2}, \tag{11}$$

where $g_* \sim 10^2$, $T_R \sim 0.1(M_{Pl}\Gamma)^{1/2}$. Then for $\Gamma = 2H$, $T_R < 10^9$ GeV (see e.g. Kofman, Linde, Starobinsky 1994, 1997).

It is possible, however, and at present it is commonly accepted, that reheating proceeded more rapidly, usually called *preheating*. In the pioneer works (see e.g. Dolgov, Kirilova 1990, Kofman, Linde, Starobinsky 1994, Boyanovski 1995) it was found that the decay of ψ may proceed non-perturbatively into bosons due to broad resonance. In such case the reached temperatures are much higher, $T_R \sim 10^{12}$ GeV.

However, if thermalization is delayed (due to small ψ couplings $\alpha_\psi \sim 10^{-11}$ and/or big m_ψ) - smaller T_R can result. For detail consideration of the different possibilities for thermalization (see e.g. Mazumdar, Zaldivar 2014, Moghaddam 2017).

We have considered different types of thermalization and scenarios for reheating applicable to the studied inflationary models.

4. BARYON ASYMMETRY GENERATED IN DIFFERENT INFLATIONARY MODELS

As a result of the numerical analysis of several studies (see e.g. Kirilova, Panayotova 2019, Kirilova, Panayotova 2020, Kirilova, Panayotova 2020b) we have found that SFC baryogenesis model produces baryon asymmetry by orders of magnitude bigger than the observed one for $T_R \sim 10^{12}$ GeV for the following inflationary models: new inflation (see e.g. Linde 1982, Albrecht, Steinhardt 1982), new inflation model by Shafi and Vilenkin (see e.g. Shafi, Vilenkin 1984), MSSM inflation (see e.g. Ferrantelli 2017), chaotic inflation (see e.g. Linde, 1985, 1990), simplest Shafi-Vilenkin chaotic inflationary model.

For these models SCF baryogenesis needs strong diluting mechanisms in order to reduce the resultant baryon excess at low energies to its observational value today.

SFC baryogenesis model predicts close to the observational value of the baryon asymmetry in the following inflationary models: Modified Starobinsky inflation (see e.g. Kofman, Linde, Starobinski 1985) for $T_R \sim 10^9$ GeV, Chaotic inflation in SUGRA (see e.g. Nanopoulos, Olive, Srednicki 1983), chaotic inflationary model for $T_R \sim 10^9$ GeV, and Quintessential inflation (see e.g. Salo, Haro 2017) for $T_R \sim 10^5$ GeV, see Table 1.

In the table we present the results for these inflationary models. The second column gives the H_I and T_R parameter values of the considered inflationary models, the next columns provide the parameter sets of the SFC baryogenesis model for which the baryon asymmetry close to the observed one is produced, namely the model parameters - the mass of the scalar field m, α, the self-coupling constants λ_i and the value of the produced baryon asymmetry β.

Table 1: Production of baryon asymmetry value for particular sets of SFC model parameters in different inflationary scenarios

Starobinsky Inflation	$H_I = 10^{11}$ GeV; $T_R = 10^9$ GeV	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 100$ GeV, $\beta = 9.3 \times 10^{-10}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 200$ GeV, $\beta = 1.7 \times 10^{-9}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 1.5 \times 10^{-9}$
	$H_I = 10^{12}$ GeV; $T_R = 10^9$ GeV	$\lambda_1 = \alpha = 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 2.1 \times 10^{-9}$	$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 500$ GeV, $\beta = 2.6 \times 10^{-9}$	$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 3 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 6.6 \times 10^{-10}$
		$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 8.0 \times 10^{-10}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 1.2 \times 10^{-10}$	
Quintessential Inflation	$H_I = 10^{12}$ GeV; $T_R = 2 \times 10^5$ GeV	$\lambda_1 = \alpha = 10^{-3}$, $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 4.3 \times 10^{-9}$	$\lambda_1 = 5 \times 10^{-3}$, $\alpha = 10^{-3}$ $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 4.6 \times 10^{-10}$	$\lambda_1 = 10^{-2}$, $\alpha = 10^{-3}$ $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 7.8 \times 10^{-10}$
		$\lambda_1 = 10^{-2}$, $\alpha = 10^{-3}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 1.2 \times 10^{-9}$	$\lambda_1 = 10^{-2}$, $\alpha = 10^{-3}$ $\lambda_2 =$ $\lambda_3 = 5 \times 10^{-3}$, $m = 350$ GeV, $\beta = 1.8 \times 10^{-10}$	$\lambda_1 = 3 \times 10^{-2}$, $\alpha = 10^{-3}$ $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 7.0 \times 10^{-9}$
		$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 10^{-3}$, $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 1.1 \times 10^{-9}$		
Chaotic Inflation in SUGRA	$H_I = 10^{11}$ GeV; $T_R = 1.9 \times 10^9$ GeV	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 100$ GeV, $\beta = 1.8 \times 10^{-9}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 200$ GeV, $\beta = 3.3 \times 10^{-9}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 2.8 \times 10^{-9}$
Chaotic Inflation, Efficient Thermalization	$H_I = 10^{12}$ GeV; $T_R = 6.2 \times 10^9$ GeV	$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 3 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 4.1 \times 10^{-9}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 5.0 \times 10^{-9}$	$\lambda_1 = \alpha =$ 5×10^{-2}, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 7.4 \times 10^{-10}$
Chaotic Inflation, Delayed Thermalization	$H_I = 10^{12}$ GeV; $T_R = 4.5 \times 10^8$ GeV	$\lambda_1 = 10^{-2}$, $\alpha = 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 9.5 \times 10^{-10}$	$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 10^{-2}$ $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 4.5 \times 10^{-9}$	$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 10^{-2}$ $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 500$ GeV, $\beta = 1.2 \times 10^{-9}$
		$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 3 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 3.0 \times 10^{-10}$	$\lambda_1 = 5 \times 10^{-2}$, $\alpha = 5 \times 10^{-2}$ $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 3.6 \times 10^{-10}$	

It is remarkable that from the results for successful production of the baryon asymmetry value in case of Starobinsky, chaotic and SUGRA inflationary scenarios for $T_R \in [4.5 \times 10^8 - 6.2 \times 10^9]$ GeV and $H_I \in [10^{11}, 10^{12}]$ GeV, the SFC parameters can be determined. Namely they should lie within the following ranges: $m \sim 350$ GeV (with one exception) $\alpha \in [10^{-2}, 5 \times 10^{-2}]$, $\lambda_1 \sim 5.10^{-2}$, $\lambda_{2,3} \in [10^{-3}, 10^{-2}]$. Fixing the inflationary model we can set the parameters of the SFC baryogenesis model, for illustration see Fig. 1 in Kirilova & Panayotova (2020b).

In case of quintessential inflation, however, for $H_I \sim 10^{12}$ GeV and $m \sim 350$ GeV, the reheating temperature and the rest of the SFC parameters - the coupling constants, are much lower $T_R \sim 2.10^5$ GeV, $\alpha \sim 10^{-3}$, $\lambda_1 \in [5.10^{-3}, 10^{-2}]$, $\lambda_{2,3} \in [10^{-4}, 5.10^{-3}]$.

5. CONCLUSIONS

We discuss Scalar Field Condensate Baryogenesis Model and its capability to produce the observed baryon asymmetry of the Universe in different inflationary scenarios and for different types of reheating.

On the basis of the numerical analysis of the evolution of the baryon charge produced in SFC baryogenesis model and the estimation of the produced baryon asymmetry for different sets of models parameters and different reheating temperatures of several inflationary scenarios we have shown that baryon asymmetry close to the observed one is generated in the modified Starobinsky inflation, chaotic inflationary scenario (delayed thermalization), chaotic inflation in SUGRA and Quintessential inflation. In new inflationary scenario, chaotic inflation with high reheating temperatute and MSSM inflation baryon asymmetry is strongly overproduced by several orders of magnitude.

It is noticeable that Starobinsky inflationary scenario and the quintessential inflation are also among the preferred scenarios by the latest Planck CMB data analysis constraints on inflationary models.

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