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Can Decaying Particles Raise the Upperbound on the Peccei-Quinn Scale? *

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Abstract

We have reexamine the effect of entropy production on the cosmic axion density and find that the Peccei-Quinn scale F_a larger than about 10^{15} GeV is not allowed even if large entropy is produced by the decays of coherent oscillations or non-relativistic massive particles. We stress that this result is independent of the details of models for the decaying particles.

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1 Introduction

The axion [1, 2, 3, 4] is the Nambu-Goldstone boson associated with the Peccei-Quinn symmetry breaking which was invented as a natural solution to the strong CP problem in QCD [5]. The breaking scale F_a of Peccei-Quinn symmetry is stringently constrained by laboratory experiments, astrophysics and cosmology. The consideration of cooling processes due to the axion emission in red giants and SN1987A requires that F_a should be greater than about 10^{10} GeV[6]. On the other hand, F_a should be less than about 10^{12}GeV so that the energy density of the coherent oscillations of the axion field should be less than the critical density of the universe [7]. Thus the allowed range of F_a is given between 10^{10} GeV and 10^{12} GeV which is called the axion window.

However, Steinhardt and Turner [8] showed that the entropy production due to the first order phase transition or the out-of-equilibrium decays of massive particles dilutes the axion density and makes the upperbound on F_a as large as 10^{18}GeV. The upperbound ($F_a \lesssim 10^{18}$ GeV) was obtained by requiring the entropy production should not dilute the baryon density too much, *i.e.* the dilution factor should be less than 10^6 assuming the initial baryon-to-entropy ratio to be at most 10^{-4}.

However, in the case of the decaying particles, the analysis in ref. [8] is unsatisfactory since the authors assumed the radiation dominated universe when the axion field starts to oscillate. As we will show below, it is more reasonable to consider that the universe is already decaying-particle dominated at that epoch. Therefore, we reexamine the entropy production from the decays of coherent oscillations or light particles and obtain the upperbound, $F_a \lesssim 10^{15}$ GeV, by imposing the reheating temperature to be less than 1 MeV in order to keep the success for the primordial nucleosynthesis in the big-bang cosmology. We stress that this result is independent of detailed models for the decaying particles.

2 Cosmological Evolution

Let us consider the cosmological evolution of the axion field and the coherent oscillation of the field ϕ with potential $m_\phi^2\phi^2/2$ and density ρ_ϕ. This coherent oscillation is equivalent to the non-relativistic decaying particle with the same energy density. Therefore, we only consider the coherent oscillation hereafter. We assume that ρ_ϕ dominates the energy density of the universe when the oscillation of the axion starts. If the universe is radiation-dominated, the axion starts to oscillate at $T \simeq 1$ GeV. In this case the entropy production factor is given by $\sim [(T_R^4/T_1^4)(a(T_R)/a(T_1))^4]^{3/4} \simeq (T_R/T_1)^3(\rho_\phi(T_1)/T_R^4) \lesssim (T_1/T_R)$, where

a is the scale factor of the universe, T_R the temperature just after the ϕ decay and T_1 the temperature at which the axion field starts to oscillate. Since T_R should be greater than 1 MeV to keep the success of primordial nucleosynthesis, the entropy production factor becomes less than $O(10^3)$. Therefore, the ϕ-dominated universe is a good assumption as far as the large entropy production (with the entropy production factor greater than $O(10^3)$) is considered.

The axion starts to oscillate at $t = t_1$ when $3H \simeq m_a$. Thus at $t = t_1$,

$$\rho_\phi(t_1) \simeq \frac{m_a(T_1)^2 M^2}{3}, \tag{1}$$

where $M = 2.4 \times 10^{18}$GeV is the gravitational mass and $m_a(T)$ is the axion mass which depends on the temperature T as [9]

$$m_a(T) \simeq \begin{cases} 0.1 m_a (\Lambda_{\rm QCD}/T)^{3.7} & \text{for } T \gtrsim \Lambda_{\rm QCD}/\pi, \\ m_a & \text{for } T \lesssim \Lambda_{\rm QCD}/\pi, \end{cases} \tag{2}$$

where $\Lambda_{\rm QCD} \simeq 0.2$ GeV, and m_a is the axion mass at $T = 0$.

Until the coherent ϕ oscillation decays, the ratio of the axion- to ϕ-number densities stays constant. Therefore, the ratio of the energy density of the axion ρ_a to that of ϕ, ρ_ϕ, is expressed as

$$\frac{\rho_a}{\rho_\phi} = \frac{m_a}{m_\phi}\frac{m_a(T_1)F_a^2\theta^2}{\rho_\phi(t_1)/m_\phi} = \frac{3}{2}\frac{F_a^2\theta^2}{M^2}\frac{1}{\xi(T_1)}, \tag{3}$$

where $\theta \sim O(1)$[1] is the initial axion amplitude in units of F_a and $\xi(T_1) \equiv m_a(T_1)/m_a \leq 1$.

The ϕ decay occurs when $3H \simeq \Gamma_\phi$ where Γ_ϕ is the decay rate of ϕ. The cosmic temperature T_R just after the decay is given by

$$T_R \simeq \left(\frac{10}{\pi^2 g_*}\right)^{1/4} \sqrt{M\Gamma_\phi} = 0.55\sqrt{M\Gamma_\phi}, \tag{4}$$

where g_* is the effective number of massless degrees of freedom and we have taken $g_* =$ 10.75. The entropy density just after the decay is given by

$$s(T_R) = \frac{2\pi^2}{45} g_* T_R^3. \tag{5}$$

Since the energy density of the coherent ϕ oscillation just before the decay is $M^2\Gamma_\phi^2/3$, the axion density at the decay epoch becomes

$$\rho_a(T_R) \simeq \left(\frac{\rho_a}{\rho_\phi}\right)\rho_\phi(T_R) \simeq 5.3 T_R^4 M^{-2} F_a^2 \theta^2 \xi(T_1)^{-1}. \tag{6}$$

[1] θ takes $\pi/\sqrt{3}$ in the non-inflationary universe [9].

Then we can estimate the axion-to-entropy ratio as[2]

$$\frac{\rho_a}{s} \simeq 1.1 T_R F_a^2 \theta^2 M^{-2} \xi(T_1)^{-1}. \tag{7}$$

This value should be compared with the ratio of the present values of the critical density $\rho_{cr,0}$ to the entropy density s_0, which is given by

$$\frac{\rho_{cr,0}}{s_0} \simeq 3.6 \times 10^{-9} h^2 \mathrm{GeV}, \tag{8}$$

where h is the present Hubble constant in units of 100km/sec/Mpc. Then, the density parameter of axion Ω_a is expressed as

$$\begin{aligned} \Omega_a h^2 &\simeq 3.1 \times 10^8 \mathrm{GeV}^{-1} T_R F_a^2 \theta^2 M^{-2} \xi(T_1)^{-1} \\ &\simeq 5.3 \left(\frac{T_R}{1\mathrm{MeV}}\right) \left(\frac{F_a \theta}{10^{16}\mathrm{GeV}}\right)^2 \xi(T_1)^{-1}. \end{aligned} \tag{9}$$

3 Constraint on F_a

Since the entropy production should occur before the primordial nucleosynthesis, T_R should be higher than about 1 MeV. Then, from eq.(4), we get $\Gamma_\phi \gtrsim 1.3 \times 10^{-24}$ GeV. Requiring $\Omega_a h^2 \lesssim 1$ and taking $\xi \leq 1$ into account, we can obtain the upper limit on F_a from eq.(9):

$$F_a \lesssim 4.4 \times 10^{15} \theta^{-1} \mathrm{GeV}. \tag{10}$$

The above constraint might be more stringent if the cosmic temperature at t_1 is greater than about 0.1 GeV and hence $\xi \ll 1$. Therefore, we need to estimate T_1 and $\xi(T_1)$. For this end, we must take account of the fact that the temperature decreases as $T \propto a^{-3/8}$.[3] Using $a(T_R)/a(T_1) \simeq (\rho_\phi(T_R)/\rho_\phi)^{-1/3} \simeq (m_a(T_1)/\Gamma_\phi)^{2/3}$,

$$\frac{T_1}{T_R} \simeq \left(\frac{m_a(T_1)}{\Gamma_\phi}\right)^{1/4}. \tag{11}$$

From eqs.(2), (4) and (11), T_1 is given by

$$T_1 \simeq 0.07\mathrm{GeV} \left(\frac{T_R}{1\mathrm{MeV}}\right)^{0.26} \left(\frac{F_a}{10^{15}\mathrm{GeV}}\right)^{-0.13}. \tag{12}$$

When $T_R \simeq 1$ MeV and $F_a \simeq 10^{15}$ GeV, T_1 is about 0.1 GeV. At such low temperatures, the axion mass is almost equal to its zero-temperature value, *i.e.* m_a. Therefore, $\xi(T_1) \simeq 1$ and the constraint (10) is correct.

[2]This formula (7) is applicable for $T_R \lesssim 1$ GeV.

[3]Note that the decay does not occur instantaneously. During the ϕ decay, the temperature does not decrease as a^{-1} due to the heating effect of the decay. For details, see ref. [9].

4 Conclusion

We have reexamined the effect of the large entropy production on the axion density in the early universe and have found that the Peccei-Quinn scale F_a larger than about 10^{15} GeV is not allowed. This upperbound is three orders of magnitude larger than that without entropy production but much smaller than the previous estimation [8]. In the present analysis, we have assumed that the universe is dominated by the coherent oscillation or the decaying particle when the axion starts to oscillate. On the other hand the radiation-dominated universe was assumed in the previous work. However, when the entropy is increased by a factor greater than $O(10^3)$, our assumption is correct. On the other hand, in the case where the entropy production factor is less than $O(10^3)$, the upperbound on Peccei-Quinn scale F_a is raised up by $O(10^3)$ at most which completes our conclusion.

We have not discussed the dilution of the cosmological baryon number asymmetry because it depends on the details of the models for baryogenesis. For example, if we adopt the Affleck-Dine mechanism for baryogenesis [10], the ϕ decay with the reheating temperature about 1 MeV is consistent with the observed baryon number of the universe [11].

References

[1] R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. **38** (1977) 1440.

[2] F. Wilczeck, Phys. Rev. Lett. **40** (1978) 279.

[3] J.E. Kim, Phys. Rev. Lett. **43** (1979) 103;
M. Shifman, A. Vainshtein and V. Zakharov, Nucl. Phys. **B166** (1980) 493.

[4] M. Dine, W. Fischler and M. Srednicki, Phys. Lett. **B104** (1981) 199.

[5] G. 't Hooft, Phys. Rev. Lett. **37** (1976) 8.

[6] G. Raffelt, Phys. Rep. **198** (1990) 1;
M.S. Turner, Phys. Rep. **197** (1990) 67.

[7] J. Preskill, M. Wise and F. Wilczek, Phys. Lett.**B180** (1983) 127;
L. Abbott and P. Sikivie, Phys. Lett.**B180** (1983) 133;
M. Dine and W. Fischer, Phys. Lett.**B180** (1983) 137.

[8] P.J. Steinhardt and M.S. Turner, Phys. Lett. **B129** (1983) 51.

[9] E.W. Kolb and M.S. Turner, The Early Universe, Addison-Wesley (1990).

[10] I. Affleck and M. Dine, Nucl. Phys. **B249** (1985) 361.

[11] T. Moroi, M. Yamaguchi and T. Yanagida, Phys. Lett. **B342** (1995) 105.

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