Physics Letters B 719 (2013) 9–13

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Opening the window to the cogenesis with Affleck–Dine mechanism in gravity mediation

Ayuki Kamada [a], Masahiro Kawasaki [a,b], Masaki Yamada [b,*]

[a] Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[b] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

ARTICLE INFO

Article history:
Received 6 December 2012
Received in revised form 8 January 2013
Accepted 9 January 2013
Available online 11 January 2013
Editor: T. Yanagida

ABSTRACT

The observed baryon and dark matter densities are equal up to a factor of 5. This observation indicates that the baryon asymmetry and dark matter have the same origin. The Affleck–Dine baryogenesis is one of the most promising mechanisms in this context. Q balls, which are often formed in the early Universe associated with the Affleck–Dine baryogenesis, decay both into supersymmetric particles and into quarks. Recently, it was pointed out that annihilation of squarks into quarks gives a dominant contribution to the Q-ball decay rate and the branching ratio of Q-ball decay into supersymmetric particles changes from the previous estimate. In this Letter, the scenario of baryon and dark matter cogenesis from Q ball in gravity mediation is revisited in respect of the improved Q-ball decay rates. It is found that the successful cogenesis takes place when a wino with mass 400–600 GeV is dark matter.

1. Introduction

The existence of the baryon asymmetry and the dark matter is a long standing challenge in cosmology and particle physics. In supersymmetric (SUSY) extensions of the Standard Model (SM), the lightest SUSY particle (LSP) is a good candidate for dark matter if the R-parity is conserved. Furthermore, the Affleck–Dine mechanism can provide the baryon asymmetry [1,2]. In the gravity-mediated SUSY breaking model, the Affleck–Dine mechanism often predicts the formation of Q balls in the early universe [3–7]. The Q ball is a spherical condensate of scalar fields. It generally consists of squarks and sleptons, and eventually decays both into quarks and into SUSY particles before the Big Bang Nucleosynthesis (BBN), and the observed baryon asymmetry is released. Through the cascade decays, the SUSY particles produced by the Q-ball decay turn into LSPs, which can account for the dark matter in the Universe. In this case, the baryon asymmetry and dark matter have the same origin and the resultant ratio of baryon to dark matter can be $O(1)$ naturally [4,8–12].

When we consider the case that the pair annihilation of the LSPs is ineffective and assume that the Affleck–Dine field ϕ takes a circular orbit in the complex ϕ plane, the resultant ratio of baryon to dark matter from the Q-ball decay is related only with the mass of the LSP and the branching ratio of the Q-ball decay into baryons and SUSY particles. In the previous works, the branching ratio of the Q-ball decay into SUSY particles is believed to be comparable with that into quarks [4,9–14]. In this case, the mass of dark matter should be $O(1)$ GeV.[1] However, it was pointed out that the many body processes like the squark annihilation may be dominant and then the branching ratio may change drastically [15]. In this Letter, we reexamine the branching ratio into SUSY particles in respect of the many body process.

Since the effective mass of the squark inside the Q ball is smaller than that of the free squark, the Q ball cannot decay into squarks. We assume that the Q ball is kinematically allowed to decay into binos, winos (LSPs), and SM particles. When the Q-ball decay rate is saturated due to the Pauli exclusion principle [16], the branching ratio is determined only by the number of degrees of freedom in the final state. Finally, we show that the branching ratio into SUSY particles can be $O(0.01)$. By using this branching ratio, we provide a successful scenario of the baryon and dark matter cogenesis through the Q-ball decay, and show that the wino LSP with mass of 400–600 GeV can naturally explains the observed baryon to dark matter ratio in the case that the pair annihilation of the LSPs is ineffective.

This Letter is organized as follows. In Section 2, we briefly review the property of Q balls in gravity mediation. In Section 3, first we compare the saturated decay and annihilations and then derive

* Corresponding author.
E-mail address: yamadam@icrr.u-tokyo.ac.jp (M. Yamada).

[1] If we consider the case that the pair annihilation is effective, the resultant LSP density is determined by the mass of LSP, the pair annihilation rate of LSP and the decay temperature of the Q ball [10–12]. Thus, the branching ratios of the Q-ball decay do not affect the ratio of the baryon to LSPs.

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.01.017

the branching ratios. In Section 4, we discuss the thermal history in our scenario. Section 5 is devoted to the conclusion.

2. Q ball properties in gravity mediation

In SUSY extensions of the standard model, there are many flat directions in the scalar potential. The flat directions are lifted by the SUSY breaking effect, and we can take the following potential for the flat direction to see the property of the Q ball in gravity mediation:

$$V = m_\phi^2|\phi|^2\left(1 + K\log\frac{|\phi|^2}{M_P^2}\right), \tag{1}$$

where m_ϕ is the mass of the flat direction and M_P is the reduced Planck mass ($\simeq 2.4\times 10^{18}$ GeV). In gravity mediation, m_s is the same order of the gravitino mass $m_{3/2}$. The second term in the parenthesis comes from the one-loop radiative corrections, and typically $|K| \sim 0.01$–0.1. In many cases, the gluino loops have dominant contributions to the radiative corrections and lead to $K < 0$, and then there exists a Q-ball solution [4,17]. The energy of the Q ball M_Q, the radius R, the rotation speed of the field ω_0, and the field amplitude at the center of the Q ball ϕ_0 are given by

$$M_Q \simeq m_\phi(\phi_0)Q, \tag{2}$$

$$R \simeq \frac{1}{|K|^{1/2}m_\phi(\phi_0)}, \tag{3}$$

$$\omega_0 \simeq m_\phi(\phi_0), \tag{4}$$

$$\phi_0 \simeq \left(2\pi^{3/2}\right)^{-1/2}|K|^{3/4}m_\phi(\phi_0)Q^{1/2}, \tag{5}$$

where $m_\phi(\phi_0)$ is the mass defined at the energy scale ϕ_0. The rotation speed ω_0 has a further important meaning as $\omega_0 = \mathrm{d}M_Q/\mathrm{d}Q$; i.e., the Q-ball energy per unit charge.

As discussed in detail in Section 4, the decay temperature of Q balls should be sufficiently suppressed for the pair annihilation of LSPs to be ineffective. This indicates that the charge of Q balls should be $Q \gtrsim 10^{26}$ and thus the magnitude of the scalar field is $\phi_0 \gtrsim 10^{13}m_\phi(\phi_0)$. At this energy scale, the mass of the flat direction $m_\phi(\phi_0)$ is lower than the mass of squarks at the electro-weak scale due to $K < 0$, and the Q ball cannot decay into squarks.

3. Q-ball decay rates into bino–wino, and quarks

The fermion production rates from the Q ball have upper bounds due to the Pauli exclusion principle [16]. The upper bound of the each massless fermion flux $\boldsymbol{j}$ from the Q-ball surface is calculated as

$$\boldsymbol{n}\cdot\boldsymbol{j} \lesssim 2\int\frac{\mathrm{d}^3k}{(2\pi)^3}\theta\left(\omega_0/2 - |\boldsymbol{k}|\right)\theta(\boldsymbol{k}\cdot\boldsymbol{n})\hat{\boldsymbol{k}}\cdot\boldsymbol{n}, \tag{6}$$

$$= \frac{2}{8\pi^2}\int_0^{\omega_0/2}k^2\,\mathrm{d}k = \frac{\omega_0^3}{96\pi^2}, \tag{7}$$

where $\boldsymbol{n}$ is the outward-pointing normal. We double the flux and take the upper limit of integration as $\omega_0/2$, because one of the decay products has energy less than $\omega_0/2$. We obtain the upper bound for the production rate from the Q ball by multiplying Eq. (7) by the area of the Q-ball surface $4\pi R^2$. The decay rate is saturated when $g\phi_0 > \omega_0$ for the interaction $g\phi\xi\eta$ (ξ, η: massless fermions). The condition $g\phi_0 > \omega_0$ is almost always satisfied due to the large Q value (see Eq. (5)).

In the case of the massive fermion χ, the upper bound of the flux is lower than Eq. (7). We consider the process of squark $\to$ quark $+\chi$, and treat the quark as a massless particle. The fermion χ can obtain the energy in the range of $[m_\chi, \omega_0]$, and the quark obtain the energy in the range of $[0, \omega_0 - m_\chi]$. Taking this into account, we just change the integral of Eq. (7) as

$$\frac{1}{8\pi^2}\int_0^{\omega_0 - m_\chi}k^2\,\mathrm{d}k, \tag{8}$$

for $\omega_0 > m_\chi > \omega_0/2$, and as

$$\frac{1}{8\pi^2}\left[\int_0^{\omega_0/2}k^2\,\mathrm{d}k + \int_{m_\chi}^{\omega_0/2}k^2\,\mathrm{d}k\right], \tag{9}$$

for $m_\chi < \omega_0/2$. Thus, the χ flux is given by

$$\boldsymbol{n}\cdot\boldsymbol{j}_\chi \simeq \frac{\omega_0^3}{96\pi^2}\times f(m_\chi/\omega_0), \tag{10}$$

$$f(x) \equiv \begin{cases} 4(1-x)^3 & \text{for } 1/2 < x < 1, \\ 4[(1/2)^3 + (1/2 - x)^3] & \text{for } x < 1/2. \end{cases} \tag{11}$$

Q balls can also decay into quarks via heavy gluino/higgsino exchange $\phi\phi \to qq$. This reaction rate is also saturated by the Pauli exclusion principle. The detailed discussion is given in Ref. [7,18]. The saturated flux is Eq. (7) with ω_0 replaced by $2\omega_0$, which is the total energy available in this process. Thus, we obtain the each quark flux as

$$\boldsymbol{n}\cdot\boldsymbol{j}_{\mathrm{quark}} \simeq \frac{(2\omega_0)^3}{96\pi^2}. \tag{12}$$

This is larger than Eq. (7) by a factor of 8. Notice that this flux is valid only for $M > \omega_0$, where M is the gluino/higgsino mass, and we assume it in this Letter. In Appendix A, we show $N(\geqslant 3)$ body processes are not saturated and negligible.

Now, let us compare the branching ratios of the Q-ball decay into binos, winos, and quarks. The bino or wino production rate is given by Eq. (10), while the quark production rate is given by Eq. (12). Here we should note that since the saturated production rate is determined by the Pauli exclusion principle, the total quark production rate is Eq. (12) times the number of degrees of freedom for quarks produced in the decay. We can count it once we specify the flat direction. Hereafter, we consider the flat direction $\bar{u}_i^a\bar{d}_j^b\bar{d}_k^c\epsilon_{abc}$ ($j \neq k$), where a, b, and c are the color indices and i, j, and k are the family indices. The Q ball can decay into all right handed quarks via gluino exchange and into all left handed quarks via higgsino exchange, because the flat direction contains all colors and, in general, all families. (Even if the flat direction does not contain all families, it can decay into all families through flavor mixings.) The $U(1)_Y$ charge conservation allows one up-type quarks for each two down-type quarks. The Q ball cannot directly decay into winos because the $\bar{u}\bar{d}\bar{d}$ flat direction has no tree-level interaction with winos. However, winos are produced via subsequent decays of binos if the LSP is wino. In this Letter we consider winos as the LSPs.

We conclude that the total decay rate of the Q ball and the branching ratios of the decay into quarks and bino are calculated as

$$\sum_{\mathrm{all}}\frac{\mathrm{d}N}{\mathrm{d}t} \simeq \left[8\times 36\times\frac{3}{4} + f\left(\frac{m_{\tilde{b}}}{\omega_0}\right)\right]\frac{R^2\omega_0^3}{24\pi}, \tag{13}$$

$$B_{\mathrm{quarks}} \simeq \frac{8\times 36\times 3/4}{8\times 36\times 3/4 + f(m_{\tilde{b}}/\omega_0)}, \tag{14}$$

$$B_{\mathrm{bino}} \simeq \frac{f(m_{\tilde{b}}/\omega_0)}{8\times 36\times 3/4 + f(m_{\tilde{b}}/\omega_0)}. \tag{15}$$