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Study of the primordial lithium abundance

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Lithium isotopes have attracted an intense interest because the abundance of both ^{6}Li and ^{7}Li from big bang nucleosynthesis (BBN) is one of the puzzles in nuclear astrophysics. Many investigations of both astrophysical observation and nucleosynthesis calculation have been carried out to solve the puzzle, but it is not solved yet. Several nuclear reactions involving lithium have been indirectly measured at China Institute of Atomic Energy, Beijing. The Standard BBN (SBBN) network calculations are then performed to investigate the primordial Lithium abundance. The result shows that these nuclear reactions have minimal effect on the SBBN abundances of ^{6}Li and ^{7}Li.

big bang nucleosynthesis, element abundance, nuclear reaction network

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1 Introduction

Since the pioneering work of Spite and Spite [1], the lithium abundance in the metal-poor halo stars has been confirmed as a plateau, independent of metallicity and effective temperature. Up to now, the most widely accepted interpretation is that the lithium observed in metal-poor stars has been produced in the big bang nucleosynthesis (BBN). According to the standard big bang (SBBN) model, the relative abundances of the light elements (^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li) depend only on one parameter, namely, the baryon-to-photon ratio η. Using the precisely determined η from cosmic microwave background fluctuations, the lithium-to-hydrogen ratio is predicted to be ^{7}Li/H = $(4.15\pm0.5)\times10^{-10}$ [2], which is higher than that observed in metal poor halo stars by roughly a factor of three. Even worsely, the recent claims of detection of isotope-shifted lithium absorption lines in a subset of the stars point to a ^{6}Li abundance some three orders of magnitude larger than that expected in SBBN [3].

Where is the tremendous difference of lithium abundances between observation and SBBN model from? Is the lithium problem one of the very few hints that there may be a problem with the big bang model? Are there dissenting views on the interpretation of the stellar spectra? The lithium abundance problems immediately catch the high attention of astronomers, astrophysicists and scientists in the field of nuclear physics. They try to solve the problems in different ways. At the present, the lithium problem is more serious than ever, since the improved observations of stars suggest that they contain even less ^{7}Li than previously thought [4].

Although the hot SBBN model code contains most of the nuclear reactions that could be relevant to BBN [5,6], some reactions on short-lived nuclei are not well studied, and in some cases have not been included. Only when all the reac-

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tions involving lithium are taken into account correctly, can the BBN code give the reasonable primordial lithium abundance. It seems appropriate to reexamine the BBN reaction network in order to be sure that all possible reactions are included, and to study the potential effects of those reactions for which data did not consider previously.

Based on the above consideration, a series of reactions involving lithium, such as ^{6}Li(n, γ)^{7}Li, ^{7}Li(n, γ)^{8}Li, ^{8}Li(n, γ)^{9}Li, ^{6}Li(p, γ)^{7}Be, ^{6}He(p, γ)^{7}Li, ^{6}He(p, n)^{6}Li, ^{6}He(d, n)^{7}Li, ^{8}Li(p, γ)^{9}Be, ^{8}Li(p, d)^{7}Li, ^{8}Li(p, t)^{6}Li, ^{8}Li(d, p)^{9}Li and ^{8}Li(d, n)^{9}Be, were measured at HI-13 tandem accelerator, Beijing. The rates of these nuclear reactions were deduced and then used in the BBN network calculations.

2 Experiments

Figure 1 shows the reaction network used in the present work. The reactions labeled with the dashed line are newly included in the calculations, they may destroy more ^{7}Li and increase the abundance of ^{6}Li. The experiments of these reactions are described as below.

2.1 ^{6}Li(n, γ)^{7}Li and ^{6}Li(p, γ)^{7}Be

The only existing direct measurement of the ^{6}Li(n, γ)^{7}Li reaction is not consistent with the values used in some previous reaction network calculations [7,8], thus an independent measurement is needful for clarifying this discrepancy. We measured the angular distributions of the ^{7}Li(^{6}Li, ^{6}Li)^{7}Li elastic scattering and ^{7}Li(^{6}Li, ^{7}Li$_{g.s.}$)^{6}Li, ^{7}Li(^{6}Li, ^{7}Li$_{0.48}$)^{6}Li transfer reactions at $E_{c.m.}$=23.7 MeV [9]. The angular distribution for ^{7}Li ground state is shown in Figure 2.

By comparing the experimental result with the distorted-wave Born approximation (DWBA) calculation, the neutron spectroscopic factors for the ground and first exited states in ^{7}Li were determined to be 0.78 ± 0.04 and 1.02 ± 0.07, respectively. The results were used to calculate the cross sections of ^{6}Li(n, γ)^{7}Li direct capture reaction. The rates were derived to be $(8.1\pm0.6)\times10^3$ cm^{3}mol^{-1}s^{-1} at the energies of astrophysical interests. Our result is higher by a factor of 1.6 than the value adopted in previous reaction network calculations.

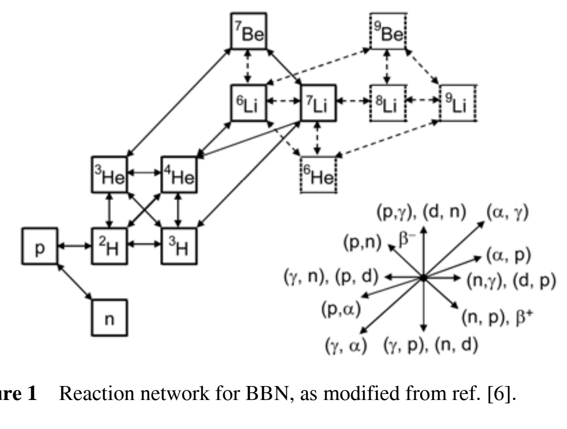

Figure 1 Reaction network for BBN, as modified from ref. [6].

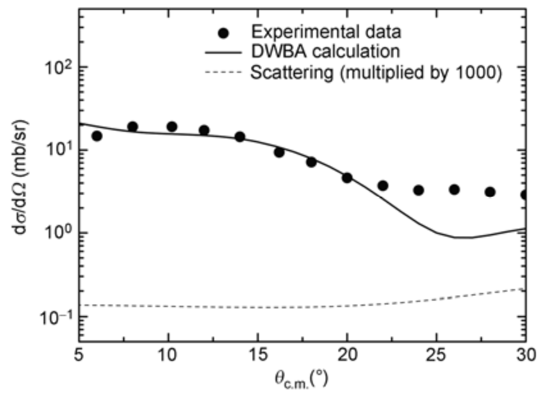

Figure 2 Angular distribution of ^{7}Li(^{6}Li, ^{7}Li$_{g.s.}$)^{6}Li at $E_{c.m.}$ = 23.7 MeV.

According to charge symmetry, the astrophysical ^{6}Li(p, γ)^{7}Be S(E)-factors were derived with the deduced spectroscopic factor. The result indicates that the contributions of ground and first exited states in ^{7}Be are about 63% and 37%, respectively.

The calculated astrophysical ^{6}Li(p, γ)^{7}Be S(E) factors are in good agreement with the measured total S(E) factors [9].

2.2 ^{6}He(d, n)^{7}Li and ^{6}He(p, γ)^{7}Li

The angular distribution of the ^{6}He(d, n)^{7}Li reaction, shown in Figure 3, was measured with a ^{6}He beam of 36.4 MeV for the first time [10]. The proton spectroscopic factor of ^{7}Li was extracted to be 0.42 ± 0.06 by the normalization of the calculated differential cross sections with the DWBA to the experimental data [10,11]. The ^{6}He(p, γ)^{7}Li cross section as a function of $E_{c.m.}$ was deduced with the extracted ^{7}Li proton spectroscopic factor, as shown in Figure 4.

2.3 ^{6}He(p, n)^{6}Li reaction

The ^{6}He(p, n)^{6}Li reaction is supposed to be a way to in-crease the primordial ^{6}Li abundance. The angular distri-

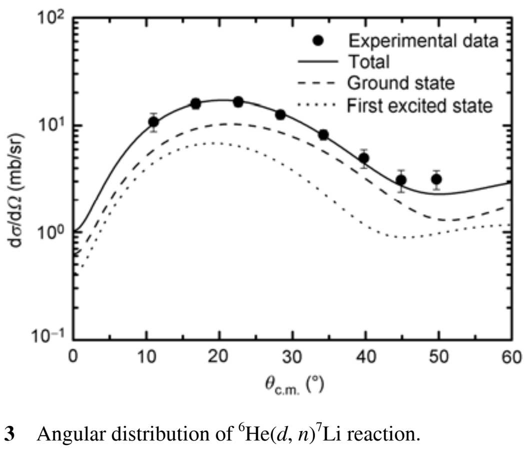

Figure 3 Angular distribution of ^{6}He(d, n)^{7}Li reaction.

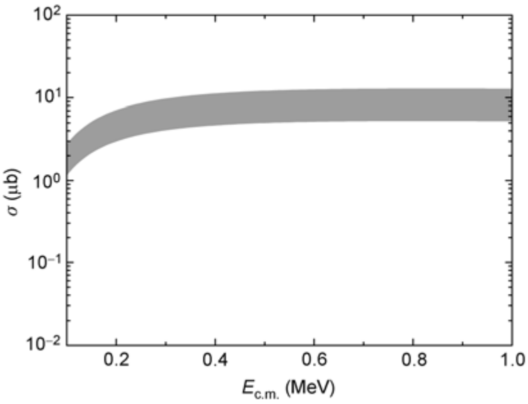

Figure 4 Cross sections of ^{6}He(p, γ)^{7}Li reaction at $E_{c.m.}$ < 1.0 MeV.

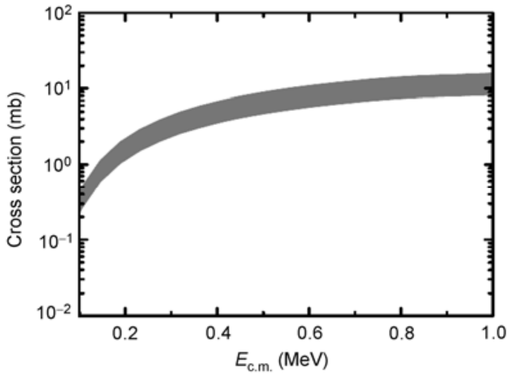

Figure 5 Cross section as a function of $E_{c.m.}$ for the ^{6}He(p, n)^{6}Li reaction.

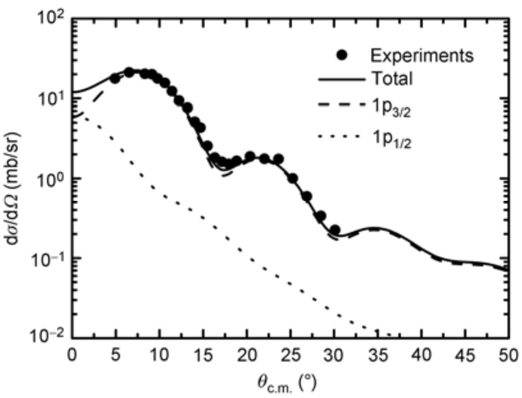

Figure 6 Angular distribution of ^{13}C(^{7}Li, ^{8}Li)^{12}C reaction E(^{7}Li)=44 MeV. The dashed and dotted lines represent the contributions of $1p_{1/2}$ and $1p_{3/2}$ orbits, respectively.

butions of ^{6}He(p, n)^{6}Li reaction leading to the ground and 3.563 MeV 0^+ states of ^{6}Li have been measured using the ^{6}He radioactive beam at energy of 4.17 AMeV [12]. The experiment reveals the proton-neutron halo structure of the secondary excited state of ^{6}Li, which was predicted by Arai et al. [13]. The dependence of the cross section as a function of energy in the center of mass frame is calculated with the nuclear reaction code Talys [14] to obtain its reaction rates in the energies of astrophysical interest. Figure 5 shows the normalized cross sections with our experimental data. The errors are from the statistics and theoretical calculations.

2.4 ^{7}Li(n, γ)^{8}Li reaction

We have measured the angular distributions of ^{13}C(^{7}Li, ^{8}Li)^{12}C one neutron transfer reaction and ^{13}C+^{7}Li and ^{12}C + ^{7}Li elastic scatterings. The optical potential parameters were derived from the elastic scatterings and then used in the calculation of transfer angular distribution. The experimental data and the normalized calculation results are shown in Figure 6. The ratio of the contributions by the $1p_{1/2}$ and $1p_{3/2}$ orbits was determined to be 0.10(3) and the neutron spectroscopic factor of ^{8}Li was extracted to be 0.55 $\pm$0.06. The spectroscopic factor was then used to deduce the cross section of the ^{7}Li(n, γ)^{8}Li reaction. As can be seen in Figure 7, our indirect measurement is in good agreement with the direct experimental data [15, 16].

2.5 ^{8}Li(d, p)^{9}Li and ^{8}Li(n, γ)^{9}Li

Figure 8 shows the angular distribution of the ^{8}Li(d, p)^{9}Li reaction, which was measured at $E_{c.m.}$=7.8 MeV in inverse kinematics using coincidence detection of ^{9}Li and the recoil proton [17]. Based on DWBA analysis, the ^{8}Li(d, p)^{9}Li cross section was determined to be 7.9$\pm$2.0 mb. The cross sections in the energy range of Gamow window can then be deduced via code Talys with the normalized results of the experimental cross section.

The single particle spectroscopic factor $S_{1,3/2}$ for ^{9}Li= ^{8}Li$\otimes n$ was derived to be 0.68$\pm$0.14, which was then used to calculate the direct capture cross sections for the ^{8}Li(n, γ)^{9}Li reaction at energies of astrophysical interest. The reaction rates as a function of T_9 were displayed in Figure 9. The astrophysical ^{8}Li(n, γ)^{9}Li reaction rate for the direct capture was found to be 3970$\pm$950 cm^3 mole^{-1} s^{-1} at T_9 = 1. This presents the first experimental constraint for the ^{8}Li(n, γ)^{9}Li reaction rates of astrophysical relevance.

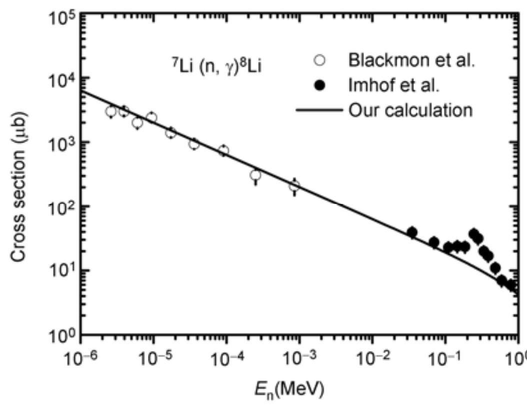

Figure 7 The cross section of ^{7}Li(n, γ)^{8}Li reaction as a function of incident neutron energy. The experimental data are from refs. [15] and [16].

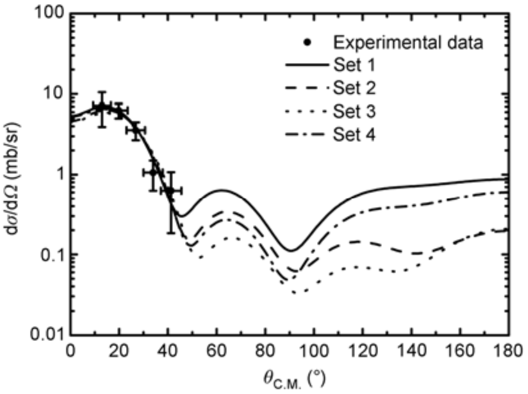

Figure 8 Angular distribution of ^{8}Li(d, p)^{9}Li reaction.

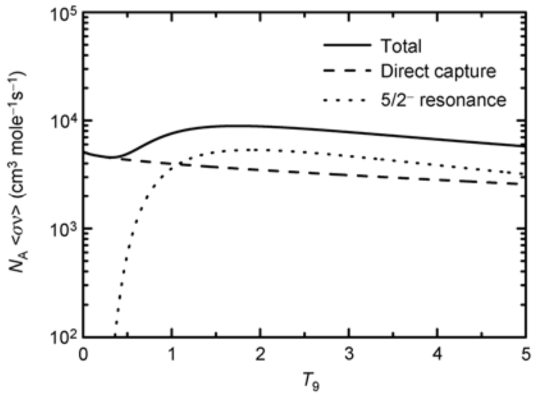

Figure 9 ^{8}Li(n, γ)^{9}Li reaction rates as a function of T_9.

2.6 ^{8}Li(d, n)^{9}Be and ^{8}Li(p, γ)^{9}Be

The ^{8}Li(d, n)^{9}Be angular distribution shown in Figure 10 was measured firstly in inverse kinematics using a $\Delta E- E_r$ counter telescope which was composed of a 19.3-μm-thick silicon detector and a 300-μm-thick three-ring silicon detector in 2004. The cross section of this reaction was determined to be 9.0±3.4 mb, and the astrophysical S-factor was derived to be 272±103 keV b [18]. The spectroscopic factor of ^{9}Be=^{8}Li+p was found to be 0.64±0.21 with the standard bound state potential parameters (radius r_0= 1.25 fm, diffuseness a = 0.65 fm) [19]. The energy dependence of direct capture cross section for the ^{8}Li(p, γ)^{9}Be reaction was then calculated with the spectroscopic factor and the optical potential model.

In 2008, a joint group of scientists from America, Brazil and Mexico measured the angular distribution of ^{9}Be(^{8}Li, ^{9}Be)^{8}Li elastic transfer reaction, and deduced the proton spectroscopic factor of ^{9}Be to be 1.50±0.28 [20]. Their value is larger than ours by a factor of 2. To clarify this dispersion, we measured the angular distribution of ^{13}C(^{9}Be, ^{8}Li)^{14}N at HI-13 tandem accelerator very recently. The experimental data were plotted in Figure 11 and the proton spectroscopic factor of ^{9}Be was extracted to be 0.72±0.15. The result proved the correctness of the ^{9}Be proton spectroscopic factor extracted from the ^{2}H(^{8}Li, ^{9}Be)n reaction.

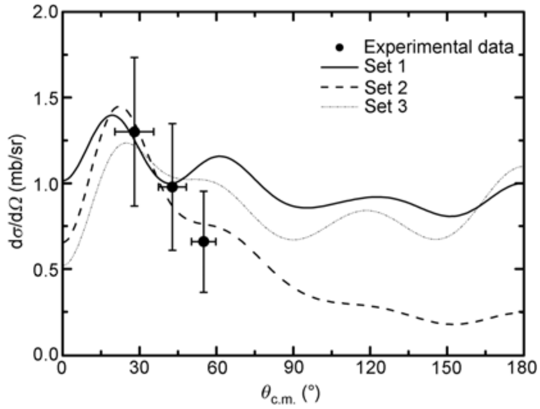

Figure 10 Angular distribution of ^{8}Li(d, n)^{9}Be reaction.

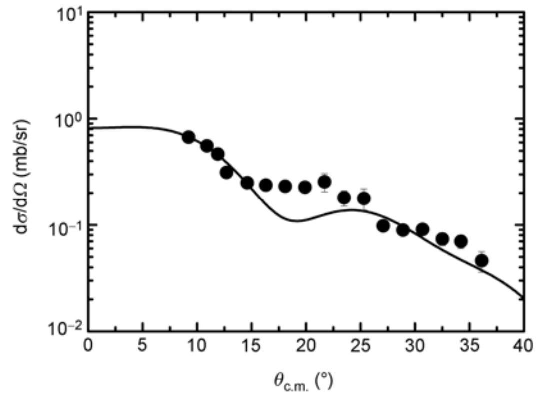

Figure 11 Angular distribution of ^{13}C(^{9}Be, ^{8}Li)^{14}N reaction at E(^{9}Be)=40 MeV.

2.7 ^{8}Li(p, d)^{7}Li and ^{8}Li(p, t)^{6}Li

The ^{8}Li(p, d)^{7}Li angular distribution at backward angles, shown in Figure 12, was measured in inverse kinematics at $E_{\mathrm{c.m.}}$ = 4.0 MeV by using the ^{8}Li secondary beam for the first time [21]. The ratio of the contributions from ^{8}Li(p, d_0)^{7}Li and ^{8}Li(p, d_1)^{7}Li* is estimated through energy spectrum of deuteron. The ^{8}Li(p, d_0)^{7}Li component is approximately in agreement with the result deduced from the existing ^{7}Li(d, p_0)^{8}Li reaction data via the principle of detailed balance.

The ^{8}Li(p, t)^{6}Li angular distribution was also obtained from the same experiments, as shown in Figure 13. The reaction chain of ^{7}Li(n, γ)^{8}Li(p, t)^{6}Li is thought to be a process for destroying ^{7}Li and generating ^{6}Li.

3 Network calculations

With the cross sections of the above mentioned reactions, the thermonuclear reaction rates $\langle\sigma v\rangle$ can be calculated by

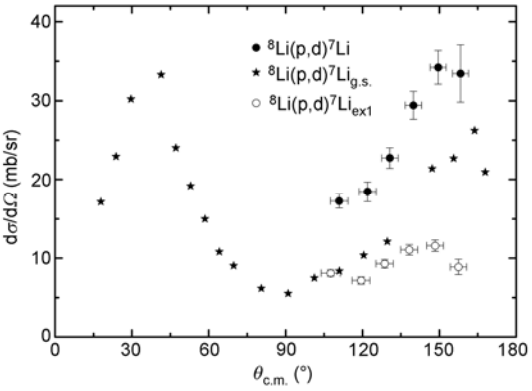

Figure 12 Angular distributions of ^{8}Li(p, d)^{7}Li reaction.

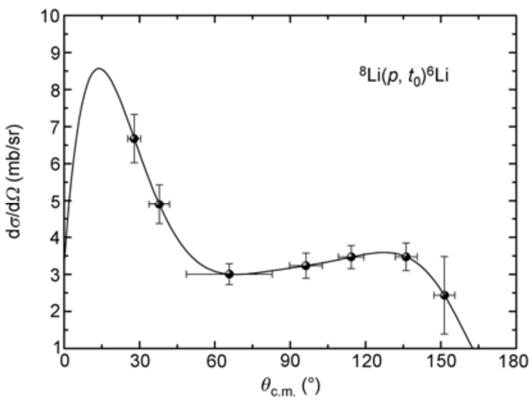

Figure 13 Angular distribution of ^{8}Li(p, t)^{6}Li reaction.

$$\langle \sigma v \rangle = \left[\frac{8}{\pi \mu}\right]^{1/2} [kT]^{-3/2} \int \sigma(E) E e^{-E/kT} \mathrm{d}E, \tag{1}$$

where μ is the reduced mass of the system, E is the energy in the center of mass system, k is the Boltzmann constant, and T is the temperature in Kelvin.

The reaction network calculations have been done with the modification code based on the computational routines of Wagoner [6]. The rate for the abundance change of any nucleus i is determined by the rate equation

$$\frac{dY_i}{dt} = \sum_{i,k,l} N_i \left(-\frac{Y_i^{N_i} Y_j^{N_j}}{N_i!N_j!}[ij]_k + \frac{Y_l^{N_l} Y_k^{N_k}}{N_l!N_k!}[lk]_j \right), \tag{2}$$

where Y_i is the mass fraction contained in nucleus i, N_m is the number of nuclear m. $[ij]_k$ represents the reaction rate for the reaction between i and j, including the decay rate of nuclear i. The sum in eq. (2) includes all reactions involving nucleus i.

The evolution of the abundance for ^{6}Li, ^{7}Li and ^{7}Be of our calculations is shown in Figure 14. In general, it was found that the added reactions slightly changed the lithium abundance at t<1000 s, but nearly no effect at t>1000 s. This may be attributed to the small binding energies of lithium.

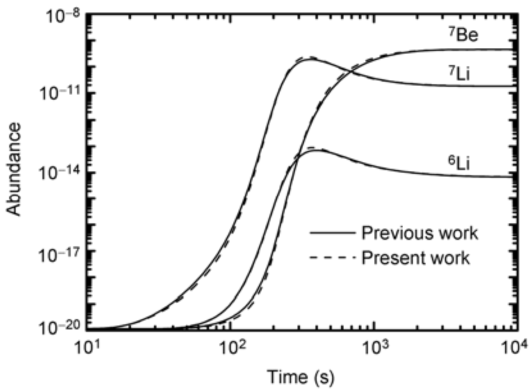

Figure 14 Nuclear abundance as a function of times.

The detailed study showed that ^{6}Li(p, α)^{3}He could have large effect for destroying ^{6}Li, leading to the disappearance of the effect of the added reaction. The abundance of ^{7}Li is sensitive to the ^{2}H(p, γ)^{3}He, ^{3}He(α, γ)^{7}Be, and ^{7}Li(p, α)^{4}He reaction rates. Unfortunately, the existing experimental data have large uncertainties. Reducing the uncertainties of these reactions is necessary to solve ^{7}Li problem.

4 Conclusion

We have determined the reaction rates of twelve reactions involving lithium and done the BBN calculations with an expanded network. Unfortunately, the attempts to solve the lithium abundance problem failed. This may result from the large uncertainties of the reaction rates for ^{2}H(α, γ)^{6}Li, ^{2}H(p, γ)^{3}He, ^{3}He(α, γ)^{7}Be and ^{7}Li(p, α)^{4}He. High precision measurements of these reactions would reduce the uncertainty on lithium abundance calculations. In addition, it is of interest to determine some unknown reactions, such as ^{7}Be(d, ^{3}He)^{6}Li and ^{4}He($2n$, γ)^{6}He, and they may produce more ^{6}Li during BBN.

It is very important to investigate the BBN model more carefully. The improvements of the lithium observations in very metal poor stars could also help us to solve the lithium problem.

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