

# Signatures of long-lived exotic strongly interacting massive particles on light element abundances through reactions triggered by the particles

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**Abstract.** A primordial  ${}^7\text{Li}$  abundance inferred from observations of metal-poor halo stars is a factor of about three smaller than predictions of standard big bang nucleosynthesis (BBN) model. Some particle models beyond the standard model include heavy long-lived colored particles with mass much larger than 1 GeV. They would be confined inside exotic heavy hadrons, i.e., strongly interacting massive particles. We have found possible reactions which destroy  ${}^7\text{Be}$  and  ${}^7\text{Li}$  in the scenario of BBN including a long-lived sub-strongly interacting massive particle (sub-SIMP,  $X$ ). The destruction is associated with non radiative  $X$  captures of the nuclei, and it can be realized only if the interaction strength between an  $X$  and a nucleon is properly weaker than that between two nucleons. Binding energies of nuclei to an  $X$  and nuclear reaction rates associated with the  $X$  are estimated. We perform a network BBN calculation using the estimated rates, and suggest that the  ${}^7\text{Li}$  problem can be solved if long-lived sub-SIMPs have existed.

## 1. Introduction

The standard big bang nucleosynthesis (BBN) model is characterized by one parameter, the baryon-to-photon number ratio  $\eta$ . The ratio is precisely determined for a specified cosmological model from the observation of the cosmic microwave background (CMB) radiation with Wilkinson Microwave Anisotropy Probe (WMAP) [1]. Theoretical values of primordial abundances of light element is rather consistent with observations. However, the  ${}^7\text{Li}$  abundances of the standard BBN (SBBN) model are different from those inferred from observations of metal-poor halo stars (MPHSs) [2, 3]. Observed abundance levels are roughly constant as a function of metallicity [4, 5, 2, 3, 6, 7, 8] at  ${}^7\text{Li}/\text{H} = (1 - 2) \times 10^{-10}$ . The SBBN prediction is a factor of 2–4 higher, e.g.,  ${}^7\text{Li}/\text{H} = (5.24^{+0.71}_{-0.67}) \times 10^{-10}$  [9], when the baryon-to-photon ratio  $\eta$  from WMAP determination [1] is adopted. In SBBN,  ${}^7\text{Li}$  nuclei are produced almost as  ${}^7\text{Be}$  in BBN epoch, and they are converted to  ${}^7\text{Li}$  via electron capture at a later epoch of cosmological recombination. The  ${}^7\text{Li}$  problem may be caused by an astrophysical process reducing  ${}^7\text{Li}$  abundances in surface layers of observed stars or by a cosmological process reducing a  ${}^7\text{Be}$  abundance in the early universe.

A possible primordial abundance of  ${}^6\text{Li}$  also has been suggested from spectroscopic observations of MPHSs [3, 10, 11]. The observed level is about thousand times as high as

theoretical predictions of SBBN. Primordial abundances of nuclides heavier than Li isotopes, i.e., Be [12, 13, 14, 15], B [16, 17], and C [18] are not yet detected by observations of MPHSs.

Long-lived heavy ( $m \gg 1$  GeV) colored particles appear in some particle models beyond the standard model, e.g. split supersymmetry [19, 20]. The long-lived colored particles would be confined at temperatures  $T_C \sim 180$  MeV inside exotic heavy hadrons [21], i.e., strongly interacting massive particles (SIMPs) [22, 23, 24] which we call  $X$  particles.

If the SIMPs annihilate with their cross sections given by a typical value for strong interaction, i.e.,  $\sigma \sim \mathcal{O}(\text{GeV}^{-1})^2$ , the relic abundance of  $X$  particles in the early universe is naively estimated [21] to be  $N_X/n_b \sim 0.5 \times 10^{-8}$ , where  $N_X$  is the number density of the  $X$  particle and  $n_b$  is the number density of baryons. A real relic abundance should, however, reflect microscopic details on a hadronic annihilation of  $X$  [25]. Thermal relic abundances depend on the annihilation cross section which is not known precisely. We then take the freezeout  $X$  abundance as a free parameter in this study.

Effects of exotic neutral stable hadrons on BBN were studied in Refs. [26, 27]. In the two studies, binding energies of an exotic hadron  $X$  to nuclei are taken to be those of a  $\Lambda$  hyperon. The strong force between an  $N$  and an  $X$  was, therefore, assumed to be similar to that between an nucleon ( $N$ ) and a  $\Lambda$ . It has also been assumed that the mass of  $X$  is about that of  $\Lambda$ , i.e.,  $m_X \sim 1.116$  GeV [28] implicitly.

Recently effects on BBN of long-lived SIMPs of  $m \gg 1$  GeV, such as a weak-scale mass [ $m = \mathcal{O}(0.1\text{--}1$  TeV)] have been studied [29]. The interaction strength between an  $X$  and an  $N$  is assumed to be similar to that between two nucleons. Rates of many reactions involving the  $X$  particle were estimated, and a network calculation of the nucleosynthesis including effects of the  $X$  was performed. The constraint on the decay lifetime of such particles, i.e.,  $\tau_X \lesssim 200$  s was derived from a comparison of calculated light element abundances with observational abundance constraints.

This model predicts two interesting observable signatures of the  $X$ . One is that  ${}^9\text{Be}$  and B can be produced in amounts more than predicted in the SBBN. Another is the possibility of high isotopic ratio, i.e.,  ${}^{10}\text{B}/{}^{11}\text{B}$ . The high ratio is never reproduced by boron productions from the cosmic ray nucleosynthesis [30, 31, 32] and the supernova neutrino process [33, 34].

The strength of interaction between an  $X$  and an  $N$  is unknown. We then investigate effects of a long-lived  $X$  in multiple cases of interaction strengths, and report a new possibility that reactions associated with the  $X$  particle can reduce  ${}^7\text{Be}$  abundance. The reduction of  ${}^7\text{Be}$  (and  ${}^7\text{Li}$ ) can be a solution to the  ${}^7\text{Li}$  problem.

In this paper the destruction mechanism of  ${}^7\text{Be}$  is reported. We perform a network calculation of BBN assuming the existence and an interaction of a long-lived SIMP. In Sec. 2 assumptions on the  $X^0$  particle and estimations for binding energies between nuclei and an  $X^0$  are described. In Sec. 3 the destruction processes of  ${}^7\text{Be}$  and  ${}^7\text{Li}$  are described. Based on results of the network calculations of BBN, we delineate the parameter region in which the  ${}^7\text{Be}$  and  ${}^7\text{Li}$  destructions possibly operate. In Sec 4 we summarize this work. See Ref. [35] for details of this work.

We use the notation, i.e., 1(2,3)4, for a reaction  $1 + 2 \rightarrow 3 + 4$ .

## 2. Model

A strongly interacting massive particle (SIMP), i.e.,  $X$ , is assumed to exist during the BBN epoch. The spin is zero, and charge is also zero. The mass is one parameter. Two types of nuclear potentials between an  $X^0$  and a nucleon ( $N$ ) are considered in Ref. [35]. In this paper, however, the result for only the Gaussian potential between an  $X^0$  and an  $N$  ( $XN$ ) is shown. The potential is given by  $v(r) = v_0 \delta \exp[-(r/r_0)^2]$ , where  $v_0 = -72.15$  MeV and  $r_0 = 1.484$  fm [36]. The interaction strength is varied by changing  $\delta$ , the second parameter. When the  $\delta$  equals unity then the binding energy of deuteron, i.e., 2.224 MeV, is derived.

The potential between an  $X^0$  and a nuclide  $A$  ( $XA$ ) is given by  $V(r) = \int v(\mathbf{x})\rho(\mathbf{r}') d\mathbf{r}'$ , where

$\mathbf{r}$  is the radius from an  $X$  to the center of mass of  $A$ ,  $\mathbf{r}'$  is the distance between the center of mass of  $A$  and a nucleon inside the nuclide  $A$ ,  $\mathbf{x} = \mathbf{r} + \mathbf{r}'$  is the distance between the  $X$  and the nucleon, and  $\rho(\mathbf{r}')$  is the nucleon density of the nucleus which is generally distorted by potential of an  $X^0$  from the density of normal nucleus.

The nucleon density  $\rho(\mathbf{r})$  is approximately given by the undistorted one for normal nucleus. The nucleon density of nuclei with mass number  $A_m \geq 2$  is assumed to be spherically symmetric and of Gaussian shape, i.e.,

$$\rho(r) = \rho(0) \exp \left[ -(r/b)^2 \right], \quad (1)$$

where  $\rho(0) = A_m \pi^{-3/2} b^{-3}$  is the nucleon density at  $r = 0$  and satisfies the normalization  $\int \rho(r) d\mathbf{r} = A_m$ , with  $A_m$  the mass number. The parameter for the width of density, i.e.,  $b$ , is related to the root mean square nuclear matter radius determined from experiments, i.e.,  $b = \sqrt{2/3} r_m^{\text{RMS}}$ .

### 2.1. Nuclear Binding Energies

Binding energies of nuclides to an  $X$  are estimated. We solve the two-body Schrödinger equation by a variational calculation with the Gaussian expansion method [37]. Binding energies and eigenstate wave functions of the bound states of nuclei  $A$  and an  $X$ , i.e.,  $X$ -nuclei or  $A_X$ , are obtained.

If the mass of the  $X^0$  particle, i.e.,  $m_X$ , is much heavier than light nuclides, the reduced mass  $\mu$  approaches asymptotically to the mass of the nuclide. The binding energies, therefore, also approach to asymptotic values in the limit of large  $m_X$ .

The interaction strength  $\delta$  and the mass  $m_X$  of the  $X$  particle are taken as parameters. Binding energies of ground state  $X$ -nuclei are calculated. Using the obtained binding energies,  $Q$ -values of various reactions are calculated. We also calculate binding energies of nuclear excited states of  ${}^4\text{He}_X^*$  and  ${}^8\text{Be}_X^*$  with relative angular momentum of  $L = 1$ .

### 2.2. Reaction rates

It is hard to calculate rates for nonradiative nuclear reactions precisely. We then approximately take rates of different reactions which has been measured experimentally. For example, the rate of  $X({}^7\text{Be}, {}^3\text{He}){}^4\text{He}_X$  is taken from the nonresonant component in the rate of  ${}^6\text{Li}(n, \alpha){}^3\text{H}$ , and we corrected the rate for a reduced mass dependence of cross sections.

Calculations of rates for radiative reactions are relatively easy. Rates of reactions, i.e.,  $X(\alpha, \gamma){}^4\text{He}_X$ ,  ${}^4\text{He}_X(d, \gamma){}^6\text{Li}_X$  and  ${}^4\text{He}_X(\alpha, \gamma){}^8\text{Be}_X$  are calculated with the code RADCAP [38].

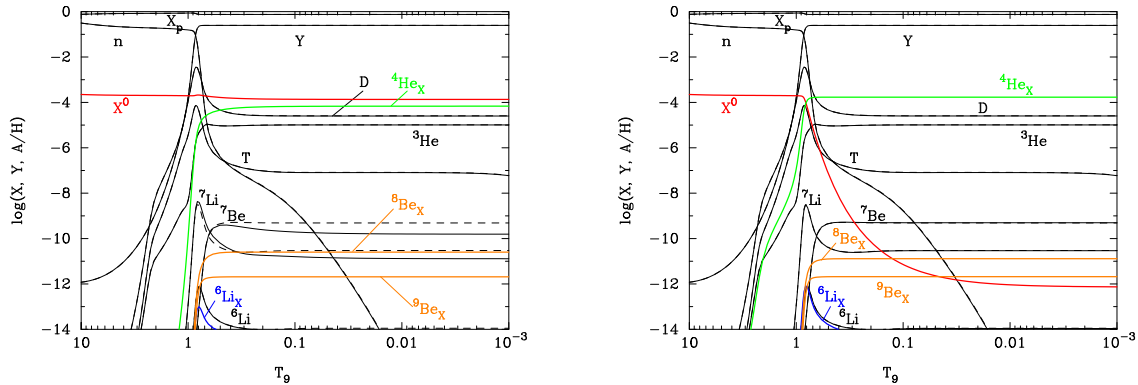
Our estimation for rates of nonradiative and radiative nuclear reactions and  $\beta$ -decay as well as a nuclear reaction network are explained in Ref. [35]. There are large uncertainties in the estimation so that realistic calculations with quantum many-body models are needed in future.

## 3. Results

Figure 1 shows calculated results of the abundances of normal and  $X$ -nuclei as a function of temperature for  $\delta = 0.1$  (left panel) and  $\delta = 0.2$  (right), respectively. The initial abundance of the  $X$  is  $N_X/n_b = 1.7 \times 10^{-4}$  ( $Y_X \equiv N_X/s = 1.5 \times 10^{-14}$ ), where  $N_X$  and  $n_b$  are the number densities of the  $X^0$  particles and baryons, respectively ( $s$  is the entropy density). The  $X^0$  particle is assumed to be long-lived compared to the BBN time scale, and have been long extinct by now, i.e.,  $200 \text{ s} \ll \tau_X \ll 10 \text{ Gyr}$ .

- Case 1 ( $\delta = 0.1$ )

At high temperatures  $T_9 \gtrsim 1$ , the  $X^0$  particles are in the free state since efficient photodisintegrations of  $X$ -nuclei destroy bound states  $A_X$ . At  $T_9 \sim 1$  the  ${}^4\text{He}$  is produced as in SBBN, and about one third of  $X^0$  particles are captured by  ${}^4\text{He}$ .  ${}^4\text{He}_X$  nuclei



**Figure 1.** Calculated abundances of normal and  $X$ -nuclei (solid lines) as a function of  $T_9 \equiv T/(10^9 \text{ K})$ . The mass of  $X^0$  particle was assumed to be  $m_X = 100 \text{ GeV}$ , and the interaction strength of  $XN$  force is 0.1 and 0.2 times that of  $NN$  force, i.e.,  $\delta = 0.1$  (left panel) and  $\delta = 0.2$  (right), respectively. The  $X^0$  abundance is taken to be  $N_X/n_b = 1.7 \times 10^{-4}$  ( $Y_X \equiv N_X/s = 1.5 \times 10^{-14}$ ), and its lifetime is assumed to be much longer than BBN time scale, i.e.,  $\tau_X \gg 200 \text{ s}$ . The  $X^0$  reaction rates are given in Ref. [35] for cases of the two  $\delta$  values. The dashed lines correspond to the abundances of normal nuclei in SBBN model. This figure is reprinted from Ref. [35]

react with normal nuclei, and affect abundances of  ${}^7\text{Li}$  [by  ${}^4\text{He}_X(t, {}^7\text{Li})X$ ],  ${}^6\text{Li}_X$  [by  ${}^4\text{He}_X(d, \gamma){}^6\text{Li}_X$ ], and  ${}^8\text{Be}_X$  [by  ${}^4\text{He}_X(\alpha, \gamma){}^8\text{Be}_X$ ]. Note that  ${}^6\text{Li}_X$  nuclei produced at  $T_9 \sim 1$  experience a strong destruction process, i.e.,  ${}^6\text{Li}_X(p, {}^3\text{He}\alpha)X$ .  ${}^9\text{Be}_X$  is produced by  ${}^8\text{Be}_X(d, p){}^9\text{Be}_X$ . Finally, free  $X^0$  particles which survived the capture by  ${}^4\text{He}$  react with  ${}^7\text{Be}$  [by  $X({}^7\text{Be}, {}^3\text{He}){}^4\text{He}_X$ ] and  ${}^7\text{Li}$  [by  $X({}^7\text{Li}, t){}^4\text{He}_X$ ]. Abundances of  ${}^7\text{Be}$  and  ${}^7\text{Li}$  thus decrease.

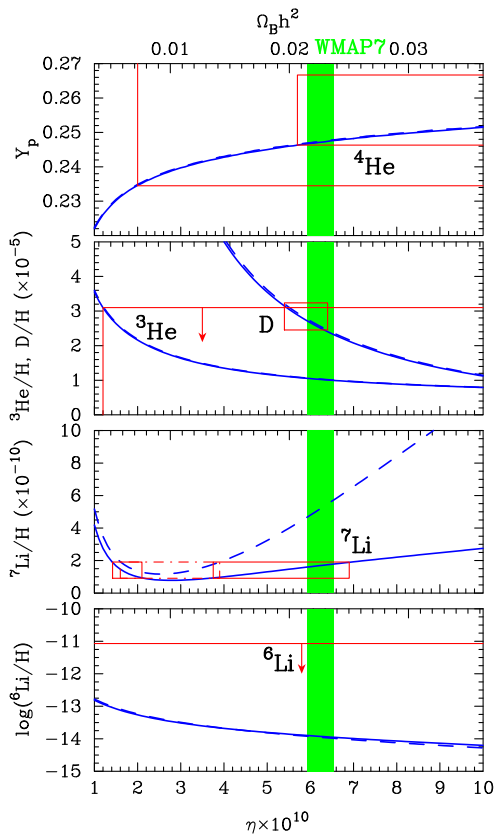
- Case 2 ( $\delta = 0.2$ )

The abundance evolution is similar to that in Case 1 at high temperatures  $T_9 \gtrsim 1$ . However, almost all of  $X^0$  particles are captured by  ${}^4\text{He}$  following the  ${}^4\text{He}$  synthesis at  $T_9 \sim 1$ . The abundance of free  $X^0$  particle then significantly reduces at this time. The destruction of  ${}^7\text{Be}$  and  ${}^7\text{Li}$ , therefore, does not occur as seen in Fig 1.

The reason for the difference between Cases 1 and 2 is as follows: When the interaction strength ( $\delta$ ) is large and the excited state  ${}^4\text{He}_X^*$  ( $L = 1$ ) exists, the reaction rate of  $X({}^4\text{He}, \gamma){}^4\text{He}_X$  increases. The  ${}^7\text{Be}$  and  ${}^7\text{Li}$  destruction reactions are then hindered by the depletion of free  $X^0$  particles [35]. In Case 1, there is no excited state of  ${}^4\text{He}_X^*$ . The reaction  $X({}^4\text{He}, \gamma){}^4\text{He}_X$  then proceeds mainly from the initial scattering  $p$ -wave to the final bound  $S$ -state. In Case 2, on the other hand, an excited state of  ${}^4\text{He}_X^*$  exists. The reaction  $X({}^4\text{He}, \gamma){}^4\text{He}_X$  can then proceed mainly from the initial scattering  $s$ -wave to the final bound  $P$ -state.

Figure 2 shows abundances (solid curves) of  ${}^4\text{He}$  (mass fraction),  $\text{D}$ ,  ${}^3\text{He}$ ,  ${}^7\text{Li}$  and  ${}^6\text{Li}$  (by number relative to  $\text{H}$ ) as a function of the baryon-to-photon ratio  $\eta$  or the baryon energy density  $\Omega_B h^2$  of the universe. The solid curves are the calculated result in this BBN affected by  $X$  for  $(m_X, \delta, Y_X, \tau_X) = (100 \text{ GeV}, 0.1, 1.5 \times 10^{-14}, \infty)$ . The dashed curves are those in the SBBN. The boxes correspond to the adopted constraints on primordial abundances [35]. The vertical stripe is the  $2\sigma$  limits on  $\Omega_B h^2 = 0.02258_{-0.00056}^{+0.00057}$  provided by WMAP [1] for the  $\Lambda\text{CDM} + \text{SZ} + \text{lens}$  model.

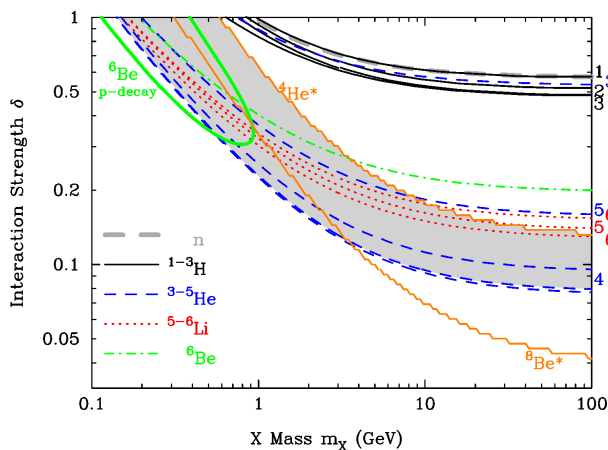
A decrease in  ${}^7\text{Li}$  abundance is found, while other nuclear abundances are not changed. A solution to the  ${}^7\text{Li}$  problem is thus found in this model.



**Figure 2.** Abundances of  ${}^4\text{He}$  (mass fraction),  $\text{D}$ ,  ${}^3\text{He}$ ,  ${}^7\text{Li}$  and  ${}^6\text{Li}$  (by number relative to  $\text{H}$ ) as a function of the baryon-to-photon ratio  $\eta$  or the baryon energy density  $\Omega_B h^2$  of the universe. The solid curves are the calculated results in the BBN model including  $X$  for the parameter set of  $(m_X, \delta, Y_X, \tau_X) = (100 \text{ GeV}, 0.1, 1.5 \times 10^{-14}, \infty)$ , while the dashed curves are those in SBBN. The boxes represent the adopted abundance constraints from Refs. [39, 40] for  ${}^4\text{He}$ , [41] for  $\text{D}$ , [42] for  ${}^3\text{He}$ , [5] for  ${}^7\text{Li}$ , and [3] for  ${}^6\text{Li}$ , respectively. The vertical stripe corresponds to the  $2\sigma$   $\Omega_B h^2$  limits provided by WMAP [1]. This figure is reprinted from Ref. [35]

If the strength of  $XN$  interaction is relatively weak, most strong reactions for the  $X^0$  particle to get bound to nuclei are non-radiative  $X^0$ -capture reactions which are found important in the present model.  $X({}^6\text{Li}, d){}^4\text{He}_X$ ,  $X({}^7\text{Li}, t){}^4\text{He}_X$ , and  $X({}^7\text{Be}, {}^3\text{He}){}^4\text{He}_X$  are important reactions in this BBN scenario including  $X$  effects.

Figure 3 shows contours in the parameter space  $(m_X, \delta)$  for critical binding energies of  $X$ -nuclei (thin and thick smooth curves). Above the respective contours,  $Q$ -values for respective reactions [35] are positive. Zigzag curves show boundaries above which an excited state of  ${}^4\text{He}_X^*$  with  $L = 1$  (upper line) and  ${}^8\text{Be}_X^*$  with  $L = 1$  (lower) exist, respectively.



**Figure 3.** Contours of binding energies between nuclei and an  $X^0$  particle corresponding to  $Q = 0$  of reactions [35] (thin and thick smooth curves). Numbers attached to the contours indicate mass numbers of nuclei. Above the contours, reaction  $Q$ -values are positive. Zigzag curves correspond to boundaries above which an excited state of  ${}^4\text{He}_X^*$  (upper line) and  ${}^8\text{Be}_X^*$  (lower) exist, respectively. In the shaded region, the  ${}^7\text{Li}$  problem can be resolved. This figure is reprinted from Ref. [35]

In Fig. 3, it is found that the contour of the boundary for existence of  ${}^4\text{He}_X^*$  are above the contours of the reaction  $X({}^7\text{Be}, {}^3\text{He}){}^4\text{He}_X$  (the second lowest thin dashed lines). In the parameter region in right upper side from the curve of  ${}^4\text{He}_X^*$ , free  $X^0$  particles are captured onto  ${}^4\text{He}$  before they can react with  ${}^7\text{Be}$  to reduce its abundance.

In the shaded region below that curve and above the curve of  $X({}^7\text{Be}, {}^3\text{He}){}^4\text{He}_X$ , free  $X^0$ s would possibly remain, and they can reduce the  ${}^7\text{Be}$  abundance. This shaded region is, therefore, a possible parameter region solving the  ${}^7\text{Li}$  problem.

#### 4. Summary

We study effects of a long-lived strongly interacting massive particle (SIMP)  $X^0$  on BBN. The property of the SIMP is roughly described by the mass  $m_X$  and the strength of  $XN$  interaction, i.e.,  $\delta$ . Binding energies of  $X$ -nuclei (bound states of nuclei and an  $X^0$  particle) are calculated for two types of  $XN$  potentials, i.e., Gaussian and well types [35].

We estimate  $Q$ -values and rates for possibly important reactions which exist in the presence of  $X^0$  particle. Evolutions of elemental abundances are then calculated under the assumption of existence of a SIMP which interacts with a nucleon by a strength about 0.1 times as large as that of a nucleon. Such a SIMP with relatively weak strong interaction is called sub-SIMP. It is found that if there is no excited bound state of  ${}^4\text{He}_X$  with a relative angular momentum  $L = 1$ , a significant fraction of the  $X$  can escape the capture by  ${}^4\text{He}$ . In such a situation,  ${}^7\text{Be}$  and  ${}^7\text{Li}$  can be destroyed by the nuclear capture reactions by free  $X^0$  particles, i.e.,  $X({}^7\text{Be}, {}^3\text{He}){}^4\text{He}_X$  and  $X({}^7\text{Li}, t){}^4\text{He}_X$ . We suggest that the  ${}^7\text{Li}$  problem could be solved based on a network calculation of BBN, and constrain the parameter region in the  $(m_X, \delta)$  plane where the  ${}^7\text{Li}$  problem can be solved.

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