Axino dark matter and baryon number from $Q$-ball decay

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Abstract. We investigate the $Q$-ball decay into the axino dark matter in the gauge-mediated supersymmetry breaking. In our scenario, the $Q$ ball decays mainly into nucleons and partially into axinos to account for the baryon asymmetry and the dark matter of the universe simultaneously. The $Q$ ball decays well before the big bang nucleosynthesis so that it is not affected by the decay. The decay into the supersymmetric particles of the minimal supersymmetric standard model is kinematically prohibited until the very end of the decay, and we could safely make their abundances small enough for the successful big bang nucleosynthesis. We show the regions of axino model parameters which realize this scenario.

1. Introduction

The origin of baryon number asymmetry and the dark matter of the universe have been discussed for decades, but are still some of the main unsolved mysteries in cosmology. No solution can be found in the standard model (SM), and we must seek for something beyond SM. One good way is to consider supersymmetry (SUSY). In SUSY, the lightest supersymmetric particle (LSP), with $R$ parity conservation, is stable and, in most cases, scarcely interacts with other particles. These natures make the LSP a strong candidate of the dark matter. SUSY could also explain the origin of baryon number asymmetry. The Affleck Dine (AD) baryogenesis is one of the promising mechanism [1]. The AD field, carrying the baryon number, has a large VEV during inflation and rotates in the potential after inflation, and the baryon number is created. It finally decays into quarks to become the baryon asymmetry of the universe. In the minimal supersymmetric standard model (MSSM), there exist many flat directions, which consist of squarks, sleptons and Higgs fileds, which thus carry baryon and/or lepton number. Therefore, the flat direction could be responsible for the AD field.

The very attractive feature of the AD mechanism is to provide both the baryon asymmetry and the dark matter of the universe simultaneously in the context of the $Q$-ball cosmology [2–12]. During the rotation, the AD condensate may fragment into nontopological solitons, $Q$ balls. These $Q$ balls can be the dark matter if they are stable, while the LSP dark matter could be produced from unstable $Q$ balls. Stable $Q$ balls form if the charge $Q$ is large enough in the gauge-mediated SUSY breaking [2, 6]. On the other hand, $Q$ balls are unstable in the gravity mediation producing the neutralino LSP [3, 7], the gravitino LSP [8], and the axino LSP [9], and in the gauge mediation creating the gravitino LSP if the charge is small enough [10–12].
In this paper, we investigate a model where the $Q$ ball decays into axino LSPs in gauge-mediated SUSY breaking. (Similar situation in the gravity mediation was investigated in Ref. [9].) The axino is a fermionic superpartner of the axion, which is introduced as a dynamical scalar field to solve the strong CP problem in quantum chromodynamics known as Peccei-Quinn (PQ) mechanism [13]. In our model, $Q$ ball decays mainly into nucleons and partially into axinos directly in order to account for both the baryon asymmetry and the dark matter of the universe. The decay of the $Q$ ball takes place well before the big bang nucleosynthesis (BBN) so that the decay itself does not affect the BBN. Almost throughout the process, it is kinematically prohibited to decay into the lightest supersymmetric particle (LSP) of MSSM, whose decay may destroy light elements synthesized during the BBN. However, the MSSM LSPs (MLSPs) would be produced at the very end of the $Q$-ball decay when the charge becomes small enough to open the kinematically allowed channel to the MLSP production [12, 14].

2. $Q$ ball in gauge mediation
The AD field $\Phi$ is a combination of squarks, sleptons and higgs whose potential is flat in the SUSY exact limit. Because of the SUSY breaking in gauge mediation, the flat potential is lifted below the messenger scale, while it is flat above the messenger scale, $V \sim M_F^4$ [2, 15]. Here $M_F$ is related to the $F$ component of a gauge-singlet chiral multiplet $S$ in the messenger sector as $M_F^2 \equiv \frac{g^2}{4\pi} (F S)^2$ where $g$ is a gauge coupling constant in the standard model, and $M_F$ is allowed in the following range: $10^3$ GeV $\lesssim M_F \lesssim 10^4 \sqrt{m_{3/2} M_p}$, where $m_{3/2}$ and $M_p = 2.4 \times 10^{18}$ GeV are the gravitino and the reduced Planck masses, respectively.

When the Hubble parameter becomes smaller than the curvature of the potential, the AD field begins to oscillate giving the baryon number. During the helical motion, it transforms into $Q$ balls. The typical charge of the formed $Q$ ball is estimated as [4] $Q = \beta \left( \phi_{osc} \right)^4 / M_F$, where $\phi_{osc}$ is the field amplitude when the oscillation begins, and $\beta \simeq 6 \times 10^{-4}$ when the oscillating field has a nearly circular orbit $\epsilon = 1$ ($\epsilon$: ellipticity of the orbit) and $\beta \simeq 6 \times 10^{-5}$ when $\epsilon \lesssim 0.1$. The charge $Q$ is just the $\Phi$-number, and relates to the baryon number of the $Q$ ball as $B = bQ$, where $b$ is the baryon number carried by a $\Phi$ particle. For example, $b = \frac{1}{3}$ for the $udd$ direction.

3. $Q$-ball decay
A $Q$-ball decay occurs when some decay particles have the same kind of charges as the $Q$ ball and the mass of each decay particle is less than the $Q$-ball mass per charge $M_Q / Q$. The decay rate $\Gamma_Q$ has an upper bound $\Gamma_Q^{(\text{sat})}$ [16]. This saturation occurs approximately when $f_{\text{eff}} \phi_Q \gtrsim \omega_Q$, where $f_{\text{eff}}$ is the effective coupling constant by which the interaction is written as $\mathcal{L}_{\text{int}} = f_{\text{eff}} \phi \psi \bar{\psi}$. On the other hand, for the weak coupling limit such as $f_{\text{eff}} \phi_Q \ll \omega_Q$, the decay rate is calculated as [16] $\Gamma_Q \simeq 12 \left( \frac{f_{\text{eff}} \phi_Q}{\omega_Q} \right)^2 \Gamma_Q^{(\text{sat})}$. Here we are interested in the case where the $Q$ ball decays into nucleons but not into MLSPs. It is described by the condition $b m_N < M_Q / Q < m_{\text{MLSP}}$ where $m_N$ and $m_{\text{MLSP}}$ are the nucleon and MLSP masses, respectively. The elementary process of the $Q$-ball decay into nucleon is squark + squark $\rightarrow$ quark + quark via gluino exchanges and this process is saturated. Next, we consider the $Q$-ball decay into axinos. The condition for the decay into axinos is described by $m_\tilde{a} < M_Q$. The elementary process is squark $\rightarrow$ quark + axino whose effective coupling is given by [17] $f_{\text{eff}}^{(\tilde{a})} = \frac{\alpha_s^2}{\sqrt{2} \pi^2} m_\tilde{a} \log \left( \frac{M_Q}{m_\tilde{a}} \right)$, where $f_\alpha$ is the axion decay constant, $\alpha_s$ is the coupling strength for strong interaction and $m_\tilde{a}$ is the gluino mass. The decay may be saturated depending on the parameters $f_\alpha$ and $Q$, contrary to the case of the gravitino dark matter [12].
4. Baryon, axino and MLSP abundances from Q-ball decay

The number densities of the baryon, the axino and the MLSP are expressed in terms of the AD field number density $n_\phi$ as

$$n_b \simeq \epsilon b n_\phi,$$

$$n_\tilde{a} \simeq B_\tilde{a} n_\phi,$$

$$n_{\text{MLSP}} \simeq \frac{Q \epsilon}{Q} n_\phi,$$

respectively, where $B_\tilde{a} \equiv \frac{\Gamma(\tilde{a})}{\Gamma(\text{sat})}$ is the branching ratio and $B_\tilde{a} = 1$ in the saturated case. From the observations (such as the WMAP observation [18]), the ratio of the dark matter to baryon energy densities is $\rho_{\text{DM}}/\rho_b \simeq 5$. Through calculations, one can see typically $\epsilon \ll 1$, so the orbit of the AD field is oblate, thus we generally set $\beta = 6 \times 10^{-5}$ below. Assuming the MLSP mass $m_{\text{MLSP}} \simeq 100$ GeV, the MLSP abundances for the saturated and unsaturated case are obtained as

$$\frac{\rho_{\text{MLSP}}}{s}|_{\text{sat}} \simeq 1.1 \times 10^{-25} \text{GeV} \left( \frac{m_\tilde{a}}{\text{GeV}} \right)^{-3} \left( \frac{T_{\text{RH}}}{10^7 \text{GeV}} \right)^{-2} \left( \frac{T_D}{3 \text{MeV}} \right)^4,$$

$$\frac{\rho_{\text{MLSP}}}{s}|_{\text{unsat}} \simeq 7.8 \times 10^{-10} \text{GeV} \left( \frac{m_\tilde{a}}{\text{GeV}} \right)^{-2} \left( \frac{f_a}{10^{14} \text{GeV}} \right)^4 \left( \log \frac{f_a}{10^3 \text{GeV}} \right)^{-4} \times \left( \frac{T_{\text{RH}}}{10^7 \text{GeV}} \right)^{-1} \left( \frac{T_D}{3 \text{MeV}} \right)^6,$$

respectively, where $T_D$ is the decaying temperature of $Q$ ball.

5. Constraints on models

In this section, we see that the MLSP abundance is bounded from above by BBN constraints and bounded from below by the highest possible reheating temperature such that thermally produced axinos or gravitinos do not dominate the dark matter in the universe. We show the allowed region for the axino parameters $f_a$ and $m_\tilde{a}$.

The upper limit on the MLSP abundance is given by the fact that the decay of the MLSP may affect abundances of light elements synthesized during the BBN. Here we assume the MLSP decays hadronically and neutralino as the MLSP, then adopt the BBN constraints from [19] which has the dependance of the MLSP lifetime. Comparing the lifetime of MLSP into axino [20] and gravitino [19] and using the smaller lifetime of two, we obtain the upper bound of the MLSP abundance.

On the other hand, the lower limit on the MLSP abundance comes from constraints on the reheating temperature. The constraints are due to the condition that thermally produced axinos and gravitinos cannot be the dominant component of the dark matter in the universe. We adapt the amount of the primordial abundance of the MLSP in [19]. The MLSP abundance from the $Q$-ball decay depends on the reheating temperature $T_{\text{RH}}$ (Eqs.(4) and (5)). The upper limit of $T_{\text{RH}}$ comes from the requirement that the thermally produced axinos and gravitinos should satisfy $\text{max}(\Omega_\tilde{a}^h h^2, \Omega_3^{h/2} h^2) \lesssim \Omega_{\text{DM}} h^2 \simeq 0.11$, where $\Omega_\tilde{a}^h$ and $\Omega_3^{h/2}$ respectively denote the density parameters of thermally produced axino and gravitino, and $h$ is the Hubble constant in units of 100 km/s/Mpc. The constraint from the gravitino is written as [21],

$$T_{\text{RH}} \lesssim T_{\text{RH,max}}^{(3/2)} \equiv 3 \times 10^7 \text{GeV} \left( \frac{m_\tilde{a}}{500 \text{ GeV}} \right)^{-2} \left( \frac{m_3^{h/2}}{\text{GeV}} \right) \simeq 3 \times 10^7 \text{GeV} \left( \frac{m_\tilde{a}}{\text{GeV}} \right),$$

where $m_3^{h/2}$ is the mass of the gravitino.
where the gravitino mass is assumed to be the same as the axino mass $m_\tilde{a}$. On the other hand, the constraint from the axino depends on axion models. Here we consider two classes of axion models, the Kim-Shifman-Vainshtein-Zakharov (KSVZ) [22] and Dine-Fischer-Srednicki-Zhitnitskii (DFSZ) [23] models. In the KSVZ model, using the thermally produced axino density parameter [24], the constraint on $T_{\text{RH}}$ is given as

$$T_{\text{RH}} \lesssim T_{\text{RH,max}}^{(\text{KSVZ } \tilde{a})} = 1.1 \times 10^8 \text{ GeV} \left( \frac{m_\tilde{a}}{\text{GeV}} \right)^{-1} \left( \frac{f_a}{10^{14} \text{ GeV}} \right)^2.$$ (7)

Inserting the stronger constraint of Eqs. (6) and (7) into Eqs.(4) and (5), we obtain the lowest possible abundances of the MLSP in the saturated and the unsaturated cases. On the other hand, in the DFSZ model, the axino production is dominated by the higgsino decay through the axino-Higgsino-Higgs interaction at the low reheating temperature ($T_{\text{RH}} \lesssim 2 \times 10^7 \text{ GeV}$) [25], while by scatterings due to $\text{SU}(2)_L$ coupling at the high reheating temperature ($T_{\text{RH}} \gtrsim 2 \times 10^7 \text{ GeV}$). Thus using the abundance of thermally produced axinos [26], for $T_{\text{RH}} \gtrsim 2 \times 10^7 \text{ GeV}$, we obtain the upper limit on $T_{\text{RH}}$ as

$$T_{\text{RH}} \lesssim T_{\text{RH,max}}^{(\text{DFSZ } \tilde{a})} = 1.1 \times 10^9 \text{ GeV} \left( \frac{m_\tilde{a}}{\text{GeV}} \right)^{-1} \left( \frac{f_a}{10^{14} \text{ GeV}} \right)^2.$$ (8)

On the other hand, for $T_{\text{RH}} \lesssim 2 \times 10^7 \text{ GeV}$, the condition $\Omega_{\tilde{a}}^{\text{TH}}h^2 \lesssim \Omega_{\text{DM}}h^2 \approx 0.11$ only leads to the constraint on $f_a$ and $m_\tilde{a}$ as

$$\left( \frac{m_\tilde{a}}{\text{GeV}} \right) \left( \frac{f_a}{10^{14} \text{ GeV}} \right)^{-2} \lesssim 55,$$ (9)

and we must use $T_{\text{RH,max}}^{(3/2)}$ in order to obtain the lowest possible abundance.

From those upper and lower constraints, we put constraints on the parameters $m_\tilde{a}$ and $f_a$. They are restricted by the condition that there exists the allowed range for the MLSP abundance; the lowest possible MLSP abundance for the KSVZ and DFSZ model must be smaller than the upper limits from the BBN. These constraints are shown in the blue solid lines in Fig. 1.

We show the allowed region for the parameters $m_\tilde{a}$ and $f_a$ in both the KSVZ and the DFSZ models in Fig. 1. Q balls must be kinematically allowed to decay into axinos, which is expressed as $m_\tilde{a} < \frac{M_Q}{2}$, so we obtain the upper limit on $m_\tilde{a}$ as the red dashed double-dotted lines. In the KSVZ model (the left panel), the upper left region is excluded by the condition $\epsilon \leq 1$ which corresponds to the black dashed dotted line, above which we cannot have enough baryon number compared to the axino dark matter. On the other hand, in the DFSZ model (the right panel), the upper left region is excluded by the condition that the higgsino decay produces too much axinos which corresponds to the black dash dotted line, which is the main difference from the KSVZ model and considerably cuts out the allowed region compared to that in the KSVZ case. The allowed region is bounded from below for both $f_a$ and $m_\tilde{a}$. The former is due to the fact that the observed neutrino cooling of SN 1987A excludes the axion decay constant smaller than $6 \times 10^9 \text{ GeV}$ [27], shown as the grey regions in Fig. 1. The latter comes from the constraint on the Q-ball parameter $M_F$ such that $M_F \lesssim 0.1 \sqrt{m_\tilde{a}^2} = 0.1 \sqrt{m_\tilde{a} M_F}$ which corresponds to the dark blue dotted lines. We find that the scenario works for rather wide range in the parameter space such that $6 \times 10^9 \text{ GeV} \lesssim f_a \lesssim 5 \times 10^{14} \text{ GeV}$ and $m_\tilde{a} = O(0.1 \text{ MeV}) - O(\text{GeV})$ in the KSVZ model, while the allowed region is restricted to $2 \times 10^{11} \text{ GeV} \lesssim f_a \lesssim 5 \times 10^{14} \text{ GeV}$ and $m_\tilde{a} = O(0.1 \text{ MeV}) - O(10 \text{ MeV})$ in the DFSZ model.

Using the allowed region in the parameter space ($f_a$, $m_\tilde{a}$), it is possible to check the realizations of the successful scenario for particular parameter sets of ($f_a$, $m_\tilde{a}$) in terms of Q-ball parameters, $Q$ and $M_F$. Our scenario works for approximately $Q = 10^{20} - 10^{25}$ and $M_F = 10^5 - 10^7 \text{ GeV}$.
Figure 1. Allowed regions in \((f_a, m_{\tilde{a}})\) plane for the KSVZ (left) and the DFSZ (right) models are shown as blue filled regions. Below the dark red wide-dotted lines, there is no BBN constraint due to the small MLSP lifetime. The pink long-dashed lines divide the \(Q\)-ball decay into the saturated (on their left side) and unsaturated (on their right side) cases. The orange short-dashed lines distinguish which the upper limit of \(T_{RH}\) comes from: the thermally produced axinos (their above) or gravitinos (their below). The green dashed lines denote the iso-\(T_{RH,max}\) contours.

6. Summary
We have investigated the \(Q\)-ball scenario in the gauge-mediated SUSY breaking model where the \(Q\) ball decays into axinos and nucleons, providing simultaneously the dark matter and the baryon asymmetry of the universe. In our scenario, the \(Q\) ball has small enough charge to decay into nucleons and axinos, while it is large enough to kinematically forbid the decay channel to the SUSY particles in the MSSM, e.g., the lightest neutralinos. This prohibition holds almost through the decay process until the very end of the decay when the charge becomes small enough to open the channel into the MSSM LSPs, or MLSPs. We have evaluated the MLSP abundance, and imposed the condition that it should not affect the success of the BBN, which has resulted in the upper limit on the MLSP abundance. Meanwhile, the lower bound of the MLSP abundance has been obtained by the highest possible reheating temperature which comes from the condition that the thermally produced axinos and/or gravitinos are not the dominant component of the dark matter of the universe.

These conditions have led us to constrain the axino model parameters, the axino mass \(m_{\tilde{a}}\) and the axion decay constant \(f_a\), as well as from the condition that the axino can be produced kinematically from the \(Q\)-ball decay. The successful scenario resides in the region typically where \(m_{\tilde{a}} = O(0.1\text{MeV}) - O(\text{GeV})\) and \(6 \times 10^9 \text{GeV} \lesssim f_a \lesssim 5 \times 10^{14} \text{GeV}\) in the KSVZ model, while the small \(f_a\) region \((f_a \lesssim 10^{11} \text{GeV})\) and the large \(m_{\tilde{a}}\) region \((0.01 \text{GeV} \lesssim m_{\tilde{a}})\) are excluded in the DFSZ model.

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