Study of the primordial lithium abundance

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Lithium isotopes have attracted an intense interest because the abundance of both 6Li and 7Li 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 6Li and 7Li.

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 (1H, 2H, 3He, 4He, 6Li, and 7Li) 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 7Li/H = (4.15 ± 0.5) × 10^{-10} [2], which is higher than that observed in metal poor halo stars by roughly a factor of three. Even worse, the recent claims of detection of isotope-shifted lithium absorption lines in a subset of the stars point to a 6Li 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 7Li 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 $^6\text{Li}(n, \gamma)^7\text{Li}$, $^7\text{Li}(n, \gamma)^8\text{Li}$, $^8\text{Li}(n, \gamma)^9\text{Li}$, $^7\text{Li}(p, \gamma)^7\text{Be}$, $^6\text{He}(p, \gamma)^7\text{Li}$, $^6\text{He}(p, n)^6\text{Li}$, $^6\text{He}(d, n)^7\text{Li}$, $^8\text{Li}(p, \gamma)^7\text{Be}$, $^8\text{Li}(p, d)^7\text{Li}$, $^8\text{Li}(d, p)^7\text{Li}$ and $^8\text{Li}(d, n)^7\text{Be}$, 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 $^7\text{Li}$ and increase the abundance of $^8\text{Li}$. The experiments of these reactions are described as below.

2.1 $^6\text{Li}(n, \gamma)^7\text{Li}$ and $^6\text{Li}(p, \gamma)^7\text{Be}$

The only existing direct measurement of the $^6\text{Li}(n, \gamma)^7\text{Li}$ 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 $^7\text{Li}$($^6\text{Li}$, $^7\text{Li}$) elastic scattering and $^7\text{Li}$($^6\text{Li}$, $^7\text{Li}_g.s.)^6\text{Li}$, $^7\text{Li}$($^6\text{Li}$, $^7\text{Li}_{1.0.48})^7\text{Li}$ transfer reactions at $E_{\text{cm}}=23.7$ MeV [9]. The angular distribution for $^7\text{Li}$ 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 $^7\text{Li}$ were determined to be $0.78\pm 0.04$ and $1.02\pm 0.07$, respectively. The results were used to calculate the cross sections of $^6\text{Li}(n, \gamma)^7\text{Li}$ direct capture reaction. The rates were derived to be $(8.1\pm 0.6)\times 10^3$ 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.

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

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

2.2 $^6\text{He}(d, n)^7\text{Li}$ and $^6\text{He}(p, \gamma)^7\text{Li}$

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

2.3 $^6\text{He}(p, n)^5\text{Li}$ reaction

The $^6\text{He}(p, n)^5\text{Li}$ reaction is supposed to be a way to in-crease the primordial $^6\text{Li}$ abundance. The angular distri-