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Big-bang nucleosynthesis and the relic abundance of dark matter in a stau-neutralino coannihilation scenario

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A scenario of the big-bang nucleosynthesis is analyzed within the minimal supersymmetric standard model, which is consistent with a stau-neutralino coannihilation scenario to explain the relic abundance of dark matter. We find that we can account for the possible discrepancy of the abundance of ^{7}Li between the observation and the prediction of the big-bang nucleosynthesis by taking the mass of the neutralino as 300 GeV and the mass difference between the stau and the neutralino as (100–120) MeV. We can therefore simultaneously explain the abundance of the dark matter and that of ^{7}Li by these values of parameters. The lifetime of staus in this scenario is predicted to be O(100–1000) sec.

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The supersymmetric models are attractive candidates of the theory beyond the standard model. While no experiments so far have found any evidence of the supersymmetry, the LHC is expected to find its first signal in the near future. On the other hand, the analysis of the cosmological implications of the supersymmetry is an approach complementary to the direct search. The lightest supersymmetric particle (LSP) is stabilized by the R parity and naturally qualifies as the cosmological dark matter. A possible candidate of the LSP, and hence of the dark matter, is the neutralino $\tilde{\chi}^0$. The neutralinos as the LSP with their mass of O(100 GeV) can be responsible for the present abundance of the dark matter when the mass of the next-lightest supersymmetric particle (NLSP) is close to that of the LSP's and allow them to coannihilate with each other in the early universe.

We put this coannihilation scenario into the perspective of the big-bang nucleosynthesis (BBN). The recent results from the Wilkinson Microwave Anisotropy Probe experiment [1], combined with the standard BBN scenario, suggest twice or thrice as much abundance of ^{7}Li as suggested from the observation of metal-poor halo stars [2–4]. This discrepancy may imply that the ^{7}Li nuclei were destructed in the BBN era through processes of physics beyond the standard model, although there might still be a possible astrophysical process to deplete ^{7}Li uniformly [5]. We introduced in Ref. [6] a scenario in which an exotic negatively-charged massive particle form a bound state with a nucleus and therethrough initiate the destruction. There we analyzed the minimal supersymmetric standard model with the coannihilation scenario where the NLSP is the stau $\tilde{\tau}$. Staus serve as charged massive particles that trigger the destruction of ^{7}Li through the interaction

$$\mathcal{L}_{\rm int} = \tilde{\tau}^* \bar{\tilde{\chi}}^0 (g_{\rm L} P_{\rm L} + g_{\rm R} P_{\rm R})\tau + \frac{4G_{\rm F}}{\sqrt{2}} \nu_\tau \gamma^\mu P_{\rm L} \tau J_\mu^{\rm had} + \frac{4G_{\rm F}}{\sqrt{2}} (\bar{l}\gamma^\mu P_{\rm L}\nu_l)(\bar{\nu}_\tau \gamma_\mu P_{\rm L}\tau) + {\rm H.c.}, \qquad (1)$$

where $G_{\rm F} = 1.166 \times 10^{-5}\ {\rm GeV}^{-2}$ is the Fermi constant, $P_{\rm L}$ and $P_{\rm R}$ are the chiral projection operators, $l \in \{e, \mu\}$, $g_{\rm L}$ and $g_{\rm R}$ are the coupling constants, and $J_\mu^{\rm had}$ is the hadron current. The stau $\tilde{\tau}$ in Eq. (1) is the mass eigenstate, which is given by the linear combination of the superpartner of the left-handed tau $\tilde{\tau}_{\rm L}$ and that of the right-handed tau $\tilde{\tau}_{\rm R}$ as $\tilde{\tau} = \tilde{\tau}_{\rm L} \cos\theta_\tau + \tilde{\tau}_{\rm R} e^{-i\gamma_\tau} \sin\theta_\tau$, where θ_τ and γ_τ are the left-right mixing angle and CP-violating phase, respectively. The formation of a stau-^{7}Be bound state $\tilde{\tau} + {}^7{\rm Be} \rightarrow (\tilde{\tau}{}^7{\rm Be}) + \gamma$ is immediately followed by an internal conversion process $(\tilde{\tau}{}^7{\rm Be}) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7{\rm Li}$, and subsequent spallation of ^{7}Li by the energetic protons in the background. We assumed in Ref. [6] the rapid formation of the stau-nucleus bound state and ignored the effect of the expansion of the Universe, as the use of the Saha equation implies.

In the present paper, we improve the previous analysis by considering the expansion effect of the Universe. The Boltzmann equation is employed instead of the Saha equation to estimate the stau-nucleus bound states. We also include the resonant formation of the bound state pointed out in Ref. [7]. We thereby show that the LSP and NLSP, both with mass of O(100 GeV), can account for the problem of the dark matter and that of the abundance of ^{7}Li. The relevant parameters in considering our BBN scenario are the mass difference between staus and neutralinos $\delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}^0}$, where $m_{\tilde{\tau}}$ and $m_{\tilde{\chi}^0}$ are the masses of staus and neutralinos, respectively, and the yield value of

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the staus at the *freeze-out* time $Y_{\tilde{\tau},\mathrm{FO}} \equiv n_{\tilde{\tau}}/s|_{\mathrm{Freeze\ Out}}$, where $n_{\tilde{\tau}}$ and s are the densities of the number of staus and the entropy, respectively. Other parameters are fixed throughout this paper to $\theta_\tau = \pi/3$, $\gamma_\tau = 0$, and $m_{\tilde{\chi}^0} = 300$ GeV. By varying the values of δm and $Y_{\tilde{\tau},\mathrm{FO}}$, we search for the parameter region that can account for the present abundance of ^{7}Li. Staus play a major role in the BBN when δm is small so that staus become longevous enough to survive until the BBN era. The lifetime of staus indeed becomes 100 sec or longer when $\delta m \lesssim 100$ MeV [6,8].

We show in Fig. 1 the evolutions of the bound ratios of ^{4}He, ^{7}Li, and ^{7}Be, where we define the bound ratio by the number density of a nucleus that forms a bound state with a stau, divided by the total number density of that nucleus. We trace the evolution of the number density of the stau-nucleus bound states by the Boltzmann equation, using the cross sections shown in Ref. [9].

The yield value of staus at the time of *the formation of the bound state* with nuclei t_{BF}, which we denote by $Y_{\tilde{\tau},\mathrm{BF}}$, is changed from 10^{-10} to 10^{-16} in each figure. It is related with $Y_{\tilde{\tau},\mathrm{FO}}$ using the lifetime of stau $\tau_{\tilde{\tau}}$ as

$$Y_{\tilde{\tau},\mathrm{BF}} = Y_{\tilde{\tau},\mathrm{FO}} e^{-t_{\mathrm{BF}}/\tau_{\tilde{\tau}}}. \tag{2}$$

The bound ratio of ^{4}He shown in Fig. 1(a) is crucial to estimate the creation rate of ^{6}Li due to the catalyzed fusion process [10,11] $(\tilde{\tau}^4\mathrm{He}) + \mathrm{D} \to {}^6\mathrm{Li} + \tilde{\tau}$, while that of ^{7}Be shown in Fig. 1(b) is necessary to evaluate the reduction rate of the ^{7}Li. Since the present ^{7}Li originates from the premordial ^{7}Be, the abundance of ^{7}Li is reduced as follows. We first convert ^{7}Be into ^{7}Li by an internal conversion process $(\tilde{\tau}^7\mathrm{Be}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{Li}$, and successively destruct the daughter ^{7}Li by either a collision with a background proton or a subsequent internal conversion $(\tilde{\tau}^7\mathrm{Li}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He}$. The ^{7}Be is efficiently reduced if its bound ratio plotted in Fig. 1(b) is of $O(1)$. The successive destruction of ^{7}Li by internal conversion is effective when its bound ratio plotted in Fig. 1(c) is also of $O(1)$. We find in Figs. 1(b) and 1(c) that both bound ratios of ^{7}Be and ^{7}Li are of $O(1)$ when $Y_{\tilde{\tau},\mathrm{FO}} \gtrsim (10^{-13}\text{–}10^{-12})$.

The parameter region that can solve the ^{7}Li problem is numerically calculated in the $(\delta m, Y_{\tilde{\tau},\mathrm{FO}})$ plane and presented in Figure 2, in which Fig. 2(a) does not include effects of the resonant formation and photo-dissociation processes of the bound state pointed out in Ref. [7], while Fig. 2(b) includes these effects. The white region is the parameter space, which is consistent with all the observational abundance including that of ^{7}Li/H. The region enclosed by dashed lines is excluded by the observational abundance of ^{6}Li/^{7}Li [12], and the one enclosed by solid lines are allowed by those of ^{7}Li/H [3]. The thick dotted line is given by the upper bound of the yield value of dark matter

$$Y_{\mathrm{DM}} = 4.02 \times 10^{-12} \left(\frac{\Omega_{\mathrm{DM}} h^2}{0.110}\right)\left(\frac{m_{\mathrm{DM}}}{10^2\ \mathrm{GeV}}\right)^{-1}, \tag{3}$$

taking $\Omega_{\mathrm{DM}} h^2 = 0.1099 + 0.0124$ (upper bound of 95% confidence level) [1] and $m_{\mathrm{DM}} = m_{\tilde{\chi}^0}$. This line gives the upper bound of $Y_{\tilde{\tau},\mathrm{FO}}$, since the supersymmetric particles after their freeze-out consist of not only staus but neutralinos as well in our scenario.

The allowed region shown in Fig. 2 lies at $\delta m \simeq (100\text{–}120)$ MeV, which is tiny compared with $m_{\tilde{\chi}^0} = 300$ GeV. These values of parameters allow the coannihilation between neutralinos and staus, and thus can account also for the abundance of the dark matter. We therefore find that the values of $m_{\tilde{\chi}^0} = 300$ GeV and $\delta m \simeq 100$ MeV can

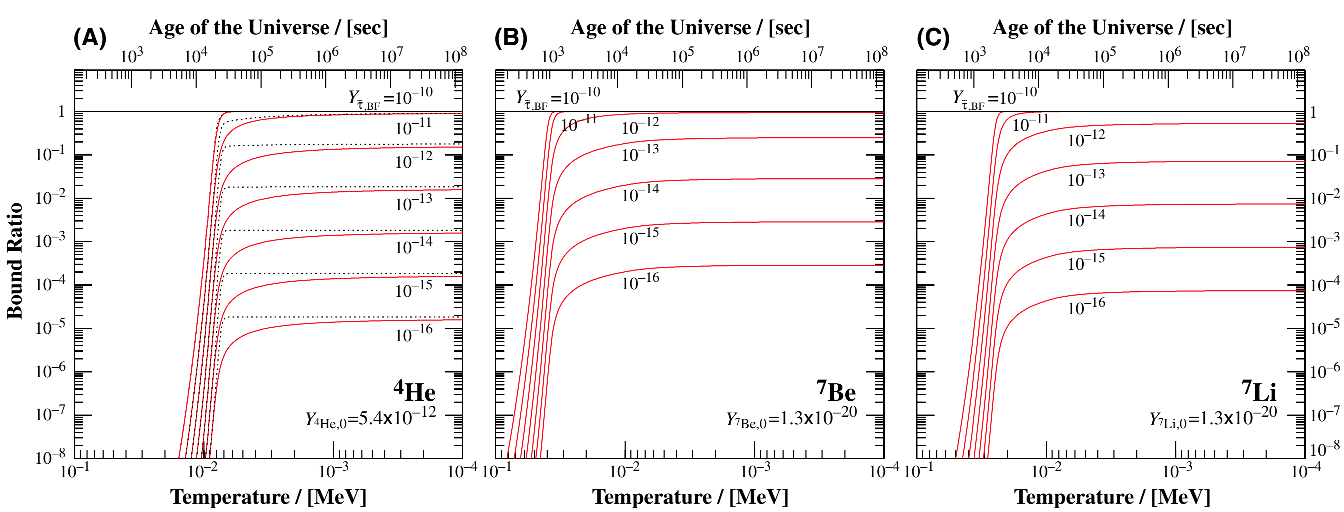

FIG. 1 (color online). Evolutions of the bound ratio of the nuclei ^{4}He, ^{7}Be, and ^{7}Li. We vary the abundance of the stau at the time of the formation of the bound state from 10^{-10} to 10^{-16} in each figure. In Fig 1(a), we also plotted by dotted lines corresponding curves predicted using the Saha equation for reference.

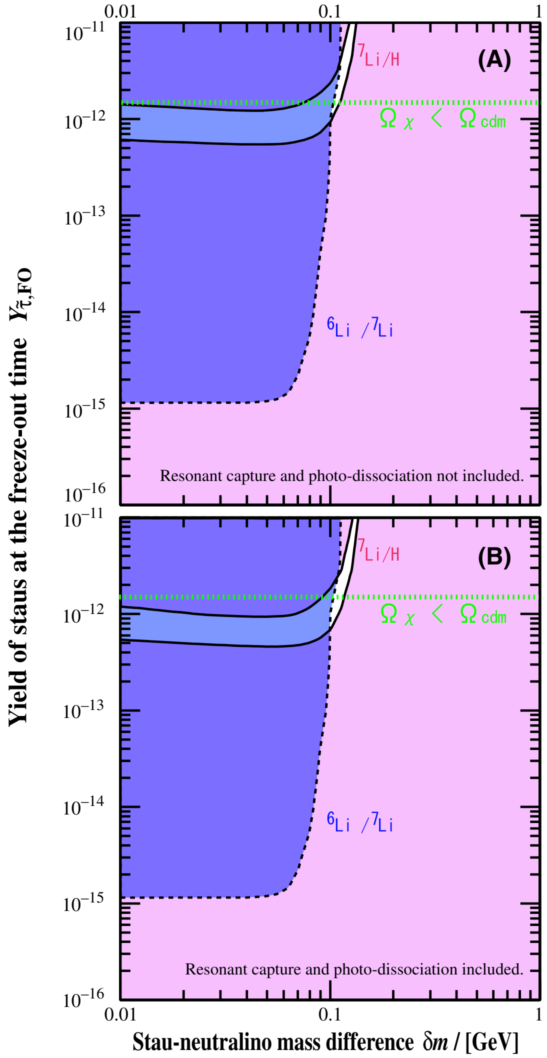

FIG. 2 (color online). Allowed region in δm-$Y_{\tilde{\tau},FO}$ plane. The resonant capture and the photo dissociation are (a) not included, and (b) included. The white region is the parameter space, which is consistent with all the observational abundance including that of ^{7}Li/H. The region enclosed by dashed lines is excluded by the observational abundance of ^{6}Li/^{7}Li [12], and the one enclosed by solid lines are allowed by those of ^{7}Li/H [3]. The thick dotted line is given by the upper bound of the yield value of dark matter. This line gives the upper bound of $Y_{\tilde{\tau},FO}$.

simultaneously explain the abundance of dark matter and of ^{7}Li.

We compare Figs. 2(a) and 2(b) to find that the allowed region is shifted downward in Fig. 2(b). Of the two processes included in Fig. 2(b), the resonant formation process makes the bound ratio larger, the value of $Y_{\tilde{\tau}}$ smaller, and push the allowed region downward in the figure. On the other hand, the photo-dissociation process makes the bound ratio smaller through the destruction of the bound state, makes the value of $Y_{\tilde{\tau}}$ larger, and push the allowed region upward. We thus find that the resonant formation of the bound state is relevant while the photo dissociation is inconsequential.

The qualitative feature of the allowed region is explained from the following physical consideration. First, we note that $Y_{\tilde{\tau},FO} \gtrsim (10^{-13}$–$10^{-12})$ is required so that a sufficient number of bound state ($\tilde{\tau}^7$Be) is formed to destruct ^{7}Be by the internal conversion into ^{7}Li. The daughter ^{7}Li is broken either by an energetic proton or by the internal conversion $(\tilde{\tau}^7\mathrm{Li}) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He}$, and consequently ^{7}Li/H is reduced. Bearing this physical situation in mind, we consider parameter regions in detail.

(1) $\delta m \gtrsim 120$ MeV.
Since the staus decay before they form a bound state with ^{7}Be, the value of $Y_{\tilde{\tau},BF}$ is much lower than 10^{-13} and hence the abundance of neither ^{7}Be nor ^{7}Li is reduced. Therefore this parameter region is excluded.

(2) $100 \text{ MeV} \lesssim \delta m \lesssim 120$ MeV.
The staus are just decaying at the formation time of the bound state. The necessary condition of $Y_{\tilde{\tau},BF} \sim 10^{-13}$ can still be retained even in a case where the value of $Y_{\tilde{\tau},FO}$ is sufficiently large. The allowed region in this area of δm thus bends upward. In this region, a daughter ^{7}Li from the internal conversion of ($\tilde{\tau}^7$Be) is broken mainly by an energetic proton.

(3) $Y_{\tilde{\tau},FO} \lesssim 10^{-13}$.
In this case $Y_{\tilde{\tau},BF}$ is necessarily less than 10^{-13}, and the bound ratio of ^{7}Li and ^{7}Be are much less than $O(1)$ as seen in Fig. 1. Therefore, the final abundance of ^{7}Li is not reduced sufficiently. This parameter region is thus excluded.

(4) $Y_{\tilde{\tau},FO} > 10^{-12}$ and $\delta m < 100$ MeV.
In this region $Y_{\tilde{\tau},BF} = Y_{\tilde{\tau},FO} > 10^{-12}$ and hence the bound ratio of ^{7}Be is 1 (see Fig. 1). It means that ^{7}Be and consequently ^{7}Li are destructed too much. Hence, the upper-left region is excluded.

(5) $\delta m \lesssim 100$ MeV and $Y_{\tilde{\tau},FO} \gtrsim 10^{-15}$.
In this region, the stau acquires the long lifetime enough to form a bound state ($\tilde{\tau}^4$He). Then the catalyzed fusion process $(\tilde{\tau}^4\mathrm{He}) + \mathrm{D} \rightarrow {}^6\mathrm{Li} + \tilde{\tau}$ leads to the overproduction of ^{6}Li and to the disagreement to the observational limit. Therefore, this parameter region is excluded, which is consistent with calculations by Ref. [13].

Excluding all the parameter regions described above, we obtain a small allowed region of $m_{\tilde{\chi}^0} \simeq m_{\tilde{\tau}} \simeq 300$ GeV and $\delta m = (100$–$120)$ MeV as presented in Fig. 2, and these values are at the same time consistent to the coannihilation scenario of the dark matter.

We obtained a strict constraint on the mass of the neutralinos and staus by improving an analysis of a solution to the overproduction problem of ^{7}Li or ^{7}Be through the internal conversion in stau-nucleus bound states,

$(\tilde{\tau}^7\mathrm{Be}) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{Li}$ and $(\tilde{\tau}^7\mathrm{Li}) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He}$, given in Ref. [6]. We included the resonant capture process of ^{7}Be and photo-dissociation process pointed out in Ref. [7]. We also took into account the expansion of the Universe by an explicit use of the Boltzmann equation instead of the Saha equation to obtain a more accurate number of the stau-nucleus bound states. By varying the yield value of the stau at its freeze-out time, we found that most of ^{7}Li and ^{7}Be nuclei form a bound state with a stau for $Y_{\tilde{\tau},\mathrm{BF}} \gtrsim (10^{-12}\text{–}10^{-13})$. Taking the values of $m_{\tilde{\chi}^0} = 300$ GeV, $\theta_\tau = \pi/3$, $\gamma_\tau = 0$, and $\eta = (6.225 \pm 0.170) \times 10^{-10}$ [1], we compared the primordial abundances with and without the resonant capture and/or photo dissociation, and found that the resonant capture process is relevant while the photo-dissociation process of the bound state is inconsequential. We obtained a parameter region consistent with the observed abundance of ^{7}Li within $Y_{\tilde{\tau},\mathrm{FO}} = (7\text{–}10) \times 10^{-13}$ and $\delta m = (100\text{–}120)$ MeV. The region of $\delta m \leq 100$ MeV is excluded due to the overproduction of ^{6}Li by the catalyzed fusion. Furthermore, the parameter region obtained in this paper lies in the coannihilation region, which can explain the relic abundance of dark matter. Therefore, the stau with $m_{\tilde{\tau}} \sim 300$ GeV and $\delta m \sim 100$ MeV can simultaneously solve the problems on the relic abundance of the light elements and the dark matter. As shown in Ref. [8], the stau with $m_{\tilde{\tau}} = 300$ GeV and $\delta m = 100$ MeV has the lifetime of $O(100\text{–}1000)$ sec. It is very possible that Large Hadron Collider will find some staus with a very long lifetime [14].

We need further improvement on our analysis to obtain a more precise result of the mass and the mass difference. We have to derive $Y_{\tilde{\tau}}$ as a function of the parameters in the Lagrangian, although we regarded $Y_{\tilde{\tau}}$ as a free input parameter in this paper. Then, we can determine the allowed region of δm and $m_{\tilde{\chi}^0}$ more precisely by varying other parameters such as θ_τ and γ_τ. We leave this for our future work.

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