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Stau relic density at the Big-Bang nucleosynthesis era consistent with the abundance of the light element nuclei in the coannihilation scenario

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We calculate the relic density of stau at the beginning of the Big-Bang Nucleosynthesis (BBN) era in the coannihilation scenario of minimal supersymmetric standard model (MSSM). In this scenario, stau can be long-lived and form bound states with nuclei. We put constraints on the parameter space of MSSM by connecting the calculation of the relic density of stau to the observation of the light elements abundance, which strongly depends on the relic density of stau. Consistency between the theoretical prediction and the observational result, both of the dark matter abundance and the light elements abundance, requires the mass difference between the lighter stau and the lightest neutralino to be around 100MeV, the stau mass to be 300 – 400 GeV, and the mixing angle of the left and right-handed staus to be $\sin\theta_\tau = (0.65 - 1)$.

I. INTRODUCTION

Cosmological observations have established the existence of the non-baryonic dark matter (DM) [1]. These observations suggest that the DM is a stable and weakly-interacting particle with a mass of $\mathcal{O}(100)$ GeV. Many hypothetical candidates for the DM have been proposed in models of particle physics beyond the standard model (SM), and one of the most attractive candidates is the lightest neutralino, $\tilde{\chi}^0$, in supersymmetric extensions of the SM with R parity conservation. Neutralino is a linear combination of the superpartners of $U(1)$, $SU(2)$ gauge bosons and the two neutral Higgses, and is stable when it is the lightest supersymmetric particle (LSP). Indeed it accounts for the observed DM abundance when it is degenerate in mass to the next lightest supersymmetric particle (NLSP) and hence coannihilates with the NLSP [2]. We consider the setup that the LSP is a neutralino consisting of mainly bino, the superpartner of $U(1)$ gauge boson, and the NLSP is the lighter stau, the superpartner of tau lepton. This is naturally realized in the MSSM with the unification condition at the grand unified theory scale. The minimal supersymmetric SM (MSSM) has two eigenstates of stau as physical state. In absence of inter-generational mixing the mass eigenstate of stau is given by the linear combination of the left-handed stau $\tilde{\tau}_L$ and the right-handed stau $\tilde{\tau}_R$ as

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

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

In a scenario of the coannihilation, the NLSP stau can be long-lived if the mass difference, δm, between neutralino and stau is small enough to forbid two-body decays of stau into neutralino. It was shown in [3] that the lifetime of stau is longer than 1000 second for $\delta m \lesssim 100$ MeV. It is known [4–18] that the long-lived charged particles affect the relic abundance of the light nuclei during or after the big-bang nucleosynthesis (BBN).

There is a discrepancy, the so-called ^{7}Li problem, on the primordial ^{7}Li abundance between the prediction from the standard BBN (SBBN) and the observations [19, 20]. Combined with the up-to-date values of baryon-to-photon ratio, $\eta = (6.225 \pm 0.170) \times 10^{-10}$ from Wilkinson Microwave Anisotropy Probe (WMAP) [1], the SBBN predicts the ^{7}Li to proton ratio, $(^7\mathrm{Li/H})_{\mathrm{SBBN}} = 5.24^{+0.71}_{-0.67} \times 10^{-10}$, which is by about four-times larger than its observed value in poor-metal halos [19, 21]. Because there exists no general agreements about astrophysical scenarios to reduce the ^{7}Li abundance [22–25], it is natural to consider nonstandard effects.

The authors have investigated the BBN including the long-lived stau [14, 15]. The long-lived stau form a bound state with nuclei ($\tilde{\tau}N$), and consequently convert it into a nucleus with a smaller atomic number. Here N stands for a nucleus. In this scenario, the abundance of ^{7}Li is reduced through the conversion process, $(\tilde{\tau}\,^7\mathrm{Be}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{Li}$ and the further destruction of ^{7}Li by either a collision with a background proton or another conversion process, $(\tilde{\tau}\,^7\mathrm{Li}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He}$. Therefore, the more these bound states are formed, the more the ^{7}Li abundance is reduced. The number density of the bound state is determined by the relic density of stau. In [14, 15], we assumed $Y_{\tilde{\tau},\mathrm{FO}}$ and δm to be free parameters of the scenario, where $Y_{\tilde{\tau},\mathrm{FO}}$ is the yield value of stau at the time of decoupling from the thermal bath. The full calculation of the light nucleus abundances showed a region in $(\delta m, Y_{\tilde{\tau},\mathrm{FO}})$ plane where the ^{7}Li problem is solved consistently with the observational constraints on the other nuclei. The region points $Y_{\tilde{\tau},\mathrm{FO}}$ to be close to