Possible solution to the ^{7}Li problem by the long lived stau

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Modification of standard big-bang nucleosynthesis is considered in the minimal supersymmetric standard model to resolve the excessive theoretical prediction of the abundance of primordial lithium 7. We focus on the stau as a next-lightest superparticle, which is long lived due to its small mass difference with the lightest superparticle. It provides a number of additional decay processes of ^{7}Li and ^{7}Be. A particularly important process is the internal conversion in the stau-nucleus bound state, which destroys the ^{7}Li and ^{7}Be effectively. We show that the modification can lead to a prediction consistent with the observed abundance of ^{7}Li.

I. INTRODUCTION

The theory of big-bang nucleosynthesis (BBN) has been successful in predicting the abundance of light elements in the Universe from a single parameter, baryon-to-photon ratio η. The recent results of the Wilkinson microwave anisotropy probe (WMAP) experiment [1], however, put this theory into challenge. The extraordinarily precise results from WMAP are put together with the standard BBN (SBBN) to predict the abundance of ^{7}Li to be $(4.15^{+0.49}_{-0.45}) \times 10^{-10}$ [2] if we adopt $\eta = 6.1 \times 10^{-10}$ (68% C.L.) [1]. This prediction is inconsistent with the observation of metal-poor halo stars which implies $(1.23^{+0.32}_{-0.25}) \times 10^{-10}$ [3] reported by Ryan *et al.* [4]. The inconsistency persists even if we adopt the recent observations, which give the less restrictive constraint of $(2.19^{+0.30}_{-0.26}) \times 10^{-10}$ [5] and $(2.34^{+0.35}_{-0.30}) \times 10^{-10}$ [6]. This discrepancy can be hardly attributed to the correction of the cross section of nuclear reaction [7,8], and astrophysical solutions are pursued [9].

Another interesting approach to this problem would be to consider the effects induced by new physics beyond the standard model (SM). Exotic particles which interact with nuclei will open new channels to produce and destroy the nuclei, giving a potential solution to the ^{7}Li problem. In this paper we investigate a possibility that the interaction is initiated by a formation of the bound state of exotic negatively charged massive particles (CHAMPs) and a nucleus. (For the other solutions, see [10–12].)

So far the bound-state effects by CHAMPs have been attracting many interests [13–18]. For doubly charged particles, see also Refs. [19]. In particular, a significant enhancement of a ^{6}Li-production rate through ^{4}He + D → ^{6}Li + γ by the bound state with ^{4}He was reported [15] for

the first time and recently confirmed [20]. This hinders the compatibility between particle physics models and BBN [21].

In addition, some nonstandard effects on the abundance of ^{7}Li and ^{7}Be were also considered in Ref. [16] and more recently in Ref. [22]. Introducing the CHAMPs with the mass of electroweak scale, the authors in Ref. [22] newly considered several destruction channels of ^{7}Be nuclei through the trapping of the CHAMPs to show that the abundance of the CHAMPs needs to be larger than 0.02 per baryon and that their lifetime has an allowed window between 1000 and 2000 sec.

We put the CHAMP BBN scenario in the minimal supersymmetric standard model (MSSM) with the conservation of R parity. MSSM doubles the particle content of the SM by introducing superparticles, which can accommodate the CHAMPs. The CHAMPs need a lifetime long enough to sustain the sufficient abundance at the time of nucleosynthesis. Although the R-parity conservation stabilizes the lightest superparticles (LSPs), the observational constraints exclude charged superparticles as a candidate for LSPs, which is usually considered to be neutralinos $\tilde{\chi}^0$ or gravitinos. A possible candidate of CHAMPs is the next-lightest superparticle (NLSP) with electric charge, which can have a long lifetime by assuming a small mass difference from the LSP [23].

We assume in the present paper that the LSP is a neutralino and the NLSP is a stau $\tilde{\tau}$, the superpartner of tau lepton τ. The staus can decay into neutralino LSP with the hadronic current, through which they also interact with the nuclei. The gravitino LSP, on the other hand, does not couple with hadronic current. We consider the bound state of ^{7}Be and $\tilde{\tau}^-$ in the early Universe and the subsequent decay chain of nucleus ^{7}Be → ^{7}Li → ^{7}He due to the interactions of the two. The ^{7}He nuclei rapidly decay into ^{6}He nuclei, which are effectively stable in the considered time scale. With the freedom of the mass of stau $m_{\tilde{\tau}}$ and its lifetime $\tau_{\tilde{\tau}}$, we search for the possible solution to the ^{7}Li problem that are phenomenologically acceptable.

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This paper is organized as follows. In Sec. II we overview some new decay channels by stau and estimate their lifetimes. Here we will see that stau-nucleus bound states play an important role in ^{7}Be/^{7}Li reducing processes. In Sec. III we numerically calculate primordial abundances of light elements while taking into account the new channels. Then we will see the possible solution of the ^{7}Li problem. Finally, summarization is made in Sec. IV.

II. THE DESTRUCTION OF ^{7}Be/^{7}Li IN MSSM

A. Elementary interactions of the staus

We consider a modification of the SBBN scenario under the MSSM. MSSM introduces a set of superparticles as the partners of the particle appearing in the standard model (SM). The superparticles interact with the standard particles and thus introduce additional decay channels of ^{7}Be and ^{7}Li to the standard BBN theory. The additional channels give a possible solution to the problem where the theoretical prediction of the abundance of ^{7}Be and ^{7}Li, or collectively ^{7}Be/^{7}Li, exceeds the observational results by a factor of $\sim$2–3. We consider in the present paper that the destruction of primordial ^{7}Be/^{7}Li nuclei is due to their interaction with the negatively charged staus $\tilde{\tau}^-$, the superpartner of the tau lepton τ^-, which we identify as the next-lightest superparticle (NLSP). The mass eigenstate of the stau is given by the linear combination of the left-handed stau $\tilde{\tau}_L$ and the right-handed staus $\tilde{\tau}_R$ as

$$\tilde{\tau} = \cos\theta_\tau \tilde{\tau}_L + \sin\theta_\tau e^{-i\gamma_\tau} \tilde{\tau}_R, \quad (1)$$

where θ_τ is the left-right mixing angle and γ_τ is the *CP*-violating phase.

Staus have attractive features when considering the destruction of ^{7}Be/^{7}Li. First, staus have a negative charge and can form a bound state with nuclei so that they interact efficiently. Second, staus couples with the hadronic current J^μ, through which they interact with nuclei as we see below. Third, staus can be abundant at the time of BBN. They can acquire the sufficiently long lifetime when the staus and LSPs, which we assume as the neutralinos, have a mass difference tiny enough.

The interaction of staus is described by the Lagrangian

$$\mathcal{L}_{\text{int}} = \tilde{\tau}^* \bar{\tilde{\chi}}^0 (g_L P_L + g_R P_R)\tau + \frac{4G}{\sqrt{2}} \nu_\tau \gamma^\mu P_L \tau J_\mu$$

$$+ \frac{4G}{\sqrt{2}} (\bar{l}\gamma^\mu P_L \nu_l)(\bar{\nu}_\tau \gamma_\mu P_L \tau) + \text{H.c.}, \quad (2)$$

where $G = 1.166 \times 10^{-5}$ GeV^{-2} is the Fermi constant, P_L and P_R are the chiral projection operators, $l \in \{e, \mu\}$, and g_L and g_R are the coupling constants. These coupling constants are written in terms of the SU(2)$_L$ gauge-coupling constant g; when the neutralino is binolike, for instance, they are given by

$$g_L = \frac{g}{\sqrt{2}\cos\theta_W} \sin\theta_W \cos\theta_\tau, \quad (3)$$

$$g_R = \frac{\sqrt{2}g}{\cos\theta_W} \sin\theta_W \sin\theta_\tau e^{i\gamma_\tau}, \quad (4)$$

where θ_W is the Weinberg angle. The interaction Lagrangian (2) give rise to the following decay channels (see Fig. 1):

$$\tilde{\tau} \rightarrow \tau\tilde{\chi}^0, \quad (5)$$

$$\tilde{\tau} \rightarrow \pi\nu_\tau\tilde{\chi}^0, \quad (6)$$

$$\tilde{\tau} \rightarrow l\nu_l\nu_\tau\tilde{\chi}^0. \quad (7)$$

Process (5) has a typical lifetime $\mathcal{O}(10^{-20})$ sec, process (6) has $(10^{-6}$–$10^2)$ sec, and (7) has $(10^2$–$10^{12})$ sec. Since the BBN takes place $(1$–$100)$ sec after the big bang, the staus will decay entirely before BBN unless the channel (5) is closed. Our scenario therefore requires $\delta m < m_\tau = 1.7$ GeV. Note that the channel (6) also closes when δm is less than the pion mass $m_\pi \simeq 140$ MeV. Although the required LSP-NLSP mass difference is small compared to the typical mass of LSP which is $\mathcal{O}(100$ GeV), it is preferable in attributing the dark matter (DM) to the neutralino LSPs since it allows the LSP-NLSP coannihilation. With this tiny δm, the neutralino naturally becomes a cold dark matter instead of warm or hot dark matter [24] even though it is produced nonthermally. Hence our model is free of the constraints from the large-scale structure formation of the Universe.

B. Interactions of staus with ^{7}Be and ^{7}Li

In this section, we consider the stau-nucleus interaction processes that are relevant to the primordial BBN. Three processes are discussed: (1) the hadronic-current interaction, (2) stau-catalyzed fusion, and (3) internal conversion of stau-nucleus bound state. We consider the lifetimes of each process because it is crucial to understand the impact upon the modification of BBN.
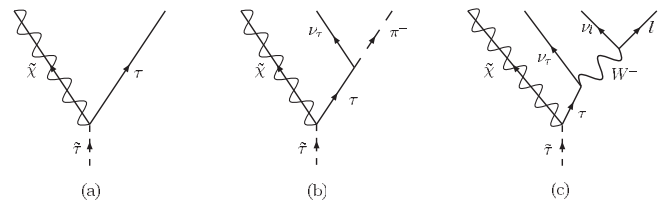

FIG. 1. Feynmann diagrams of the decay of staus. (a) $\tilde{\tau} \rightarrow \tau\tilde{\chi}^0$, (b) $\tilde{\tau} \rightarrow \pi\nu_\tau\tilde{\chi}^0$, and (c) $\tilde{\tau} \rightarrow l\nu_l\nu_\tau\tilde{\chi}^0$.

1. Destruction of nuclei by a hadronic-current interaction with free staus

Staus can interact with the nuclei through the hadronic current and thereby alter the BBN processes. The abundances of ^{7}Li/^{7}Be are changed by the new decay channels:

$$\tilde{\tau} \rightarrow \tilde{\chi}^0 + \nu_\tau + \pi^\pm, \tag{8}$$

$$\pi^+ + {}^7\text{Li} \rightarrow {}^7\text{Be}, \tag{9}$$

$$\pi^- + {}^7\text{Be} \rightarrow {}^7\text{Li}, \tag{10}$$

$$\pi^- + {}^7\text{Li} \rightarrow {}^7\text{He}. \tag{11}$$

The process $\pi^+ + {}^7\text{He} \rightarrow {}^7\text{Li}$ does not occur since ^{7}He is very unstable, while the pions can be either real or virtual; here the virtual pion should actually be regarded as a hadronic current propagating between the stau and the nucleus. The pions produced in the process (8) also change the proton-neutron ratio and thereby change the primordial abundance of the light elements.

We present the lifetime of the free stau in Fig. 2 as functions of δm [23]. Here we take $m_{\tilde{\chi}^0} = 300$ GeV, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$.

2. Stau-catalyzed fusion

Another process to destroy the ^{7}Li/^{7}Be is nuclear fusion catalyzed by staus. A nucleus has a Coulomb barrier which normally prevents the nuclear fusion, while the barrier is weakened when a stau is captured to a state bound to the nucleus. The nuclear fusion is thus promoted by forming a stau-nucleus bound state. The stau serves as a catalyst and is left out as the fusion proceeds through.
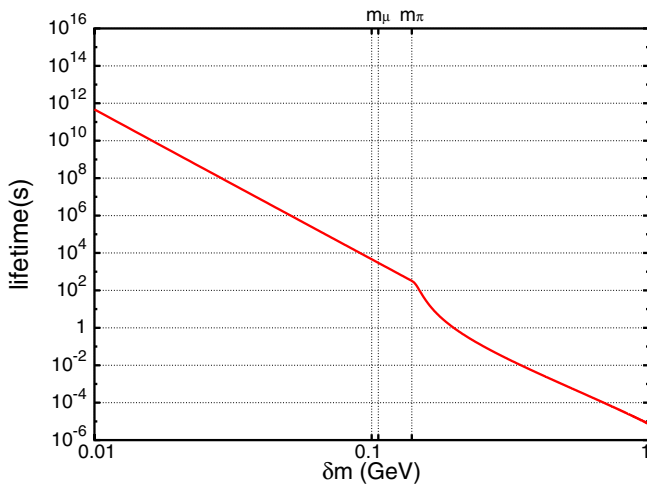
This stau-catalyzed fusion process provides the following decay channels:

$$^7\text{Be} + \tilde{\tau} \rightarrow ({}^7\text{Be}\tilde{\tau}) + \gamma, \tag{12}$$

$$^7\text{Li} + \tilde{\tau} \rightarrow ({}^7\text{Li}\tilde{\tau}) + \gamma, \tag{13}$$

$$({}^7\text{Be}\tilde{\tau}) + \text{p} \rightarrow ({}^8\text{B}\tilde{\tau}) + \gamma, \tag{14}$$

$$({}^7\text{Be}\tilde{\tau}) + \text{n} \rightarrow ({}^7\text{Li}\tilde{\tau}) + \text{p}, \tag{15}$$

$$({}^7\text{Li}\tilde{\tau}) + \text{p} \rightarrow \tilde{\tau} + 2\,{}^4\text{He} \quad \text{or} \quad \rightarrow \tilde{\tau} + 2\text{D} + {}^4\text{He}. \tag{16}$$

The lifetime of the stau-catalyzed fusion is estimated to be longer than 1 sec [18]. We follow Ref. [21] to calculate the stau-catalyzed fusion rate.

3. Internal conversion of nuclei in the stau-nucleus bound state

The interaction between a stau and a nucleus proceeds more efficiently when they form a bound state (see Fig. 3) [22] due to two reasons: (1) the overlap of the wave functions of the two becomes large since the stau and particle are packed in the small space, (2) the small distance between the two allows virtual exchange of the hadronic current even if $\delta m < m_\pi$. The stau-nucleus bound state decays through the following processes:

$$\tilde{\tau} + {}^7\text{Be} \rightarrow (\tilde{\tau}\,{}^7\text{Be}) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\text{Li}, \tag{17}$$

$$\tilde{\tau} + {}^7\text{Li} \rightarrow (\tilde{\tau}\,{}^7\text{Li}) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\text{He}, \tag{18}$$

$$^7\text{He} \rightarrow {}^6\text{He} + \text{n}, \tag{19}$$

$$^6\text{He} + \text{background particles} \rightarrow {}^3\text{He}, {}^4\text{He, etc.}, \tag{20}$$

where the parentheses denote the bound states. We note that we introduce not only reaction (17), but also reaction

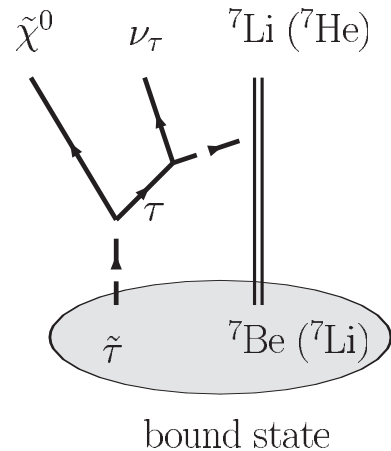FIG. 2 (color online). The lifetime of free stau as the functions of δm. Here we take $m_{\tilde{\chi}^0} = 300$ GeV, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$. The hadronic decay is dominant for $\delta m > m_\pi$ while the leptonic decay is exclusively allowed for $\delta m < m_\pi$.

FIG. 3. The Feynman diagrams of internal conversion of ^{7}Be (^{7}Li).

(18). The ^{6}He nucleus can also decay into ^{6}Li via β decay with the lifetime 817 msec. We do not take this process into account since this process is much slower than the scattering process (20).

The lifetime of the internal conversion τ_{IC} is obtained from the Lagrangian (2) as

$$\tau_{\text{IC}} = \frac{1}{|\psi|^2 \cdot (\sigma v)}, \tag{21}$$

where $|\psi|^2$ is the overlap of the wave functions of the staus and the nucleus,

$$(\sigma v) \equiv \frac{1}{2E_{\tilde\tau}2E_{\text{Be}}} \int \text{dLIPS} |\langle \tilde\chi^0 \nu_\tau {}^7\text{Li}|\mathcal{L}_{\text{int}}|\tilde\tau {}^7\text{Be}\rangle|^2 (2\pi)^4$$
$$\times \delta^{(4)}(p_{\tilde\tau} + p_{\text{Be}} - p_{\tilde\chi^0} - p_{\nu_\tau} - p_{\text{Li}}), \tag{22}$$

and

$$\text{dLIPS} = \prod_i \frac{d^3 \boldsymbol{p}_i}{(2\pi)^3 2E_i}. \tag{23}$$

Here $i \in \{\tilde\chi^0, \nu_\tau, {}^7\text{Li}\}$ for the process (17) and $i \in \{\tilde\chi^0, \nu_\tau, {}^7\text{He}\}$ for (18). The following approximations are applied to evaluate the lifetime further. We estimate the overlap of the wave functions in Eq. (21) by assuming that the bound state is in the S state of a hydrogenlike atom, and obtain

$$|\psi|^2 = \frac{1}{\pi a_{\text{nucl}}^3}, \tag{24}$$

where $a_{\text{nucl}} = (1.2 \times A^{1/3})$ fm is the radius of the nucleus. The matrix element of the nuclear conversion appearing in Eq. (22) is evaluated by the ft value of the corresponding β decay obtained from the experiments. The experimental ft value is available for $^7\text{Li} \leftrightarrow {}^7\text{Be}$ but not for $^7\text{Li} \leftrightarrow {}^7\text{He}$, however. We assume that the two processes have the same

ft value. As long as we consider the quantum numbers of the ground state of Li7 and He7 we can expect a Gamow-Teller transition can take place since they are similar with those of He6 and Li6 and we know that they make a Gamow-Teller transition. The Gamow-Teller transition is superallowed and has a similar ft value to the Fermi transition such as $^7\text{Li} \leftrightarrow {}^7\text{Be}$.

Our new effects have been treated as if ^7Li or ^7Be in its bound state would have an effectively new lifetime which is caused by the virtual exchange of the hadronic current with a stau. Thus this new process is not the two-bodies scattering. So, there is no corresponding astrophysical S factor in these processes.

The evaluated lifetimes of reactions (17) and (18) under these approximations are presented in Fig. 4 as functions of δm. There we take $m_{\tilde\chi^0} = 300$ GeV, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$ for both reactions. We find that the lifetime of the internal conversion process is in the order of 10^{-3} sec. The lifetime of stau-^7Li bound state diverges around $\delta m = m_{^7\text{Li}} - m_{^7\text{Be}} = 11.7$ MeV, below which the internal conversion is kinematically forbidden.

As we will see later, the internal conversion processes are dominant over the other processes.

III. NUMERICAL CALCULATION AND INTERPRETATION OF THE RESULT

In this section, we study the effectiveness of new decay channels on the ^7Li problem by numerical calculation. To do this, we choose the abundance of stau $Y_{\tilde\tau} \equiv n_{\tilde\tau}/s|_{t=t_{\text{freeze out}}}$ at freeze out time and mass difference δm as free parameters, since these values are sensitive to the abundance of ^7Be and ^7Li. Here s is entropy density. The number of ^7Li interacted with the stau is determined by the number density of the stau. The hadronic decay rate of stau is mainly determined by the mass difference. The decay
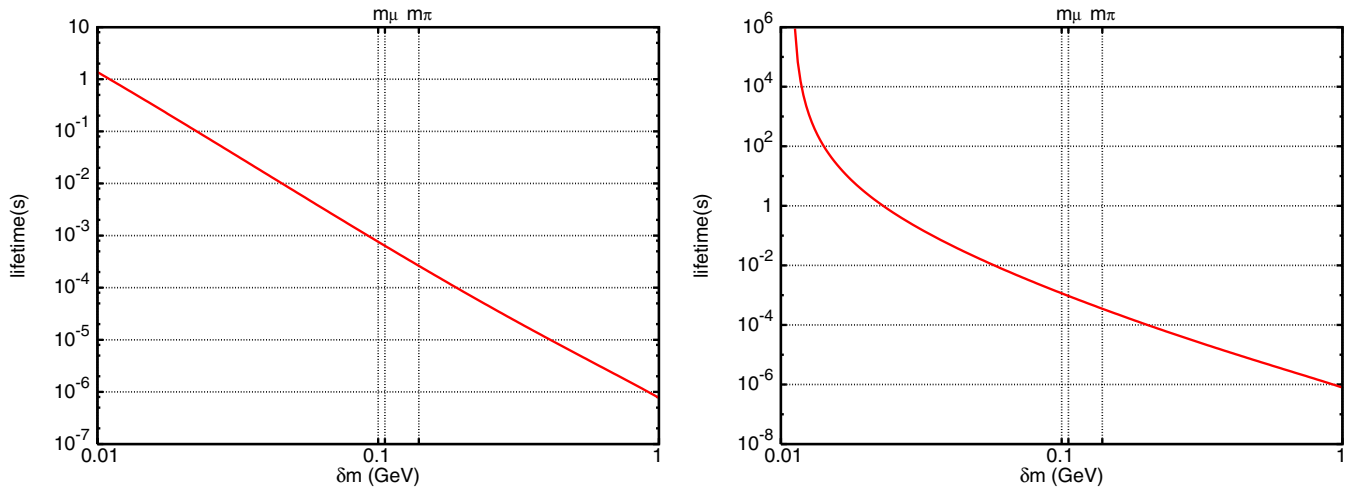

FIG. 4 (color online). The lifetimes of internal conversion processes as the function of δm. Top panel: $(\tilde\tau {}^7\text{Be}) \to \tilde\chi^0 + \nu_\tau + {}^7\text{Li}$, bottom panel: $(\tilde\tau {}^7\text{Li}) \to \tilde\chi^0 + \nu_\tau + {}^7\text{He}$. We take $m_{\tilde\chi^0} = 300$ GeV, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$ in both figures.

rate is also determined by the stau mixing angle θ_τ, CP violating phase γ_τ, and neutralino mass. As we showed in [23], however, the effects by these parameters are much less than mass difference.

We estimate the number density of bound states by using the Saha equation,

$$n_{\rm BS} = \left(\frac{m_{\rm N}T}{2\pi}\right)^{-3/2} e^{E_{\rm B}/T}(n_{\rm N} - n_{\rm BS})(n_{\tilde\tau^-} - n_{\rm BS}). \quad (25)$$

Here, $n_{\rm BS}$, $n_{\tilde\tau}$, and $n_{\rm N}$ denote the number densities of the bound state, the stau, and the nucleus, respectively; $m_{\rm N}$, $E_{\rm B}$, and T denote the nucleus mass, binding energy of the bound state, and the temperature of the Universe, respectively. The Saha equation is valid only when the expansion rate of the Universe is much smaller than the formation rate of the bound state. This condition is not quite satisfied in our case. We will explain that our results are qualitatively acceptable at the end of this section. For more detailed discussion, see [16,25].

In Fig. 5 we show the parameter region of δm and $Y_{\tilde\tau}$ allowed by the observational light-element abundances, where we take $\eta = 6.1 \times 10^{-10}$, $m_{\tilde\chi^0} = 300$ GeV, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$. The white region is the parameter space which is consistent with all the observational abundance including ^{7}Li to hydrogen ratio (^{7}Li/H). The regions enclosed by dotted (green), dashed (light blue), and dash-dotted (purple) lines are excluded by the observations on

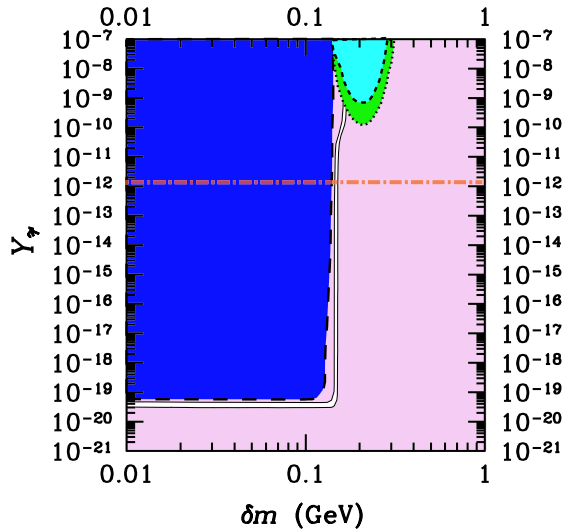FIG. 5 (color online). The constraints from the light-element abundance shown in the δm–$Y_{\tilde\tau}$ plane. The white region is the parameter space which is consistent with all the observational abundance including ^{7}Li/H $= (1.23^{+0.32}_{-0.25}) \times 10^{-10}$ [3]. The regions enclosed by dotted (green), dashed (light blue), and dash-dotted (purple) lines are excluded by the observations on ^{4}Be, D and ^{6}Li, respectively. The thick-dotted line represents a yield value of stau whose daughter particle, neutralino, accounts for all the dark matter component. Here we took $\eta = 6.1 \times 10^{-10}$, $m_{\tilde\chi^0} = 300$ GeV, $\theta_\tau = \pi/3$ and $\gamma_\tau = 0$.

the mass fraction of ^{4}He ($Y_{\rm p}$), deuterium to hydrogen ratio (D/H) and ^{6}Li to ^{7}Li ratio (^{6}Li/^{7}Li), respectively. We adopt the following observational constraints on primordial light element abundances[1][2]

$$Y_{\rm p}^{\rm obs} = 0.2516 \pm 0.0040, \quad (26)$$

$$({\rm D/H})^{\rm obs} = (2.82 \pm 0.26) \times 10^{-5}, \quad (27)$$

$$\log_{10}(^7{\rm Li/H})^{\rm obs} = -9.91 \pm 0.10, \quad (28)$$

$$(^6{\rm Li}/^7{\rm Li})^{\rm obs} < 0.046 \pm 0.022 + 0.84. \quad (29)$$

[Eq. (26), [32]; Eq. (27), [33]; Eq. (28), [3]; Eq. (29), [34]]. The thick-dotted line represents a yield value of stau whose daughter particle, neutralino, accounts for all the dark matter component. This line is given by the yield value of dark matter

$$Y_{\rm DM} = 3.80 \times 10^{-12}\left(\frac{\Omega_{\rm DM}h^2}{0.104}\right)\left(\frac{m_{\rm DM}}{10^2~{\rm GeV}}\right)^{-1}, \quad (30)$$

with $\Omega_{\rm DM}h^2 = 0.104 \pm 0.010$ (68% C.L.) [1], here $m_{\rm DM}$ is $m_{\tilde\chi^0}$. $Y_{\tilde\tau}$ must be smaller than this value, in order to prevent the overclosure of the Universe. The cosmologically interesting region is below the line.

We can find another white region even if we adopt the more restrictive value of ^{7}Li/H shown in Ref. [3]. The upper central region is excluded by the observational constrains on D/H and ^{4}He due to charged pions emitted from decaying staus [35]. In the current model, no hadrodissociation processes of light elements occur.

The qualitative feature of the allowed region is explained from the following physical consideration. First, staus need to have lifetimes $\tau_{\tilde\tau}$ longer than the time required to form the bound state of a stau and a ^{7}Be. The required time $t_{{\rm form},^7{\rm Be}}$ is estimated from the binding energy $E_{{\rm bin},^7{\rm Be}} = 1490$ keV as $t_{{\rm form},^7{\rm Be}} \sim 10^9~{\rm sec} \cdot (E_{{\rm bin},^7{\rm Be}}/{\rm keV})^{-2} \sim \mathcal{O}(10^2~{\rm sec})$. Figure 2 shows $\delta m \lesssim (100\text{–}200)$ MeV for $\tau_{\tilde\tau} \gtrsim t_{{\rm form},^7{\rm Be}}$ and hence the allowed region appears only in this region. Second, the yield value of staus $Y_{\tilde\tau}$ needs to be large compared with that of ^{7}Li which we denote by $Y_{^7{\rm Li}}$. We estimate $Y_{^7{\rm Li}}$ from the hydrogen to entropy ratio $n_{\rm H}/s \sim \mathcal{O}(10^{-10})$ and the constraint (28) as

$$Y_{^7{\rm Li}} \sim \left(\frac{n_{^7{\rm Li}}}{n_{\rm H}}\right)^{\rm obs} \cdot \frac{n_{\rm H}}{s} \sim 10^{-9.63} \times 10^{-10} \sim 10^{-20}. \quad (31)$$

We thus need $Y_{\tilde\tau} > 10^{-20}$, and again the allowed region appears in this region. Third, the excessive destruction of

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[1]Here we have used conservative errors of $Y_{\rm p}^{\rm obs}$ according to a discussion in Ref. [26]. See also the other recent observational values of $Y_{\rm p}$ in Ref. [27].

[2]About the errors of ^{6}Li/^{7}Li, see also the discussion in [28–31].

^{7}Li by the process (18) needs to be avoided due to the constraint (29). This condition puts a limit to the formation rate of the bound state of a stau and a ^{7}Li. We then need either $\tau_{\tilde{\tau}} < t_{\text{form},^7\text{Li}} \sim 10^9$ sec $\cdot (E_{\text{bin},^7\text{Li}}/\text{keV})^{-2} \sim \mathcal{O}(10^3$ sec) (here we use $E_{\text{bin},^7\text{Li}} = 952$ keV [13]), or $Y_{\tilde{\tau}}$ to be small enough. The former condition leads to $\delta m \gtrsim 100$ MeV, although this region is subject to the strong restriction considered in the previous paragraph. The latter imposes an upper limit on $Y_{\tilde{\tau}}$ in the region $\delta m \lesssim 100$ MeV, and Fig. 5 suggests that this limit is in the order of 10^{-20}. The tininess of $Y_{\tilde{\tau}}$ shows that the internal conversion processes (17) and (18) are dominant over other processes such as the pion exchange and the stau-catalyzed fusion. We can confirm this dominance by an explicit calculation of the rates of these processes.

We used the Saha equation in our calculation although the formation rate is comparable to the expansion rate. Calculation using the Boltzmann equation will give a lower number density of the bound state n_{BS} and consequently shift the allowed region upward in $\delta m < 100$ MeV in Fig. 5.

IV. SUMMARY

We have investigated a possible solution of the ^{7}Li problem in a framework of MSSM, in which the LSP and the NLSP are neutralino and stau, respectively, and have a tiny mass difference of $\delta m \lesssim (100$–$200)$ MeV. The staus then survive throughout the BBN era as shown in Fig. 2, and provide additional decay processes as mentioned in Sec. II B to reduce the primordial ^{7}Li abundance.

Taking the three new processes into account, we numerically calculated the primordial abundance of light elements varying the LSP-NLSP mass difference and the abundance of stau. Taking $\theta_\tau = \pi/3$, $\gamma_\tau = 0$, we obtained the parameter region consistent to the observed ^{7}Li abundance.

Though we have shown that the internal conversion is very important for the calculation of the primordial abundance, we need to improve our calculation for better accuracy. First, we need to include reaction processes such as $(^6\text{Li}\tilde{\tau}) \rightarrow {}^6\text{He} + \tilde{\chi} + \nu_\tau$. This process can change the prediction of ^{6}Li and hence change the allowed region. Second, we should calculate the number density of the bound states not by the Saha equation (25) but by the Boltzmann equation. At the formation temperature, the capture rate is less than the expansion rate of the Universe. Therefore we will obtain a lower number density of the bound states and consequently the upward shift of the allowed region. Third, we should explore other values of the parameters θ_τ, γ_τ, and $m_{\tilde{\chi}}$, which affect the lifetime of stau and also those of the bound states. We leave these for our future works.

ACKNOWLEDGMENTS

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