PHYSICAL REVIEW C **91**, 055802 (2015)

Revised thermonuclear rate of ^{7}Be(n,α)^{4}He relevant to Big-Bang nucleosynthesis

S. Q. Hou,[1,2] J. J. He,[1,*] S. Kubono,[1,3] and Y. S. Chen[4]

[1]*Key Laboratory of High Precision Nuclear Spectroscopy and Center for Nuclear Matter Science, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

[2]*University of Chinese Academy of Sciences, Beijing 100049, China*

[3]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

[4]*China Institute of Atomic Energy, P. O. Box 275(10), Beijing 102413, China*

(Received 13 February 2015; revised manuscript received 15 April 2015; published 8 May 2015)

In the standard Big-Bang nucleosynthesis (BBN) model, the primordial ^{7}Li abundance is overestimated by about a factor of 2 to 3 compared to astronomical observations; this is the so-called pending cosmological lithium problem. The ^{7}Be(n,α)^{4}He reaction was regarded as the secondary important reaction in affecting the ^{7}Li abundance by destructing the ^{7}Be nucleus in BBN. However, the reaction rate of ^{7}Be(n,α)^{4}He has not been well studied so far. This reaction rate was first estimated by Wagoner in 1969, which has been primarily adopted in the current BBN simulations. This simple estimate involved only a direct reaction contribution, but the resonant component should also be considered according to the later experimental results. In the present work, we revised this rate based on the indirect cross-section data available for the ^{4}He(α,n)^{7}Be and ^{4}He(α,p)^{7}Li reactions by applying the charge symmetry and the principle of detailed balance. Our new result shows that the previous rate (acting as an upper limit) is overestimated by about a factor of ten. The BBN simulation shows that the present rate leads to a 1.2% increase in the final ^{7}Li abundance compared with the result using the Wagoner rate and, hence, the present rate even worsens the ^{7}Li problem. By the present estimation, the role of ^{7}Be(n,α)^{4}He in destroying ^{7}Be is weakened from the second most importance to the third and, in turn, the ^{7}Be(d,p)2^{4}He reaction becomes of secondary importance in destroying ^{7}Be.

DOI: 10.1103/PhysRevC.91.055802 PACS number(s): 26.35.+c, 24.30.−v, 24.50.+g, 27.20.+n

I. INTRODUCTION

The discrepancy between the predicted primordial ^{7}Li abundance and the astronomical observation remains a fundamental pending problem in nuclear astrophysics studies [1–3]. As a powerful tool to study the early universe, the standard Big-Bang nucleosynthesis (BBN) model employs only one parameter η, which is the number-density ratio of baryons to photons. With the more accurate η value determined from astronomical observations [4], the predicted primordial ^{7}Li abundance is still a factor of 2 to 3 higher than that observed in the Galactic halo stars [5]. It has been argued that such discrepancy may arise from the uncertainties in the thermonuclear rates for those reactions involved in BBN [2,3,6–8]. In the past two decades, great efforts have been devoted to reduce these uncertainties. For example, Smith *et al.* [9] made a new evaluation of the reaction rates for the most important twelve reactions involved in BBN. Later on, Descouvemout *et al.* [10] re-analyzed ten key reactions by using R-matrix theory. However, the ^{7}Li discrepancy still remains unsolved with these updated data together with the recent investigations [7,11–13] for those possible reactions affecting the ^{7}Li abundance.

The final ^{7}Li abundance in BBN is contributed to both from the directly synthesized ^{7}Li, as well as those from the ^{7}Be *EC* decay and the ^{7}Be(n,p)^{7}Li reaction. However, the relic ^{7}Li nuclei mainly come from the latter *EC*-decay process because most of the directly synthesized ^{7}Li is destroyed through the ^{7}Li(p,α)^{4}He reaction immediately. The ^{7}Be production is determined owing to a balance of reactions of construction and destruction. Therefore, it is essential to accurately determine thermonuclear rates for reactions involving ^{7}Be nucleus. The key synthesizing reaction for ^{7}Be is the ^{3}He(α,γ)^{7}Be reaction, which has been extensively studied through both experiments and theories [14–17]. The reactions for destroying ^{7}Be are ^{7}Be(n,p)^{7}Li and ^{7}Be(n,α)^{4}He, being of primary and secondary important, respectively. For the ^{7}Be(n,p)^{7}Li reaction, the cross section was studied over a wide energy range from 0.025 eV up to 8 MeV [10,18], which covers entirely the BBN effective energy region. In the destruction of ^{7}Be, the ^{7}Be(n,α)^{4}He reaction could play a non-negligible role [19]. However, the ^{7}Be(n,α)^{4}He reaction rate adopted in the current BBN simulations and tabulated in the reaction-rate library [20] is still the very old Wagoner rate [21], which is based on a simple theoretical estimation involving only the direct reaction contribution, and there is no information on the sources of data.

The accurate ^{7}Be neutron capture rate also plays a very important role for the lithium problem in the nonstandard models. The lithium depleting effect beyond standard BBN model was first pointed out [22] about thirty years ago, which claimed that the extra neutron source arising from hadronic decays could alter the ^{7}Li production. Later on, the similar scenarios, such as GeV-scale metastable particle X decay, energetic nucleon injection, and free thermal neutron injection, were proposed [23–25], and all these models involved the extra neutron injection from new physics in order to cure the lithium problem. For recent review on the possible lithium solutions, see, e.g., Ref. [26].

*jianjunhe@impcas.ac.cn

In this work, we derive the thermonuclear rate of ^{7}Be(n,α)^{4}He based on the available indirect experimental data on the ^{4}He(α,n)^{7}Be and ^{4}He(α,p)^{7}Li reactions by applying charge symmetry and the principle of detailed balance [27]. With this new rate, we examine its impact on the primordial ^{7}Li abundance by carrying out a BBN simulation.

II. DERIVATION OF ^{7}Be(n,α)^{4}He CROSS SECTION

So far, there is only one direct measurement of cross section for the ^{7}Be(n,α)^{4}He reaction. This experiment was performed in 1963 by using the reactor thermal neutrons [28]. Based on this limited information and the theory of nonresonant reaction, Wagoner made the first estimate of this reaction rate, which will be discussed in detail in the next section. In this section, we present the method to derive the cross section of ^{7}Be(n,α)^{4}He by using the available data from indirect measurement.

About 30 years ago, King *et al.* [29] measured the cross section for both the ^{4}He(α,n)^{7}Be and ^{4}He(α,p)^{7}Li reactions. Under the assumption of charge symmetry, i.e., the neutron and proton configurations in the compound ^{8}Be nucleus appear to be identical, they calculated the total cross sections of ^{4}He(α,n)^{7}Be based on their data measured for ^{4}He(α,p)^{7}Li via the following equation:

$$\sigma_n = \sigma_{n_0} + \sigma_{n_1} = \frac{P_\ell^{n_0}}{P_\ell^{p_0}}\sigma_{p_0} + \frac{P_\ell^{n_1}}{P_\ell^{p_1}}\sigma_{p_1}, \quad (1)$$

where σ_{n_0} and σ_{p_0} are the cross sections leading to the ground states of ^{7}Be and ^{7}Li, respectively; and σ_{n_1} and σ_{p_1} are those leading to the corresponding first-excited states. P_ℓ is the penetrability factor defined in Refs. [29,30],

$$P_\ell(E,R) = \frac{kR}{F_\ell^2(E,R) + G_\ell^2(E,R)}, \quad (2)$$

where k is the wave number, R is the channel radius, and F_ℓ and G_ℓ are the standard Coulomb functions. It was shown that the calculated σ_n is in good agreement with their experimental data.

Inspired by this idea, we derived the cross section of ^{4}He(α,n)^{7}Be based on the measured data for ^{4}He(α,p)^{7}Li [29,31], as well as measured data for ^{7}Li(p,α)^{4}He [32] by applying the detailed-balance principle. Here, special attention is required for using such a principle in the case where identical particles are involved [30]. For the ^{4}He(α,p)^{7}Li reaction, the experimental-cross-section data and those derived from ^{7}Li(p,α)^{4}He are listed in the first and second columns of Table I.

In the astrophysical high-temperature environment, the low-lying excited states of nuclei involved can be thermally populated, contributing to the total reaction rate [34,35]. The first-excited state in ^{7}Be is located at 429 keV, which is too high to make appreciable contribution to the total rate compared to the ground state at the BBN temperature. It is then appropriate to calculate the thermonuclear rate of ^{7}Be(n,α)^{4}He by taking into account only the ground state of ^{7}Be nucleus. Relying on the first term of Eq. (1), we have derived the cross section of ^{4}He(α,n)^{7}Be (g.s.) by utilizing the cross section data of ^{4}He(α,p)^{7}Li (g.s.) listed

TABLE I. Experimental-cross-section data collected for ^{4}He(α,p)^{7}Li (g.s.), and the cross-section data derived for ^{7}Be(n,α)^{4}He, in units of mb. The adopted uncertainties in energies (in units of MeV) of E_α and $E_{c.m.}$ are ±100 keV and ±50 keV, respectively [29,31].

E_α	$\sigma_{(\alpha,p)}$	$E_{c.m.}$	$\sigma_{(n,\alpha)}$	Ref.
		0.0113	8.4 ± 8.5	[33]
		0.0196	10.7 ± 10.7	[33]
		0.0510	13.2 ± 13.2	[33]
38.23	13.0 ± 0.4[a]	0.124	17.5 ± 10.4	[32]
38.41	14.9 ± 1.4[a]	0.214	23.1 ± 8.2	[32]
38.54	24.2 ± 2.0	0.279	39.0 ± 11.1	[31]
38.96	35.5 ± 2.5	0.489	59.4 ± 10.3	[31]
38.97	29.9 ± 1.5	0.494	50.0 ± 8.2	[29]
39.44	49.2 ± 3.1	0.729	79.1 ± 9.4	[31]
39.80	59.9 ± 3.0	0.909	91.6 ± 8.3	[29]
39.94	64.6 ± 2.6	0.979	96.8 ± 7.6	[31]
40.56	30.5 ± 2.5	1.289	41.5 ± 3.9	[31]
40.99	27.0 ± 2.2	1.504	34.4 ± 3.0	[31]
41.35	23.4 ± 1.2	1.684	28.2 ± 1.6	[29]
41.61	17.9 ± 2.0	1.814	20.8 ± 2.4	[31]
41.95	12.0 ± 0.6	1.984	13.3 ± 0.7	[29]
42.57	6.5 ± 0.3	2.294	6.6 ± 0.3	[29]
43.04	13.1 ± 2.1	2.529	12.6 ± 2.0	[31]
43.52	12.0 ± 0.6	2.769	11.0 ± 0.6	[29]
44.32	52.0 ± 2.6	3.169	43.6 ± 2.2	[29]
45.64	36.5 ± 1.8	3.829	27.1 ± 1.4	[29]
46.67	27.2 ± 1.4	4.344	18.6 ± 1.0	[29]
47.65	22.7 ± 1.1	4.884	14.3 ± 0.7	[29]
49.49	15.1 ± 0.8	5.754	8.6 ± 0.5	[29]

[a]The cross-section data are derived from the ^{7}Li(p,α)^{4}He data with Eq. (1). Since their incident energies have no errors in the original paper [32], we assume the same errors as in Refs. [29,31].

in Table I. It is worth noting that the ground-state contribution is difficult to extract from the total-cross-section measured [29] for ^{4}He(α,n)^{7}Be, and these data were measured only down to $E_\alpha = 39.43$ MeV, which is much higher than the measurement for ^{4}He(α,p)^{7}Li.

The penetrability factor depends on the channel radius R, orbit angular momentum ℓ and incident center-of-mass energy E. In the treatment of King *et al.*, a channel radius of $R = 4.1$ fm, i.e., $R = r_0(\mathrm{A}_1^{1/3} + \mathrm{A}_2^{1/3})$ with $r_0 = 1.41$ fm, was utilized in both $n + {}^7$Be and $p + {}^7$Li systems. In the present work, the penetrability factor $P_\ell(E,R)$ for $p + {}^7$Li is calculated by a RCWFN code [36], and the one for the neutron channel is calculated by using Eq. (2) with the F_ℓ and G_ℓ values tubulated by Feshbach and Lax [37]. Since the α particle is a spinless boson, the wave function for two identical α particles must be symmetric under interchange. However, the wave function for an ℓ = odd state in ^{8}Be is antisymmetric by interchanging the two α particles. This implies that the compound state of ^{8}Be must have even parity for the incident $\alpha + \alpha$ channel. Note that both ground states for ^{7}Li and ^{7}Be have odd parity and, hence, the relative orbital angular momentum ℓ must be *odd*. Since the orbital centrifugal barrier [$\propto \ell(\ell + 1)$] increases fast with increasing ℓ, the p wave ($\ell = 1$) will dominate both the $n + {}^7$Be and $p + {}^7$Li exit channels. For each of energy points listed in Table I, we have calculated the cross section for ^{4}He(α,n)^{7}Be (g.s.) reaction, and the associated uncertainty is estimated by considering the uncertainties in both r_0 (in range of 1.1 to 1.5 fm [38]) and incident energy ($\pm$100 keV [29,31]). Finally, by applying the principle of detailed balance [27] the cross section of the ^{7}Be(n,α)^{4}He reaction was derived, and the results are listed in the third and fourth columns of Table I. The three listed data points for $E_{\mathrm{c.m.}} < 0.1$ MeV are derived based on the experimental data of ^{7}Li(p,α)^{4}He [33] by considering the first term in Eq. (1). The associated uncertainties are estimated by taking into account the ones of r_0 and incident energies. Alternatively, the three low-energy data of ^{4}He(α,n)^{7}Be have been estimated by linearly interpolating two data points of ^{4}He(α,p)^{7}Li at 37.48 MeV [31] and 38.09 MeV [32] and converted to the data for ^{7}Be(n,α)^{4}He. We found that the interpolated results are in a good agreement with the listed three data points at $E_{\mathrm{c.m.}} < 0.1$ MeV within uncertainties.

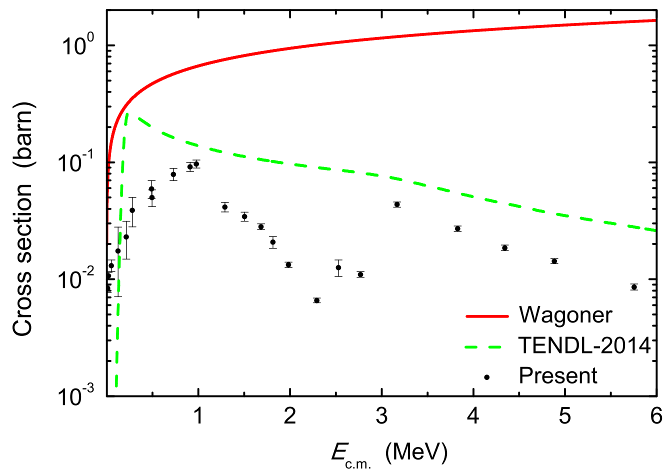

FIG. 1. (Color online) Comparison of different cross sections of ^{7}Be(n,α)^{4}He among present work and other two different origins (Wagoner's work [21] and TENDL-2014 evaluation [41]).

III. WAGONER ESTIMATION

The thermonuclear rate of ^{7}Be(n,α)^{4}He was estimated by Wagoner [21] in 1969, which has been adopted in the current BBN simulations and tabulated in the reaction-rate library [20]. In Wagoner's paper, the reaction rate was calculated by the formula

$$N_A\,\langle\sigma v\rangle = (2.05\times10^4)\,(1+3760T_9)\,. \tag{3}$$

For the nonresonant neutron-induced reaction, $\langle\sigma v\rangle$ can be calculated with the expression [30,35,39],

$$\langle\sigma v\rangle = \mathcal{S}\,(0) + 0.3312\dot{\mathcal{S}}\,(0)\,T_9^{1/2} + 0.06463\ddot{\mathcal{S}}\,(0)\,T_9, \tag{4}$$

where $\mathcal{S}(0)$ is the astrophysical S factor near zero energy. By using Eq. (3) and Eq. (4), the values of $\mathcal{S}(0)$ and its second derivative $\ddot{\mathcal{S}}(0)$ (with respect to velocity v) can be determined under the assumption of negligible first derivative $\dot{\mathcal{S}}(0)$. The direct-capture cross section for neutron-induced reaction may be then calculated by the expression [30,39],

$$\sigma = \frac{\mathcal{S}\,(0)}{v} = \frac{\mathcal{S}\,(0) + \frac{1}{2}\ddot{\mathcal{S}}\,(0)\,E}{v}. \tag{5}$$

In this way, the cross section of ^{7}Be(n,α)^{4}He has been calculated and the results are shown in Fig. 1.

The sources information of ^{7}Be(n,α)^{4}He cross-section data were not given in Wagoner's original paper [21]. Before Wagoner's estimate there was only one measurement of this reaction, which was made by Bassi *et al.* [28] at the thermal-neutron energy. For our understanding of Wagoner's approach, the total cross section of ^{7}Be(n,α)^{4}He was assumed to include two contributions, i.e., $\sigma_1 + \sigma_2$, where σ_1 and σ_2 denote the p wave incident in (n,α) and the s wave incident in (n,$\gamma\alpha$), respectively. The former obeys the law of $\sigma_1 \propto v$, and the latter obeys the law of $\sigma_2 \propto 1/v$ [30,40]. In Wagoner's estimate an upper limit of $\sigma_1 \leqslant 0.1$ mb and $\sigma_2 = 155$ mb, measured by Bassi *et al.* at thermal-neutron energy, was employed. In the BBN energy range, the p-wave contribution dominates the total cross section (or total rate). Wagoner's estimate provides, therefore, an upper limit of the cross section. Wagoner's cross sections and ours are compared in Fig. 1. Overall, the present results are lower than those of Wagoner by about a factor of ten. In addition, the recent theoretical evaluation of TENDL-2014 [41] based on a TALYS calculation is also compared in Fig. 1, which is much different from the present results. However, our results are derived based on the indirect experimental-cross-section data, including both the nonresonant and resonant contributions. Further measurements are proposed [42,43] to acquire the direct experimental data.

IV. REVISED THERMONUCLEAR RATE

The thermonuclear rate of ^{7}Be(n,α)^{4}He as a function of temperature was calculated by numerical integration of our experimental cross sections using the EXP2RATE code by Rauscher [44]. The rate values, obtained as the arithmetic mean between the low and high limits associated with the uncertainties in both the cross-section data and incident energies, are given in Table II. The present rate can be well parametrized (less than 0.4% error in 0.1–5 GK) by the following expression in the standard format of Eq. (16) in Ref. [45]:

$$\begin{aligned} N_A\langle\sigma v\rangle = \exp\big(&-17.8984 + 0.2711T_9^{-1} - 23.8918T_9^{-1/3} \\ &+ 62.2135T_9^{1/3} - 5.2888T_9 + 0.3869T_9^{5/3} \\ &- 22.6197\ln T_9\big). \end{aligned} \tag{6}$$

Our new rate is about a factor of ten smaller than the Wagoner's rate in the BBN temperature range. As discussed above, Wagoner's estimate provides just an upper limit for this rate. Therefore, we may propose that the cross section σ_1 of ^{7}Be(n,α)^{4}He at the thermal-neutron energy is about 0.01 mb,

TABLE II. Thermonuclear reaction rates for ^{7}Be(n,α)^{4}He in units of cm^3 s^{-1} mol^{-1}. The ratio between present rate and Wagoner rate is listed in the last column.

T(GK)	Present	Wagoner	Ratio
0.1	$(9.6 \pm 8.3) \times 10^5$	7.7×10^6	0.13
0.2	$(1.7 \pm 1.3) \times 10^6$	1.5×10^7	0.11
0.3	$(2.3 \pm 1.7) \times 10^6$	2.3×10^7	0.10
0.4	$(2.9 \pm 2.0) \times 10^6$	3.1×10^7	0.09
0.5	$(3.5 \pm 2.2) \times 10^6$	3.9×10^7	0.09
0.6	$(4.2 \pm 2.4) \times 10^6$	4.6×10^7	0.09
0.7	$(4.9 \pm 2.6) \times 10^6$	5.4×10^7	0.09
0.8	$(5.6 \pm 2.8) \times 10^6$	6.2×10^7	0.09
0.9	$(6.4 \pm 2.9) \times 10^6$	6.9×10^7	0.09
1.0	$(7.2 \pm 3.1) \times 10^6$	7.7×10^7	0.09
1.5	$(1.2 \pm 0.7) \times 10^7$	1.2×10^8	0.10
2.0	$(1.7 \pm 0.4) \times 10^7$	1.5×10^8	0.11
2.5	$(2.1 \pm 0.4) \times 10^7$	1.9×10^8	0.11
3.0	$(2.5 \pm 0.5) \times 10^7$	2.3×10^8	0.11
3.5	$(2.9 \pm 0.5) \times 10^7$	2.7×10^8	0.11
4.0	$(3.2 \pm 0.5) \times 10^7$	3.1×10^8	0.10
4.5	$(3.4 \pm 0.5) \times 10^7$	3.5×10^8	0.10
5.0	$(3.5 \pm 0.5) \times 10^7$	3.9×10^8	0.09

which is one order of magnitude smaller than the previous upper limit [28].

V. BIG-BANG NUCLEOSYNTHESIS SIMULATION

To investigate the impact of our new rates on the primordial abundances of D, ^{3}He, ^{4}He, and ^{7}Li, BBN was simulated by using a recently developed code [46]. This code is capable of calculating the reaction flux for every specific reaction at an arbitrary time point. In this work, the recent values of cosmological parameters and nuclear physics quantities was utilized, such as the baryon-to-photon ratio $\eta = (6.203 \pm 0.137) \times 10^{-10}$ [47] and the neutron lifetime $\tau = 880.3$ s [48]. The number of light neutrino families $N_\nu = 2.9840 \pm 0.0082$ determined by the CERN LEP experiment [49] supports the standard model prediction of $N_\nu = 3$, which is adopted in the present calculation. The reaction network contains nuclei with $A \leqslant 16$ from n to ^{16}O and the associated reaction rates adopted from the literature [9,10,14,19,21,50].

Two simulations have been performed with the Wagoner's rate and our new rate for the ^{7}Be(n,α)^{4}He reaction, respectively. The results show that the predicted abundances of D, ^{3}He, and ^{4}He do not change appreciably for the two simulations, while the abundance of ^{7}Li increases 1.2% when the new rate is used. Therefore, the present rate even worsens the ^{7}Li problem. In order to clarify the reason we performed the reaction flux [30] calculation with the present rate. Figure 2 shows the reaction flow passing though nuclei involved in the BBN network in a timescale of about 10 000 s. The reaction flux for the ^{7}Be(n,α)^{4}He channel is about 10^{-12} mol/g, marked by a solid black arrow, which is about a factor of ten weaker than the result using the Wagoner rate. According to the present simulation, for destructing ^{7}Be the role of ^{7}Be(n,α)^{4}He is weakened from the secondary importance to the third and, in turn, the ^{7}Be(d,p)2^{4}He reaction becomes the second most important. In addition, our calculation shows that the cosmological ^{7}Li problem could be solved provided the thermonuclear rate of ^{7}Be(n,α)^{4}He would be about 180 times larger than the Wagoner rate under the condition of no change in the rates for the rest involved reactions. It seems unlikely to solve the cosmological ^{7}Li problem

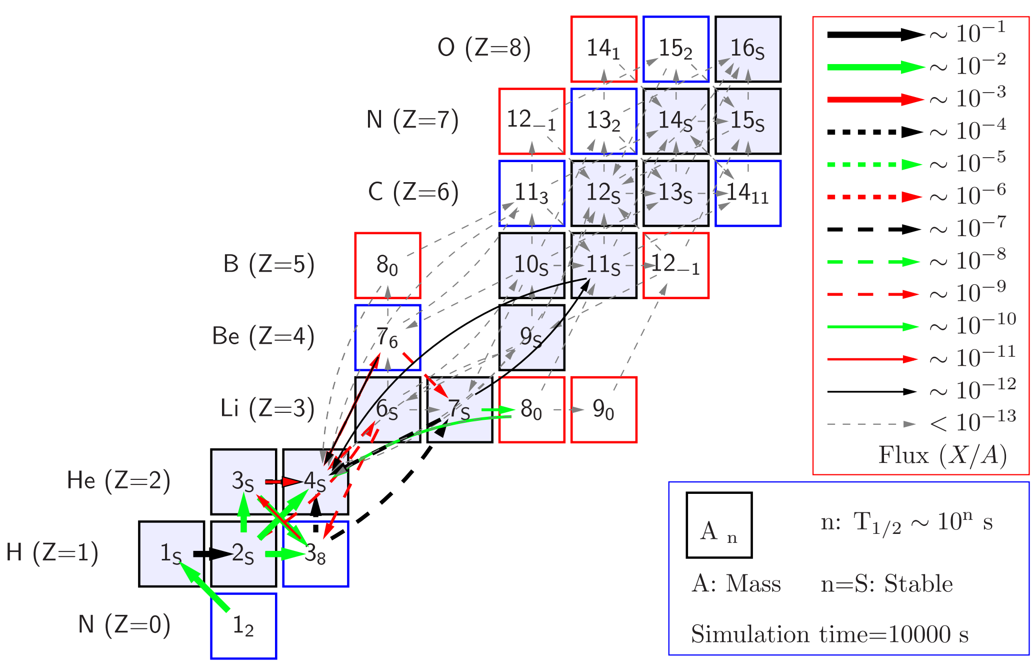

FIG. 2. (Color online) The time-integrated reaction flow for BBN network with new rate of ^{7}Be(n,α)^{4}He. Here, X and A denote the mass fraction and molar mass, respectively.

through a further study of this reaction within the standard model.

VI. CONCLUSION

We revised the thermonuclear rate of ^{7}Be(n,α)^{4}He, which was regarded as the second most important reaction in destroying the ^{7}Be nucleus in BBN, and tried to understand the cosmological ^{7}Li problem better. The present study shows that the previous Wagoner's rate for this reaction is overestimated by about a factor of ten compared to our revised rate. We recommend that our rate should be incorporated in future astrophysical network calculations. The BBN simulation shows that the adoption of the proposed rate yields almost no change in the predicted ^{7}Li abundance, only about 1.2% enhancement compared to the result using Wagoner's rate. This even worsens the ^{7}Li problem. The resolution for this mysterious problem might resort to other mechanisms or to new physics beyond the standard model (e.g., see Refs. [26,51,52]). Another possibility is, perhaps, to improve the current observation of the primordial ^{7}Li abundance by searching the metal-poor oldest stars.

ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (Grants No. 11490562, No. 11135005, and No. 11321064) and the Major State Basic Research Development Program of China (2013CB834406). S.K. acknowledges support from the Visiting Professorships Program of CAS (Grant No. 2012T1J0013) and JSPS KAKENHI (Grant No. 26287058) in Japan. S.Q.H. would like to express appreciation to K.M. Nollett (University of South Carolina, Columbia, USA) for meaningful discussions.

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