SUSY-catalyzed big bang nucleosynthesis as a solution of lithium problems

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Abstract. 6Li abundances observed in metal-poor stars appear to exhibit a plateau as a function of metallicity similar to that for 7Li. This suggests a big bang origin for 6Li. However, since the radiative capture of a deuteron by an alpha particle during the big bang nucleosynthesis (BBN) is suppressed, it is difficult to explain the observed 6Li abundance in the framework of standard BBN. The 6Li problem is thus a nagging puzzle in nuclear astrophysics. In addition, observed 7Li abundances is smaller than expected in standard BBN (SBBN). In this paper we show that there is a possible simultaneous solution to both of the lithium problems in the paradigm of catalyzed BBN by negatively charged supersymmetric particle. We also show that there is no observable signature of the particle on primordial abundances of light nuclei with mass number larger than 8. We study effects of rates for important reactions on resulting final abundances of light nuclei, and show the importance of precise theoretical calculation of reaction rates involving supersymmetric particles using a few-body model. We discuss implications of this model to constraining the mass of dark matter particles to be measured with direct detection experiments such as CDMS II.

1. Introduction
Primordial lithium abundances are inferred from measurements in metal-poor stars (MPSs). Observed abundances are roughly constant as a function of metallicity [1, 2, 3, 4, 5, 6, 7] at 7Li/H= (1 − 2) × 10−10. The theoretical prediction by the standard big bang nucleosynthesis (BBN) model, however, is a factor of 2 − 4 higher, i.e., 7Li/H=(5.24±0.71) × 10−10 [8] when its parameter, the baryon-to-photon ratio, is fixed to the value deduced from the observation with Wilkinson Microwave Anisotropy Probe of the cosmic microwave background (CMB) radiation [9]. The discrepancy indicates some mechanism of 7Li reduction having operated in some epoch from the BBN to this day. One possible astrophysical process to reduce 7Li abundances in stellar surfaces is the combination of the atomic and turbulent diffusion [10, 11]. The precise trend of Li abundance as a function of effective temperature of the metal-poor globular cluster NGC 6397 is, however, not reproduced theoretically [12].
$^{6}\text{Li}/^{7}\text{Li}$ isotopic ratios of MPSs have also been measured spectroscopically. The $^{6}\text{Li}$ abundance as high as $^{6}\text{Li}/^{H}\sim 6 \times 10^{-12}$ was suggested [4], which is about 1000 times higher than the standard BBN (SBBN) prediction. Convective motions in the atmospheres of MPSs could cause systematic asymmetries in the observed line profiles and mimic the presence of $^{6}\text{Li}$ [13]. Nevertheless, there still remain a few or several MPSs with certain detections of high $^{6}\text{Li}$ abundances after estimations of convection-triggered line asymmetries [14, 15]. This high $^{6}\text{Li}$ abundance is a problem since the standard Galactic cosmic ray nucleosynthesis models predict negligible amounts of $^{6}\text{Li}$ yields compared to the observed level in the epoch corresponding to the metallicity of $[\text{Fe}/\text{H}] < -2$ [16]. Be [17, 18, 19, 20, 21, 22, 23, 24] and B [25, 26, 27, 28] abundances are also observed in MPSs. The both abundances increase linearly as iron abundance when the Galaxy evolves chemically. So far no primordial plateau abundances of Be and B are found.

The standard cosmological model, i.e., the ΛCDM, describes well the history of the universe consistent with many astronomical observations. It, however, includes dark matter (DM) in its energy components. Since the standard particle model does not have candidates of DM, a model beyond the standard model is needed. Particle theories including supersymmetry (SUSY) or extra dimensions can provide candidates of DM, and simultaneously of exotic particles other than DM and standard model particles. The existence of long-lived exotic particle such as a supersymmetric partner of a charged lepton [29] or that of a colored gluon [30] might have affected light element abundances and caused the Li problems.

As a cosmological solution to the Li problems, BBN models including exotic decaying particles have been studied. Nonthermal nuclear reactions triggered by the radiative decay of long-lived particles can produce $^{6}\text{Li}$ nuclides in amounts greater than observed in MPSs and at most $\sim 10$ times as much as the level without causing discrepancies in abundances of other light elements or the CMB energy spectrum [31, 32]. If negatively-charged leptonic $X^-$ particles exist in the BBN epoch, they affect the nucleosynthesis [33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45]. The $X^-$ particles get bound to positively charged nuclides with binding energies of $\sim O(0.1-1)$ MeV [46]. Since the binding energies are low, the bound states between the $X^-$ and nuclides form late in BBN epoch. Nuclear reactions at this temperature are no longer efficient so that the effect of negatively-charged particles is rather small. Interestingly the $X^-$ particle can catalyze a preferential production of $^{6}\text{Li}$ [33] and weak destruction of $^{7}\text{Be}$ [36, 39]. If long-lived heavy colored particles exist [47], they would be confined in exotic hadrons. If the hadrons exist in BBN epoch, it binds to nuclei and makes heavy exotic nuclei [48]. A BBN scenario including the long-lived heavy hadrons has been suggested [49]. A solution to the $^{6}\text{Li}$ or $^{7}\text{Li}$ problems was not obtained. The scenario, however, predicts that $^{9}\text{Be}$ and B can be produced in amounts more than in SBBN, and that the isotopic ratio $^{10}\text{B}/^{11}\text{B}$ could be very high.

In this paper we show a result of nonequilibrium nuclear network calculation of BBN catalyzed by a long-lived negatively charged SUSY particle [38] with realistic cross sections from a quantum mechanical calculation [41]. It is found that $^{6}\text{Li}$ production and $^{7}\text{Li}$ reduction can simultaneously occur and that there is no likely signature in primordial abundances of Be and heavier nuclei.

2. Model

We assume the existence of a long-lived negatively charged massive particle $X^-$ [46, 50, 51] such as the spin 0 supersymmetric partners of the leptons during the BBN epoch. The $X^-$ particles become electromagnetically bound to positively charged nuclides $A$, and make bound states $A_X$, i.e., exotic atoms. Such particles can catalyze the nuclear reactions, and enhance $^{6}\text{Li}$ abundance [33] and deplete $^{7}\text{Li}$ abundance [36, 39]. We have re-investigated the catalyzed BBN with an extended nonequilibrium nuclear and chemical reaction network code [37]. We have adopted new reaction rates for an infinite $X^-$ mass case derived from quantum many-body dynamical calculations [41].
3. Result

Figure 1 shows a result of a catalyzed BBN calculation as a function of $T_9 \equiv T/(10^9 \text{ K})$ with temperature $T$. The $X^-$ abundance was taken to be $Y_X = n_X/n_b = 0.05$, where $n_X$ and $n_b$ are the number densities of the $X^-$ particles and baryons, respectively.

Neutral $X$-nuclei ($p_X, d_X$, and $t_X$) form at late times because of the small binding energies to the $X^-$ (see Table I of Ref. [37]). The neutral $X$-nuclei then react with $^4$He and lose their $X^-$. $^4$He$_X$ is thus produced, and the abundances of neutral $X$-nuclei are kept low. Nuclear reactions triggered by neutral $X$-nuclei are thus not important [45, 41, 38].

Figure 2 shows the contours of calculated $^6,^7$Li abundances in the $(Y_X, \tau_X)$ parameter plane. Both the Li problems are solved in $Y_X \geq 1$ and $\tau_X \approx (1 - 2) \times 10^3 \text{ s}$. If the $X^-$ particle decays via the weak interaction into $X^0$, $^7$Be$_X$ converts to $^7$Li, i.e. $^7$Be$_X \rightarrow ^7$Li$+X^0$ [39, 44]. The result of this case is shown in Fig. 6 of Ref. [37].

3.1. Effect of input cross sections on resulting abundances

Figure 3 shows the calculated abundances of the mass 6 and 7 nuclides. These are plotted as $^6\text{Li}/\text{H}$ (black curve of positive slope) and $^7\text{Li}/\text{H}$ (horizontal curve in low $Y_X$ region), as a function of the initial $X^-$ abundance $Y_X$. In the calculations shown in Fig. 3 we have assumed that the $X^-$ particle has a mean lifetime much longer than the typical time scale for BBN in the presence of $X^-$ particles, i.e $\tau_X \gg 5 \text{ hours}$ [37]. The dashed lines indicate the mean values.
observed in MPSs. The solid boxes indicate the range of $Y_X$ consistent with our adopted limits on the abundance of $^6\text{Li}/\text{H}$ observed in MPSs, i.e., $1.7 \times 10^{-12} \leq ^6\text{Li}/\text{H} \leq 7.1 \times 10^{-11}$ [37].

Black lines correspond to the results of realistic calculation adopting precise reaction rates [35, 41] for different values of $X^-$ mass ($m_X = 50, 100, 500$ GeV and $\infty$). It is clear from Fig. 3 that the $^6\text{Li}$ abundance increases monotonically with increasing $Y_X$. This is a consequence of the fact that $^6\text{Li}$ is mainly produced by the $^4\text{He}_X(d,X^-)^6\text{Li}$ reaction [33]. In the region of $Y_X \geq 0.1$, however, a downward departure from the linear increase due to $^6\text{Li}(X^-\gamma)^6\text{Li}_X(p,^3\text{He})^4\text{He}_X$ is observed. The abundance of $^7\text{Li}$, which results from electron capture by $^7\text{Be}$ produced in BBN, decreases at $Y_X \sim O(0.1)$ reflecting the $^7\text{Be}_X$ destruction by the $^7\text{Be}_X(p,\gamma)^8\text{B}_X$ reaction. In the region of higher $Y_X$, the $^7\text{Li}$ and $^7\text{Be}$ production via $^4\text{He}_X(t,X^-)^7\text{Li}$ and $^4\text{He}_X(^3\text{He},X^-)^7\text{Be}$ reactions increases final $^7\text{Li}$ abundances.

The red line corresponds to the case where reaction rates of $^4\text{He}_X(t,X^-)^7\text{Li}$ and $^4\text{He}_X(^3\text{He},X^-)^7\text{Be}$ are set to be zero [36] while the blue line to the case where the reaction rates are enhanced [52]. From lines of $^7\text{Li}/\text{H}$ with different input for reaction rates, it is found that rough estimates could lead to very erroneous results. The precise reaction rates derived from rigorous quantum mechanical many-body calculations [35, 41], therefore, must be used.

![Figure 3](image.png)

**Figure 3.** Calculated abundances of $^6\text{Li}/\text{H}$ and $^7\text{Li}/\text{H}$ as a function of the initial $X^-$ abundance $Y_X$. Black lines correspond to the result of realistic calculation adopting precise reaction rates [35, 41]. The red line corresponds to the case where reaction rates of $^4\text{He}_X(t,X^-)^7\text{Li}$ and $^4\text{He}_X(^3\text{He},X^-)^7\text{Be}$ are set to be zero [36] while the blue line to the case where the reaction rates are enhanced [52]. The solid boxes indicate the range of $Y_X$ consistent with the $^6\text{Li}/\text{H}$ abundance observed in MPSs.

### 3.2. Signature in abundances of nuclei heavier than Li

There is no signature in the primordial abundances of nuclei heavier than Li. Our prediction of the primordial $^9\text{Be}$ abundance in this catalyzed BBN model in the parameter region solving both of the $^6\text{Li}$ and $^7\text{Li}$ problems is negligible, $^9\text{Be}/\text{H} \sim O(10^{-25})$ similar to the SBBN prediction [38]. This value is far less than the present most stringent upper limit of $^9\text{Be}/\text{H} < 10^{-14}$ [23].

Figure 4 shows a result of abundances of nuclei with mass numbers 8 and 9 as a function of temperature, i.e., $T_9$. The abundance and life time of $X^-$ were taken to be $Y_X = 1$ and $\tau_X = 10^3$ s, respectively, which corresponds to the parameter region solving both of the $^6\text{Li}$ and $^7\text{Li}$ problems derived above. $^9\text{Be}_X$ is destroyed through the process $^9\text{Be}_X(p,^6\text{Li})^4\text{He}_X$ [37]. Another isobar, i.e., $^9\text{Be}_X$ is stabilized against the proton decay and the $\beta^+$-decay. It is, therefore, produced at the level of $^9\text{B}/\text{H}=4 \times 10^{-22}$, and can not decay into $^9\text{Be}$ or $^9\text{Be}_X$. The decay of the $X^-$ particle induces reactions $^9\text{B}_X \rightarrow p+^4\text{He}+^4\text{He}+(\text{decay products})$ since the $^9\text{B}$ nuclide is unstable to the proton decay. The $^9\text{Be}$ production through $^9\text{B}_X$ is, thus, not possible [38].

A primordial plateau abundance of Be or B, which could be found in future observations, indicates an origin other than this catalyzed BBN model. Three physical processes can realize enhanced abundances of nuclei heavier than Li. The first is the cosmological cosmic ray nucleosynthesis induced by supernova explosions during an early epoch of structure formation [53]. This model can resolve only the $^6\text{Li}$ problem and leave possible abundance plateaus of $^9\text{Be}$ and B [54, 55]. The second is the BBN model including a long-lived strongly interacting massive particle. Signatures of such particles are possibly left on the primordial
abundances of Be and B which may be found in future astronomical observations of MPSs [49]. The third is the inhomogeneous BBN model which can lead to a high abundance of $^9$Be [56, 57].

Figure 4. Calculated abundances of normal nuclei (a) and $X$-nuclei (b) as a function of $T_0 \equiv T/(10^9 \text{ K})$ (solid lines). The abundance and the lifetime of the $X^-$ particle are set to be $Y_X = 1$ and $\tau_X = 10^3 \text{ s}$, respectively.

4. Constraint on dark matter mass
We here assume that the present cold dark matter (DM) was produced by the decay of $X^\pm$ particles, i.e., $Y_{DM}(\text{present value}) \geq Y_X(\text{initial})$. The constraint on $Y_X$ indicates an allowed range for the DM mass $m_{DM}$ which satisfies the WMAP-CMB constraint on the density parameter of cold DM. In the case where the reactions $^7\text{Be}_X(p,\gamma)^8\text{B}_X$ [36, 39] destroy $^7\text{Be}_X$, the derived constraint is $m_{DM} \leq 4.5 \text{ GeV}$. On the other hand, when the $^7\text{Be}_X \rightarrow ^7\text{Li} + X^0$ reaction [44, 39] is included, $m_{DM} \leq 20 - 110 \text{ GeV}$ is derived.

Combining this result and the allowed region for the DM mass of $40 \text{ GeV} < m_{DM} < 200 \text{ GeV}$, which can successfully explain both of the DAMA/LIBRA data and the recent Cryogenic Dark Matter Search experiment (CDMS II) [58], it is found that only an $X^-$ particle decaying via the weak interaction can exist sufficiently enough to reduce $^7\text{Li}$.

5. Summary
We perform nonequilibrium network calculations of big bang nucleosynthesis (BBN) taking account of catalytic reactions involving long-lived negatively charged exotic particles such as supersymmetric particles. The newest result shows that a simultaneous solution to the $^6\text{Li}$ and $^7\text{Li}$ problems of standard BBN model is still possible in this catalyzed BBN model. It is also found that there is most likely no signature of such particle on primordial abundances of light nuclei with mass number larger than eight, i.e., $^9\text{Be}$ and heavier nuclei. In order to obtain realistic estimates of primordial light element abundances, calculations of reaction rates of catalyzed BBN with quantum mechanical few-body models are necessary. A constraint on dark matter (DM) mass can be derived from a consideration of effects of parent particles of the DM particle on BBN under the assumption that the lithium problems are caused by the catalyzed BBN due to a negatively charged particle which eventually decays into DM. The constraint is severer than that from direct DM detection experiments alone, and therefore valuable.

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