The dependence of the baryon asymmetry generation on the couplings of the baryon charge carrying scalar field

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Abstract. We discuss a scalar condensate baryogenesis model with a complex scalar field φ, carrying a baryon charge $B \neq 0$, generated at inflation. We follow the evolution of the baryon charge carrying scalar field, accounting for particle creation processes, known to be essential for B evolution and for the correct determination of the final value of B at φ decay. Here we study numerically the dependence of the produced baryon asymmetry on model parameters and find the range of parameters, for which the model predicts B value corresponding to the locally observed value of the matter-antimatter asymmetry. In particular, in this work we explore the effect of variation of self coupling constants of φ on B and φ evolution.
Key words: Scalar Condensate Baryogenesis, Particle Creation, Baryon Asymmetry

1. Introduction

One of the most intriguing physical characteristics of our Universe is the existence of baryon asymmetry in our surroundings (within radius of ~ 10 Mpc). Namely, a strong predominance of matter over antimatter is indicated by cosmic and gamma rays observations.

The baryon asymmetry usually parameterized as

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \quad (1)$$

where n_B is the baryon number density, $n_{\bar{B}}$ is the antibaryon number density and n_γ - photon number density, is measured in our neighborhood to be:

$$\beta \sim \frac{n_B}{n_\gamma} \sim 6.1 \times 10^{-10} \quad (2)$$

The baryon density n_B/n_γ is determined in different ways - the most precise determinations are based on the consistency between theoretically obtained and observationally measured abundances of the light elements produced in BBN (Beringer (PDG) 2012), on the measurements of Deuterium towards low metallicity quasars combined with BBN data (Pettini 2012) or on the measurements of the CMB anisotropy (Larson, et. al. 2011, Bennett, et. al. 2013).

In case this locally observed asymmetry is a global characteristic of the Universe, it could be due to the generation of a baryon excess at some early stage of the Universe, which evolved to the value observed today. We do not yet know the exact baryogenesis mechanism which produced the observed asymmetry's sign and value and that is why different baryogenesis possibilities exist (Dolgov 1992, Dine 2003). Constraints from observational data are used to find the most realistic baryogenesis scenarios and to fix their parameters.

2. The model description

Here we discuss a scalar field condensate baryogenesis model, a variety of the discussed in previous works models (Dolgov & Kirilova 1991, Kirilova & Chizhov, 1996, 2000), based on the Affleck and Dine baryogenesis scenario (Affleck & Dine 1985). We examine the case when after inflation there exist two scalar fields - the inflaton ψ and the scalar field φ and the inflaton density dominates: $\rho_\psi > \rho_\varphi$. Hence, when at the end of inflation period $\psi = m_{PL}(3\pi)^{-1/2}\sin(m_\psi t)$ the Hubble parameter is $H = 2/(3t)$. In the expanding Universe, φ satisfies the equation of motion:

$$\ddot{\varphi} - a^{-2}\partial_i^2\varphi + 3H\dot{\varphi} + \frac{1}{4}\Gamma\dot{\varphi} + U'_\varphi = 0, \quad (3)$$

where $a(t)$ is the scale factor, $H = \dot{a}/a$, Γ accounts for the particle creation processes and $U(\varphi)$ - the field potential is of the type:

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

The potential is chosen such that the baryon charge, contained in φ, is not conserved at large values of the field due to its self-interaction terms. The mass parameters of the potential are assumed small in comparison with the Hubble constant during inflation $m \ll H_I$, otherwise oscillation of φ will be damped in several Hubble times. m is the mass after symmetry breaking. In supersymmetric theories the constants λ_i are of the order of the gauge coupling constant α. A natural range of m in supersymmetric models is $10^2 \div 10^4$ GeV. In this work we examine specifically the dependence of the B evolution and its final value on λ_i, within a wide range of variation of their values.

The initial values for the field variables can be derived from the natural assumption that the energy density of φ at the inflationary stage is of the order H_I^4, then

$$\varphi_o^{max} \sim H_I\lambda^{-1/4} and \quad \dot{\varphi}_o = (H_I)^2. \quad (5)$$

After inflation φ starts to oscillate around its equilibrium point and its amplitude decreases due to the Universe expansion and the particle creation by the oscillating scalar field. Fast oscillations of φ result in particle creation due to the coupling of the scalar field to fermions $g\varphi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha$ (Dolgov & Kirilova, Chizhov & Kirilova 1996). The term $\Gamma\dot{\varphi}$ in the equations of motion accounts for the damping of φ as a result of particle production processes. For $\lambda_i^{3/4} > g$, Γ exceeds the ordinary decay rate of φ at the stage of baryon non-conservation and the amplitude of φ is damped $\varphi \to \varphi\exp(-\Gamma t/4)$. Hence, in case $\Gamma = const$ the baryon charge, contained in the φ condensate, is reduced exponentially due to particle creation at this stage with considerable baryon violation and will not survive till φ decays to quarks and leptons and transfers its charge to the matter components of the Universe. I.e. no successful baryogenesis is possible.

However, in case Γ is a decreasing function of time the damping process may be slow enough for the baryon charge contained in φ to survive until the B-conservation epoch (Dolgov & Kirilova 1991).

During B-conservation epoch B is transferred to the Universe plasma and excess of matter or of antimatter could be produced. This baryon charge, eventually further diluted by some entropy generating processes, determines the observed baryon asymmetry.

3. Numerical analysis and results

We have followed numerically the evolution of the scalar field φ and the baryon excess $B(t) = -i(\dot{\varphi^\star}\varphi - \dot{\varphi}\varphi^\star)$ for the period after the inflationary stage until the B-conservation epoch when φ decays, i. e. through the energy range $10^{12} \div 100 \quad GeV$. The dependence of φ and B on α, m and H_I has been explored in previous works (Kirilova & Panayotova 2006, Kirilova & Panayotova 2007).

The evolution of B was studied varying Hubble value at the inflationary stage. It has been found that B evolution becomes longer and the final B value decreases with H_I increase, when the other model parameters remain fixed.

The analysis of the model dependence on m showed that for lower values of m, B evolution becomes shorter and the final B value decreases. This is an expected behavior, as far as m value defines the onset of B-conservation epoch.

The dependence of B on α is very strong, as can be expected, knowing that particle creation processes play essential role for the evolution of φ and B, contained in it, and keeping in mind the analytical estimation $\Gamma = \alpha\Omega$ (Dolgov & Kirilova, 1990).

In refs (Kirilova & Chizhov 1996, Kirilova & Panayotova 2006) it has been found that the precise numerical account for particle creation processes gives different results for B evolution and the final value of B than the analytical estimation $\Gamma = \alpha\Omega$, where $\Omega \sim \lambda_1^{1/4}\varphi$. The difference may be considerable - about one order of magnitude in the final B value. Therefore, precise numerical account of particle creation is necessary for more reliable calculation of the Universe's baryon asymmetry in this model. As expected, when increasing α, B evolution becomes shorter and the final B decreases.

Here we extend our numerical analysis of the evolution of B and φ to explore also the dependence of the B generation on the coupling constants λ_i. We provide numerical analysis for the following fixed values of the model parameters: $\alpha = 10^{-3}$, $H_I = 10^{12}GeV$, $m = 350GeV$ while varying λ_i: $\lambda_1 = 10^{-3} \div 3 \times 10^{-2}$ and $\lambda_{2,3} = 10^{-4} \div 5 \times 10^{-3}$, correspondingly. As far as λ_i constants are not known, it is interesting to find the range of these parameters corresponding to successful B generation. In this work we explore the effect of their variation on B and φ evolution. We have provided a precise numerical analysis for different sets of parameters of the model using Runge-Kutta 4th order method to solve the system of ordinary differential equations representing the equations of motion for the real and the imaginary part of $\varphi(t)$.

Figure 1 presents the dependence of the baryon charge, at the B-conservation epoch, on the value of the λ_1 coupling constant. The analysis shows that when increasing λ_1 B evolution becomes shorter and the final B value decreases. The effect is not very strong but is enough to produce a difference in the final B value of an order of magnitude.

In Fig. 2 the results of the dependence of B and the final B value on $\lambda_{2,3}$ are presented. In this case the evolution of B tends to become longer with increasing $\lambda_{2,3}$ and the final value of B decreases. The effect provides a difference in the final B value of an order of magnitude.

For certain λ_i values within the studied ranges of λ_i it is possible to produce the baryon excess necessary to explain the observed baryon asymmetry.

In conclusion, we have found that although the dependence of baryon generation on λ_i is not as strong as the dependence on α, it is considerable. Thus this study is important for determination of the parameters range for the successful baryogenesis model.

4. Conclusion

In this work we have numerically followed the evolution of the baryon charge carrying scalar field φ and the baryon excess B from postinflationary stage until the B-conservation epoch when φ decays. In particular, we studied the dependence of φ and B on φ self coupling constants λ_i. We have found that the variation of λ_i within the studied range is significant for the baryon excess production in our model. It results in an order of magnitude change of the final B value. Thus, in this baryogenesis model it is possible to produce the baryon excess necessary to explain the observed baryon asymmetry for certain sets of parameters values within their natural range.

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References

Affleck I., Dine M., 1985, *Nucl. Phys., B249, p. 361*
Bennett C., et. al., 2013, *arXiv:1212.5225 [astro-ph.CO]*
Beringer J., et. al. (PDG), 2012, *Phys. Rev. D86, p. 010001*
Chizhov M., Kirilova D., 1996, *AATr, 10, p. 69*
Dine M., 2003, *Rev. Mod. Phys., 76, p. 1*
Dolgov A., Kirilova D., 1990, *Yad. Phys. 51 273. p. 335*
Dolgov A., 1992, *Phys. Rep., 222, p. 311*
Dolgov A., Kirilova D., 1991, *J. Moscow Phys. Soc. 1, p. 217*
Kirilova D., Chizhov M., 2000, *MNRAS, 314, p. 256*
Kirilova D., Panayotova M., 2006, *ICTP Int. Report IC/IR/2006/009*
Kirilova D., Panayotova M., 2007, *Bulg. J. Phys., 34, p. 330*
Larson D., et. al., 2011, *ApJS, 192, p. 16*
Pettini M., Cooke R., 2012, *arXiv:1205.3785 [astro-ph.CO]*

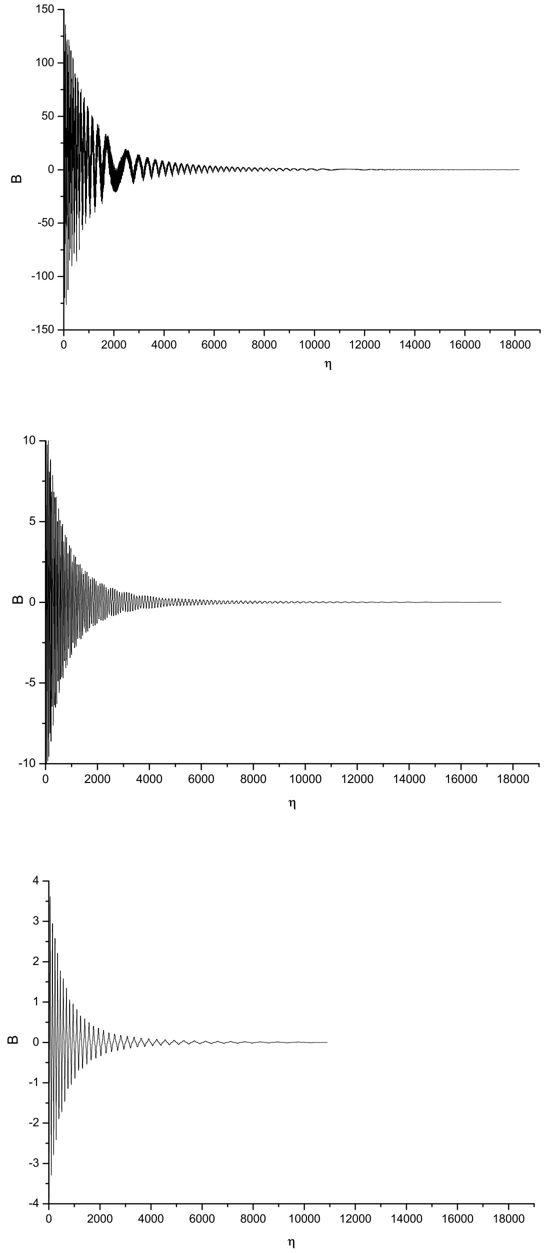

Fig. 1. The evolution of the baryon charge $B(\eta)$, where $\eta = 2(tH_I)^{1/3}$, for $\alpha = 10^{-3}$, $m = 350GeV$, $H_I = 10^{12}GeV$, $\lambda_{2,3} = 10^{-4}$ and $\lambda_1 = 10^{-3}$ (up), $\lambda_1 = 10^{-2}$ (middle) and $\lambda_1 = 3 \times 10^{-2}$ (down).

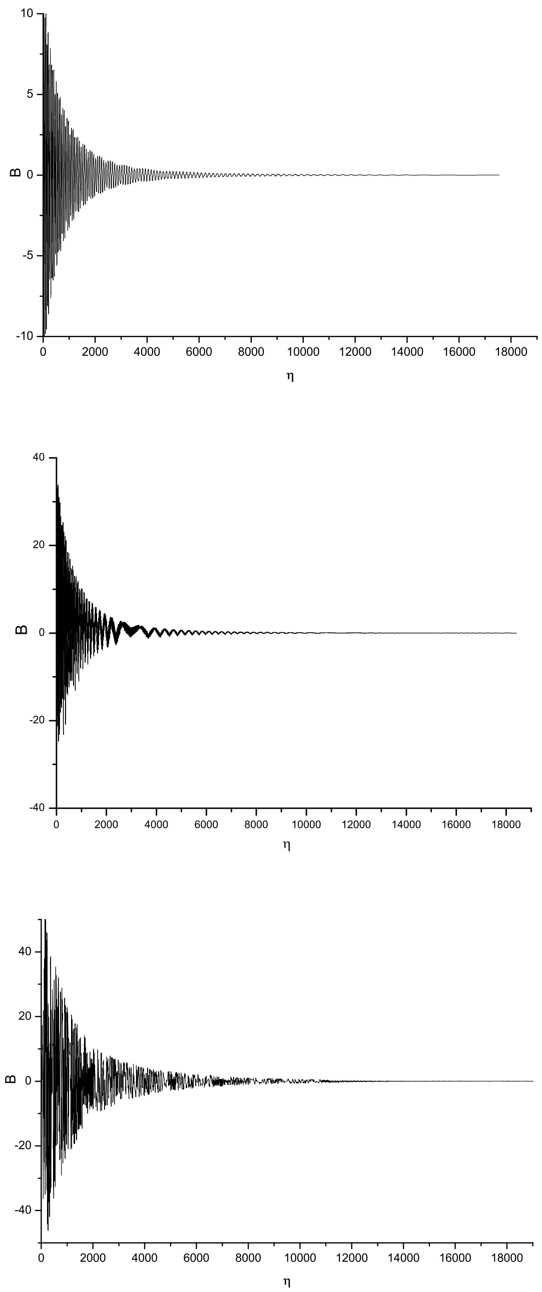

Fig. 2. The evolution of the baryon charge $B(\eta)$, where $\eta = 2(tH_I)^{1/3}$, for $\alpha = 10^{-3}$, $m = 350GeV$, $H_I = 10^{12}GeV$, $\lambda_1 = 10^{-2}$ and $\lambda_{2,3} = 10^{-4}$ (up), $\lambda_{2,3} = 10^{-3}$ (middle) and $\lambda_{2,3} = 5 \times 10^{-3}$ (down).