Axion Dark Radiation and its Dilution

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Axions in the Peccei-Quinn (PQ) mechanism provide a promising solution to the strong CP problem in the standard model of particle physics. Coherently generated PQ scalar fields could dominate the energy density in the early Universe and decay into relativistic axions, which would conflict with the current dark radiation constraints. We show that a thermal inflation driven by a $U(1)$ gauged Higgs field dilutes such axions. We discuss an available baryogenesis mechanism for the $U(1)_{B-L}$ gauge symmetry.

1 Introduction

The standard model (SM) for elementary particles has been successful in describing high energy phenomena at colliders. One shortcoming of the SM is the strong CP problem. A mechanism introduced by Peccei and Quinn [1] with the corresponding global $U(1)$ symmetry, Peccei-Quinn (PQ) symmetry, elegantly solves this problem. Although the original model has been ruled out by the experimental results, so-called invisible axion models [2, 3] are promising and viable models. As a consequence of the global $U(1)$ PQ symmetry breaking, the axion field, which is its Nambu-Goldstone (NG) boson and becomes a pseudo-NG boson due to the QCD anomaly, appears.

Cosmology based on particle theory with the PQ symmetry would be interesting but not so simple. One appealing feature is, as it is well-known, that the axion is a promising candidate for dark matter in our Universe [4]. On the other hand, for example, one may imagine the following nontrivial evolution of the early Universe. The PQ scalar field could be produced in a coherent oscillation due to its scalar nature and temporally dominate the energy density of the Universe if its decay rate is very small because of suppressed couplings. The radial direction of the PQ scalar field[1] would mostly decay into axions or SM particles through loop processes. Those overproduced massless axions act as dark radiation which is nowadays stringently constrained [5].

Thermal inflation is a well-known mechanism to dilute unwanted relics [6] and is driven by a scalar field φ, often called the flaton. We show the condition of successful thermal inflation driven by a gauged $U(1)$ Higgs field to dilute axions generated by the late decay of the dominated PQ scalar [7]. If this flaton φ is a gauge singlet and has an (approximate) global $U(1)$, then the axions associated with the flaton could be produced again as shown in Ref. [8]. Thus, in order to avoid this problem, we consider that a flaton field is charged under a local $U(1)$ symmetry.

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[1] From now on, we simply call it the PQ scalar.

We also discuss the implication in the case that this local $U(1)$ symmetry is identified with gauged $U(1)_{B-L}$ [9].

2 Thermal inflation in an axion-dominated Universe

We consider the scalar potential of the flaton φ as

$$V(\varphi) = V_0 - m^2|\varphi|^2 + \frac{|\varphi|^{2n}}{\Lambda^{2(n-2)}}. \tag{1}$$

A flaton field φ is assumed to be in thermal equilibrium through interactions with particles in the hot thermal bath and hence the thermal mass term,

$$\delta V = \frac{g_\varphi}{24} T^2 |\varphi|^2, \tag{2}$$

with T being the temperature of the thermal plasma, is added in the scalar potential. Here, g_φ is parametrizing the coefficient, while sometimes we may use an effective coupling with another particle $h \equiv \sqrt{g_\varphi}$ instead of g_φ in the rest of this paper.

The resultant number of e-fold in the axion-dominated Universe is estimated as

$$\begin{aligned} N_{2n} &= -\ln 4\sqrt{3} - \frac{1}{4}\ln\left(\frac{\pi^2}{30}g_*\right) + \frac{1}{2}\ln\frac{\Lambda}{M_P}h \\ &\quad -\frac{1}{4}\ln\frac{n^2}{4(n-1)} + \frac{1}{2}(n-2)\ln\left(\frac{M_P}{v}\right), \end{aligned} \tag{3}$$

with M_P being the reduced Planck mass. We list various physical quantities in Table 1.

Λ(GeV)	h	v(GeV)	T_i(GeV)	T_f(GeV)	N	ΔN_{eff}	T_R(GeV)
10^{16}	8.27×10^{-3}	10^8	2.79×10^3	1.03×10^3	1.00	0.05	5.9×10^3
10^{16}	8.27×10^{-2}	10^{10}	2.79×10^6	1.03×10^6	1.00	0.05	5.9×10^6
10^{16}	8.27×10^{-1}	10^{12}	2.87×10^9	1.03×10^9	1.00	0.05	5.9×10^9

Table 1: Quantities in thermal inflation by the potential (1).

3 Relic abundances

3.1 Axion dark radiation

As we have seen, if the PQ scalar field dominates the energy density of the Universe, its decay produces many axions, and the Universe ends up with relativistic axion domination. When the total energy density ρ_{total} from dominated axion ρ_a and subdominant radiation ρ_{rad} becomes comparable with $V(\varphi)$, $t = t_i$, the thermal inflation begins. After the thermal inflation, φ decays into SM particles and potentially non-SM particles again. The resultant axion dark radiation contribution is estimated in terms of ΔN_{eff} as

$$\Delta N_{eff} = \frac{43}{7}\left(\frac{43/4}{g_*}\right)^{1/3} \times \left.\frac{\rho_a}{\rho_{rad}}\right|_{H=\Gamma}. \tag{4}$$

3.2 Reheating temperature and possible baryogenesis scenarios

We adopt the reheating temperature after thermal inflation T_R under the assumption of the instantaneous reheating $\Gamma = H(t_f)$, which gives the highest reheating temperature. Available baryogenesis mechanisms depend on T_R.

For $T_R \gtrsim 10^9$ GeV, thermal leptogenesis by the lightest heavy RH neutrino decay of those with hierarchical masses is one of the simplest scenarios of baryogenesis [10, 11].

Nonthermal leptogenesis by RH neutrinos with hierarchical masses is available for a reheating temperature 10^9 GeV $\gtrsim T_R \gtrsim 10^6$ GeV [12]. If this local $U(1)$ is in fact the gauged $U(1)_{B-L}$ symmetry, φ is identified with the Higgs field to break this symmetry with the $B-L$ charge 2, and the decay φ into two RH neutrinos N_R is nothing but nonthermal production of N_R.

For $T_R \lesssim 10^6$ GeV, low-scale thermal leptogenesis requires an enhancement of CP violation. Here, for information, we note two examples. One is the so-called resonant leptogenesis, where two RH neutrino masses are strongly degenerated and CP violation is enlarged due to RH neutrino self-energy [13]. Another way is an extension of the Higgs sector, e.g., neutrinophilic Higgs model [14]. Another promising scenario would be electroweak baryogenesis [15].

3.3 Results

We summarize the viable parameter space and available baryogenesis mechanisms for some benchmark points. In order to have large enough CP violation $\varepsilon \gtrsim 10^{-6}$ in the N_R decay, we suppose $M_{N_R} \simeq 10^9$ GeV [16, 17] and that the decay $\varphi \to N_R N_R$ is kinematically forbidden for $m_\varphi < 10^9$ GeV. We consider two cases of the PQ scalar VEV, $v = 10^{10}$ and 10^{12} GeV. We note that, for baryogenesis, the conclusion is the same for $v \lesssim 10^{10}$ GeV.

3.3.1 $n = 3, v = 10^{12}$ GeV case

For most of the parameter space, we have $T_R > 10^9$ GeV. Thermal leptogenesis could work.

3.3.2 $n = 3, v = 10^{10}$ GeV case

$T_R > 10^6$ GeV is realized, however, $m_\varphi \lesssim 10^9$ GeV. Nonthermal leptogenesis by the φ decay does not work because the φ decay is kinematically forbidden. A low-scale thermal leptogenesis with an enhanced CP violation or the electroweak baryogenesis with the extension of the Higgs sector is needed.

4 Summary

We have investigated scenarios with successful thermal inflation by a gauged $U(1)$ Higgs flaton field to dilute axions generated by late decay of the dominated PQ scalar field. We find that a promising viable baryogenesis is high- or low-scale thermal leptogenesis or the electroweak baryogenesis if this $U(1)$ symmetry is the gauged $U(1)_{B-L}$.

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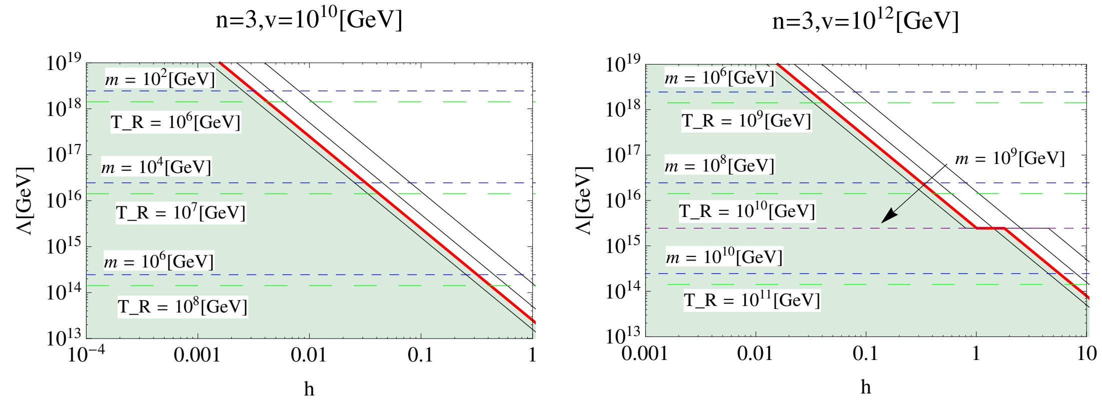

Figure 1: Contours of the resultant $\Delta N_{\rm eff} = 1, 0.4$ (thick red), 0.1, and 0.01 with solid lines from left to right, the mass of φ with dashed lines and the possible maximal reheating temperature after thermal inflation T_R with long dashed lines. The shaded region corresponds to $\Delta N_{eff} > 0.4$ which is disfavored by the Planck (2015) data.

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