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Solving the Li problem by long lived stau in a stau-neutralino coannihilation scenario

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We study the Big-Bang Nucleosynthesis (BBN) within the minimal supersymmetric standard model. 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 $300\,\mathrm{GeV}$ and the mass difference between the stau and the neutralino as $(100-120)\,\mathrm{MeV}$. 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 $O(100-1000)\,\mathrm{sec}$.

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1. ^{7}Li problem and long lived stau in the MSSM

The theory of Big-Bang Nucleosynthesis (BBN) has been successful in predicting the light-element abundance in the universe. The recent result of WMAP experiment predicts the ^{7}Li abundance to be 5.24×10^{-10} [1]. This prediction, however, is inconsistent with the observation of metal-poor stars which implies 1.23×10^{-10} [2]. The inconsistency is called ^{7}Li problem. Although the ^{7}Li problem has been studied in a framework of nuclear physics and astrophysics, an adequate solution has not been confirmed yet.

Another interesting approach to ^{7}Li problem is to consider effects induced by new physics beyond the Standard Model (SM). We focus on the Minimal Supersymmetric Standard Model (MSSM) with the conservation of R-parity. We assume the case that the Lightest Supersymmetric Particle (LSP) is the lightest neutralino (bino-like) $\tilde{\chi}$, and the Next Lightest Supersymmetric Particle (NLSP) is the lighter stau $\tilde{\tau}$. Thanks to the R-parity conservation, LSP neutralino is stable, and can be a good dark matter (DM) candidate.

Coannihilation scenario play an important role in the calculation for the relic abundance of neutralino DM [3], which make it possible for the relic abundance to be consistent with the results of cosmological observations and terrestrial experiments. The requirement for the coannihilation scenario to work well and to provide right DM abundance is the small mass difference between the NLSP stau and the LSP neutralino. In particular, we are interesting to the parameter region where the mass difference δm is smaller than the mass of tau lepton. In this case, the stau becomes long-lived charged heavy particle due to phase space suppression in its decay [4]. Fig. 1 shows the stau lifetime as a function of the mass difference between the stau and the neutralino. As shown in Fig. 1, the stau produced from thermal bath survives until the BBN era.

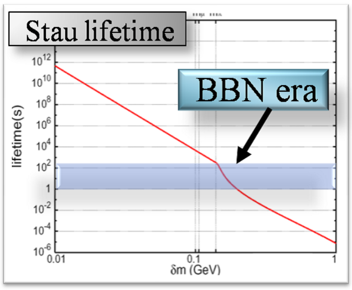

Figure 1: The lifetime of free stau as the functions of δm. Here we take $m_{\tilde{\chi}^0} = 300\,\mathrm{GeV}$, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$.

2. The destruction of ^{7}Li and ^{7}Be in the MSSM

In the BBN era, the long-lived stau can form a bound state with nuclei, and the bound state provides two type new processes [5], [6]: (1) stau-catalyzed fusion, (2) internal conversion of stau-nucleus bound state.

2.1 Stau-catalyzed fusion

A nucleus has a Coulomb barrier which 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. The lifetime of the stau-catalyzed fusion is estimated to be longer than 1 sec [7]. As shown later, the time scale of internal conversion process is much smaller than the stau-catalyzed fusion. Thus stau-catalyzed fusion is subdominant process for solving the ^{7}Li problem.

2.2 Internal conversion of stau-nucleus bound state

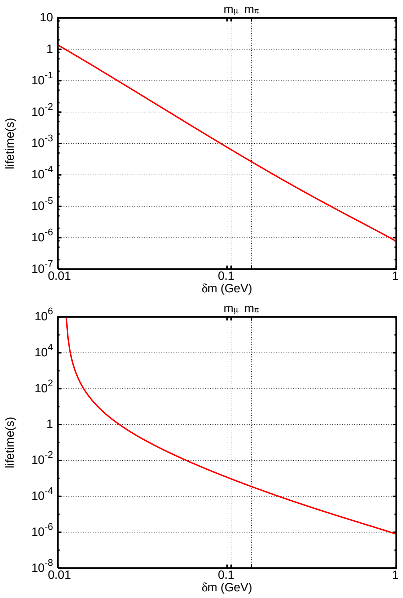

Figure 2: The lifetimes of internal conversion processes as the function of δm. Top panel: $(\tilde{\tau}^7\mathrm{Be}) \to \tilde{\chi} + \nu_\tau + {}^7\mathrm{Li}$, bottom panel: $(\tilde{\tau}^7\mathrm{Li}) \to \tilde{\chi} + \nu_\tau + {}^7\mathrm{He}$. We take m = 300GeV, $\theta_\tau = \pi/3$, and $\gamma_\tau = 0$ in both figures.

The interaction between a stau and a nucleus proceeds more efficiently when they form a bound state 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:

$$\tilde{\tau} + {}^7\mathrm{Be} \to (\tilde{\tau}\,{}^7\mathrm{Be}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{Li}, \qquad (2.1)$$

$$\tilde{\tau} + {}^7\mathrm{Li} \to (\tilde{\tau}\,{}^7\mathrm{Li}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He}, \qquad (2.2)$$

$${}^7\mathrm{He} \to {}^6\mathrm{He} + \mathrm{n}, \qquad (2.3)$$

$${}^6\mathrm{He} + \text{background particles} \to {}^3\mathrm{He}, {}^4\mathrm{He}, \text{etc.}, \qquad (2.4)$$

where the parentheses denote the bound states. 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 (2.4).

The evaluated lifetimes of reactions (2.1) and (2.2) are presented in Fig. 2 as functions of δm. There we take $m_{\tilde{\chi}^0} = 300\,\mathrm{GeV}$, $\theta_\tau = \pi/3$, 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-^{7}Li bound state diverges around $\delta m = m_{^7\mathrm{Li}} - m_{^7\mathrm{Be}} = 11.7\,\mathrm{MeV}$, below which the internal conversion is kinematically forbidden.

3. Numerical result

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 Fig. 3. The white region is the parameter space, which is consistent with all the observational abundance including that of ${}^7\mathrm{Li/H}$. The region enclosed by dashed lines is excluded by the observational abundance of ${}^6\mathrm{Li}/{}^7\mathrm{Li}$, and the one enclosed by solid lines are allowed by those of ${}^7\mathrm{Li/H}$. The thick dotted line is given by the upper bound of the yield value of dark matter $Y_{\mathrm{DM}} = 4.02 \times 10^{-12} \left(\frac{\Omega_{\mathrm{DM}} h^2}{0.110}\right) \left(\frac{m_{\mathrm{DM}}}{10^2\,\mathrm{GeV}}\right)^{-1}$, 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 qualitative feature of the allowed region is explained from the following physical consideration. First, we note that $Y_{\tilde{\tau},\mathrm{FO}} \gtrsim (10^{-13}\text{–}10^{-12})$ is required so that a sufficient number of bound state $(\tilde{\tau}\,{}^7\mathrm{Be})$ 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 $(\tilde{\tau}\,{}^7\mathrm{Li}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He}$, and consequently ${}^7\mathrm{Li/H}$ is reduced. Bearing this physical situation in mind, we consider parameter regions in detail.

1. $\delta m \gtrsim 120\,\mathrm{MeV}$.
Since the staus decay before they form a bound state with ^{7}Be, the value of $Y_{\tilde{\tau},\mathrm{BF}}$ 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. $100\,\mathrm{MeV} \lesssim \delta m \lesssim 120\,\mathrm{MeV}$.
The staus are just decaying at the formation time of the bound state. The necessary condition of $Y_{\tilde{\tau},\mathrm{BF}} \sim 10^{-13}$ can still be retained even in a case where the value of $Y_{\tilde{\tau},\mathrm{FO}}$ 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 $(\tilde{\tau}\,^7\mathrm{Be})$ is broken mainly by an energetic proton.

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

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

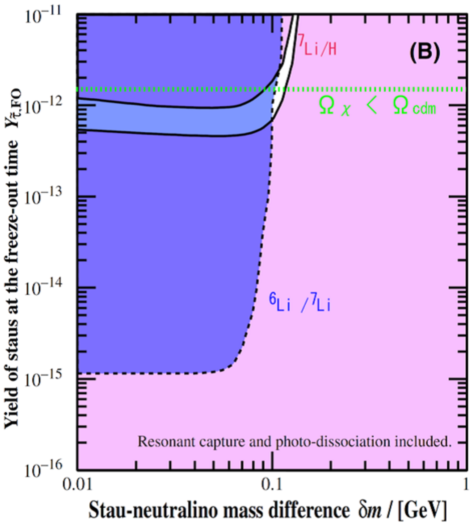

Figure 3: Allowed region in δm-$Y_{\tilde{\tau},\mathrm{FO}}$ plane. The white region is the parameter space, which is consistent with all the observational abundance including that of $^7\mathrm{Li/H}$. The thick dotted line represents the upper bound of the yield value of dark matter, and hence gives the upper bound of $Y_{\tilde{\tau},\mathrm{FO}}$.

5. $\delta m \lesssim 100\,\mathrm{MeV}$ and $Y_{\tilde{\tau},\mathrm{FO}} \gtrsim 10^{-15}$.
In this region, the stau lifetime is too long to form a bound state $(\tilde{\tau}\,^4\mathrm{He})$. Then the catalyzed fusion process $(\tilde{\tau}\,^4\mathrm{He}) + \mathrm{D} \to {}^6\mathrm{Li} + \tilde{\tau}$ leads to the overproduction of ^{6}Li. Therefore, this parameter region is excluded.

Excluding all the parameter regions described above, we obtain a small allowed region of $m_{\tilde{\chi}^0} \simeq m_{\tilde{\tau}} \simeq 300\,\mathrm{GeV}$ and $\delta m = (100\text{–}120)\,\mathrm{MeV}$ as presented in Fig. 3, and these values are at the same time consistent to the coannihilation scenario of the dark matter.

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