The Big Bang nucleosynthesis abundances of the light elements using improved thermonuclear reaction rates

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Abstract

Big Bang nucleosynthesis (BBN) is an important stage of a homogeneous and isotropic expanding universe. The results of calculation of the synthesis of light elements during this epoch can then be compared with the abundances of the light elements. The theoretical calculation of the BBN model depends on the initial conditions of the early universe and reaction cross sections measured by the nuclear physics experiment. Recently, an update of the Nuclear Astrophysics Compilation of REactions database is presented. This improved compilation comprises thermonuclear reaction rates for 34 two-body reactions on light nuclides (fifteen are particle transfer reactions and nineteen are radiative capture reactions). In this work, we calculate the BBN abundances by using these updated thermonuclear reaction rates in the framework of the code AlterBBN. Our results suggest that the new numerical result of the primordial Lithium abundance is 7.1% larger than the previous calculation.

Keywords Big Bang nucleosynthesis · Thermonuclear reaction rates · Primordial Lithium problem

BBN is one of the fundamental pillars of the cosmological standard model. Based on BBN theoretical model it is possible to calculate the abundances of the primordial light nuclides via a network of nuclear processes, which can then be compared with the observed abundances. This allows to research the universe properties during BBN epoch, which is the most ancient period observationally accessible. In standard cosmology, the dynamics of this epoch is controlled by only one free parameter, the baryon to photon ratio, which can be deduced from the observation of the Cosmic Microwave Background [1].

To calculate the abundances of the light nuclides in the standard model of cosmology, several public codes, such as PArthENoPE [2] or AlterBBN [3] already exist. The code AlterBBN provides a fast and reliable calculation of the abundance of...
the elements in the standard model of cosmology as well as in alternative scenarios, which descends from the original code NUC123 [4]. The code AlterBBN has been rewritten in C respecting the C99 standard, and it has been applied in many theoretical investigation.

During the BBN stage, the Universe contains photons $\gamma$, leptons $e^-, e^+$ and neutrinos $\nu$, hadrons $p$ and $n$. At the time of BBN, new nuclei will form over nuclear reactions (see Table 1). In the following, we describe first the physics of BBN, and present the set of equations in the standard model of cosmology (we use the natural unit $c = h = k = 1$). We then discuss the updated thermonuclear reaction rates and its effect on the calculated abundance of the light elements.

The cosmological expansion rate $\dot{a}$ governed by the Friedmann equation is a function of the total density $\rho_{tot}$:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G \rho_{tot}}{3},$$  \hspace{1cm} (1)

where $H$ is defined as the Hubble parameter and $G$ is the gravitational constant. The equation of energy conservation is given by:

$$\dot{\rho}_{tot} = -3H(\rho_{tot} + P_{tot}),$$  \hspace{1cm} (2)

in these equations, the total density $\rho_{tot}$ and pressure $P_{tot}$ are given by the sums over all the aforementioned constituents:

$$\rho_{tot} = \rho_\gamma + \rho_\nu + \rho_b + \rho_{e^-} + \rho_{e^+},$$  \hspace{1cm} (3)

$$P_{tot} = P_\gamma + P_\nu + P_b + P_{e^-} + P_{e^+}. $$  \hspace{1cm} (4)

for photons, The energy density and pressure can be calculated through statistical mechanics:

$$\rho_\gamma = \frac{\pi^2 T^4}{15}, \hspace{1cm} P_\gamma = \frac{\pi^2 T^4}{45},$$  \hspace{1cm} (5)

and for neutrino:

$$\rho_\nu = N_\nu \frac{7}{8} \frac{\pi}{15} T^4_\nu = N_\nu \frac{7\pi}{120} \left(\frac{4}{11}\right)^{4/3} T^4, \hspace{1cm} P_\nu = \frac{1}{3} \rho_\nu,$$  \hspace{1cm} (6)

where $N_\nu = 3$ is the number of neutrino families. The factor $T_\nu/T = (4/11)^{1/3}$ comes from the interaction decoupling between hadrons and neutrino.
Table 1  Network of nuclear reactions implemented in AlterBBN. If the serial number of the nuclear reaction is underlined, it indicates that the nuclear reaction rate is updated with new data [23]

| No | Reaction | References |
|----|----------|------------|
| 0  | $n \leftrightarrow p + e^- + \bar{\nu}$ | [5] |
| 1  | $^3H \rightarrow e^- + v + ^3He$ | [6] |
| 2  | $^8Li \rightarrow e^- + v + ^4He$ | [7] |
| 3  | $^{12}B \rightarrow e^- + v + ^{12}C$ | [8] |
| 4  | $^{14}C \rightarrow e^- + v + ^{14}N$ | [9] |
| 5  | $^8B \rightarrow e^+ + v + ^2He$ | [7] |
| 6  | $^{11}C \rightarrow e^+ + v + ^{11}B$ | [8] |
| 7  | $^{12}N \rightarrow e^+ + v + ^{12}C$ | [8] |
| 8  | $^{13}N \rightarrow e^+ + v + ^{13}C$ | [9] |
| 9  | $^{14}O \rightarrow e^+ + v + ^{14}N$ | [9] |
| 10 | $^{15}O \rightarrow e^+ + v + ^{15}N$ | [9] |
| 11 | $H + n \rightarrow \gamma + ^2H$ | [5] |
| 12 | $^2H + n \rightarrow \gamma + ^2H$ | [10] |
| 13 | $^3He + n \rightarrow \gamma + ^4He$ | [10] |
| 14 | $^6Li + n \rightarrow \gamma + ^7Li$ | [11] |
| 15 | $^3He + n \rightarrow p + ^3H$ | [5] |
| 16 | $^7Be + n \rightarrow p + ^7Li$ | [5] |
| 17 | $^6Li + n \rightarrow \alpha + ^3H$ | [12] |
| 18 | $^7Be + n \rightarrow \alpha + ^4He$ | [10] |
| 19 | $^2H + p \rightarrow \gamma + ^3He$ | [5] |
| 20 | $^3H + p \rightarrow \gamma + ^4He$ | [5] |
| 21 | $^6Li + p \rightarrow \gamma + ^7Be$ | [12] |
| 22 | $^6Li + p \rightarrow \alpha + ^3He$ | [12] |
| 23 | $^7Li + p \rightarrow \alpha + ^4He$ | [5] |
| 24 | $^2H + \alpha \rightarrow p + ^6Li$ | [12] |
| 25 | $^3H + \alpha \rightarrow p + ^7Li$ | [5] |
| 26 | $^3He + \alpha \rightarrow p + ^7Be$ | [5] |
| 27 | $^2H + D \rightarrow p + ^3He$ | [5] |
| 28 | $^2H + D \rightarrow n + ^3H$ | [5] |
| 29 | $^3H + D \rightarrow n + ^4He$ | [5] |
| 30 | $^3He + D \rightarrow p + ^4He$ | [12] |
| 31 | $^3He + ^3He \rightarrow 2p + ^4He$ | [12] |
| 32 | $^7Li + D \rightarrow n + \alpha + ^4He$ | [12] |
| 33 | $^7Be + D \rightarrow p + \alpha + ^4He$ | [12] |
| 34 | $^7Li + n \rightarrow \gamma + ^7Li$ | [10] |
| 35 | $^{10}B + n \rightarrow \gamma + ^{11}B$ | [10] |
| No | Reaction | References |
|----|----------|------------|
| 36 | $^{11}B + n \rightarrow \gamma + ^{12}B$ | [11] |
| 37 | $^{11}C + n \rightarrow p + ^{11}B$ | [12] |
| 38 | $^{10}B + n \rightarrow \alpha + ^{7}Li$ | [12] |
| 39 | $^{7}Be + p \rightarrow \gamma + ^{8}B$ | [12] |
| 40 | $^{9}Be + p \rightarrow \gamma + ^{10}B$ | [12] |
| 41 | $^{10}B + p \rightarrow \gamma + ^{11}C$ | [12] |
| 42 | $^{11}B + p \rightarrow \gamma + ^{12}C$ | [12] |
| 43 | $^{11}C + p \rightarrow \gamma + ^{12}N$ | [12] |
| 44 | $^{12}B + p \rightarrow n + ^{12}C$ | [12] |
| 45 | $^{9}Be + p \rightarrow \alpha + ^{6}Li$ | [12] |
| 46 | $^{10}B + p \rightarrow \alpha + ^{7}Be$ | [12] |
| 47 | $^{12}B + p \rightarrow \alpha + ^{9}Be$ | [10] |
| 48 | $^{6}Li + \alpha \rightarrow \gamma + ^{10}B$ | [12] |
| 49 | $^{7}Li + \alpha \rightarrow \gamma + ^{11}B$ | [12] |
| 50 | $^{7}Be + \alpha \rightarrow \gamma + ^{11}C$ | [12] |
| 51 | $^{8}B + \alpha \rightarrow p + ^{11}C$ | [10] |
| 52 | $^{8}Li + \alpha \rightarrow n + ^{11}B$ | [11] |
| 53 | $^{9}Be + \alpha \rightarrow n + ^{12}C$ | [12] |
| 54 | $^{9}Be + D \rightarrow n + ^{10}B$ | [4] |
| 55 | $^{10}B + D \rightarrow p + ^{11}B$ | [4] |
| 56 | $^{11}B + D \rightarrow n + ^{12}C$ | [4] |
| 57 | $^{4}He + \alpha + n \rightarrow \gamma + ^{9}Be$ | [12] |
| 58 | $^{4}He + 2\alpha \rightarrow \gamma + ^{12}C$ | [12] |
| 59 | $^{8}Li + p \rightarrow n + \alpha + ^{4}He$ | [4] |
| 60 | $^{8}B + n \rightarrow p + \alpha + ^{4}He$ | [4] |
| 61 | $^{9}Be + p \rightarrow d + \alpha + ^{4}He$ | [12] |
| 62 | $^{11}B + p \rightarrow 2\alpha + Be4$ | [12] |
| 63 | $^{11}C + n \rightarrow 2\alpha + ^{4}He$ | [12] |
| 64 | $^{12}C + n \rightarrow \gamma + ^{13}C$ | [10] |
| 65 | $^{13}C + n \rightarrow \gamma + ^{14}C$ | [10] |
| 66 | $^{14}N + n \rightarrow \gamma + ^{15}N$ | [10] |
| 67 | $^{13}N + n \rightarrow p + ^{13}C$ | [12] |
| 68 | $^{14}N + n \rightarrow p + ^{14}C$ | [12] |
| 69 | $^{15}O + n \rightarrow p + ^{15}N$ | [12] |
| 70 | $^{15}O + n \rightarrow \alpha + ^{12}C$ | [12] |
Table 1 continued

| No | Reaction | References |
|----|----------|------------|
| 71 | \( ^{12}\text{C} + p \rightarrow \gamma + ^{13}\text{N} \) | [12] |
| 72 | \( ^{13}\text{C} + p \rightarrow \gamma + ^{14}\text{N} \) | [12] |
| 73 | \( ^{14}\text{C} + p \rightarrow \gamma + ^{15}\text{N} \) | [12] |
| 74 | \( ^{13}\text{N} + p \rightarrow \gamma + ^{14}\text{O} \) | [12] |
| 75 | \( ^{14}\text{N} + p \rightarrow \gamma + ^{15}\text{O} \) | [12] |
| 76 | \( ^{15}\text{N} + p \rightarrow \gamma + ^{16}\text{O} \) | [12] |
| 77 | \( ^{15}\text{N} + p \rightarrow \alpha + ^{12}\text{C} \) | [12] |
| 78 | \( ^{12}\text{C} + \alpha \rightarrow \gamma + ^{16}\text{O} \) | [12] |
| 79 | \( ^{10}\text{B} + \alpha \rightarrow p + ^{13}\text{C} \) | [10] |
| 80 | \( ^{11}\text{B} + \alpha \rightarrow p + ^{14}\text{C} \) | [12] |
| 81 | \( ^{11}\text{B} + \alpha \rightarrow p + ^{14}\text{N} \) | [12] |
| 82 | \( ^{12}\text{N} + \alpha \rightarrow p + ^{15}\text{O} \) | [12] |
| 83 | \( ^{13}\text{N} + \alpha \rightarrow p + ^{16}\text{O} \) | [12] |
| 84 | \( ^{10}\text{B} + \alpha \rightarrow n + ^{13}\text{N} \) | [12] |
| 85 | \( ^{11}\text{B} + \alpha \rightarrow n + ^{14}\text{N} \) | [12] |
| 86 | \( ^{12}\text{B} + \alpha \rightarrow n + ^{15}\text{N} \) | [10] |
| 87 | \( ^{13}\text{C} + \alpha \rightarrow n + ^{16}\text{O} \) | [12] |

Then we write the sums of two leptons densities and pressures in terms of the modified Bessel functions \( K_i \):

\[
\rho_{e^-} + \rho_{e^+} = \frac{2m_e^4}{\pi^2} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{nz} \left( \frac{3}{4} K_3(nz) + \frac{1}{4} K_1(nz) \right) \cosh(n\phi_e),
\]

(7)

\[
P_{e^-} + P_{e^+} = \frac{2m_e^4}{\pi^2} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{K_2(nz)}{nz} \cosh(n\phi_e),
\]

(8)

where we have defined the quantity \( z = m_e / T \) and chemical potential \( \phi_e^- = \mu_e / T \).

The charge conservation of the Universe gives:

\[
n_{e^-} - n_{e^+} = \frac{h\eta T^3 \sum_i Z_i Y_i}{M_u},
\]

(9)

where \( M_u \) is the unit atomic mass, \( Z_i \) and \( Y_i \) are the charge number and abundance of nuclei species \( i \), respectively.

The baryon-to-photon ratio \( \eta \) is determined in the following way:

\[
h\eta(T) = M_u \eta(T) \frac{n_\gamma(T)}{T^3},
\]

(10)
where $h$ is parameter, $n_\gamma$ is the number density of photon. The difference in Eq. (11) can also be written as:

$$n_e^- - n_e^+ = \frac{2m_e^3}{\pi^2} \sum_{i=1}^{\infty} (-1)^{n+1} \frac{K_2(nz)}{nz} \sinh(n\phi_e). \quad (11)$$

By using of the Eqs. (11) and (13), the electron chemical potential $\phi_e$ is determined:

$$\frac{d\phi_e}{dt} = \frac{\partial \phi_e}{\partial T} \frac{dT}{dt} + \frac{\partial \phi_e}{\partial S} \frac{dS}{dt} + \frac{\partial \phi_e}{\partial a} \frac{da}{dt}. \quad (12)$$

On the other hand, the baryon energy density and pressure are determined as the sums on the $i$ nuclide, which can be found also in the manual of AlterBBN.

The set of nuclear reactions used in AlterBBN can be written as the general form:

$$N_i^{A_iZ_i} + N_j^{A_jZ_j} \leftrightarrow N_l^{A_lZ_l} + N_k^{A_kZ_k}. \quad (13)$$

Therefore, the abundance evolution for nuclei $i$ is deduced by the equation [4]:

$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left( -\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} \Gamma_{ij}^k + \frac{Y_i^{N_i} Y_k^{N_k}}{N_i! N_k!} \Gamma_{ik}^j \right), \quad (14)$$

where the nuclide abundance $Y_i$ is $X_i/A_i$, $X_i$ is the mass fraction in nuclide $i$ and $A_i$ is their atomic number. $N_i$ is the number of nuclides $i$ that enters into the nuclear reaction, $\Gamma_{ij}^k$ and $\Gamma_{ik}^j$ are the forward and reverse reaction rates respectively. AlterBBN includes a network of 88 nuclear reactions, which are gathered in the Table 1. The code sets the number of neutrino species to 3.0, the baryon-to-photon ratio to $\eta_0 = 6.09 \times 10^{-10}$ [13], the initial temperature to $2.7 \times 10^{10}$ K (corresponding to 2.3 MeV) and the lifetime of the neutron to 879.4 s [14]. Given proper initial conditions, the set of Eqs. (1, 2, 12, 14, 19) will be solved by a 4th-order Runge-Kutta integration.

Observational measurements are cited from the latest report:

$$Y_p = 0.2453 \pm 0.0034, \quad (15)$$

$$^3\text{He}/\text{H} < (1.1 \pm 0.2) \times 10^{-5}, \quad (16)$$

$$^2\text{H}/\text{H} = (2.527 \pm 0.030) \times 10^{-5}, \quad (17)$$

$$^7\text{Li}/\text{H} = (1.58_{+0.28}^{-0.35}) \times 10^{-10}. \quad (18)$$

which constrains the helium abundance $Y_p$ [15] and the primordial $^2\text{H}/\text{H}$ [16], $^3\text{He}/\text{H}$ [17] and $^7\text{Li}/\text{H}$ [18] ratios.

On the other hand, the thermonuclear reaction rates in nuclear reaction network play an significant role in big-bang nucleosynthesis investigations. The thermonuclear reaction rates of a two-body reaction $A(a, b)B$ are determined as the Avogadro number
\( N_A \) times the Maxwellian-averaged rate \(< \sigma v >\),

\[
< \sigma v >= \frac{(8/\pi)^{1/2}}{\mu^{1/2}(k_B T)^{3/2}} \int_0^\infty E \sigma(E) \exp[-E/(k_B T)] \, dE,
\]

where \( v \) being the relative velocity between the target \((A)\) and projectile \((a)\) nuclei, \( \sigma(E) \) is the reaction cross section at the center-of-mass incident energy \(E\), \( \mu \) is the reduced mass, \( T \) is the temperature and \( k_B \) is the Boltzmann constant.

The series of advance of William A. Fowler and his coworkers [19, 20] are pioneering work in this research field. Then, the so-called NACRE (Nuclear Astrophysics Compilation of REaotions) database [21] is a second important progress of such astrophysics-oriented compilations, which comprise an ensemble of 86 charged-particle induced reactions involved in BBN. Since 1999, the NACRE database has indeed been used in many stellar evolution models as well as of nucleosynthesis investigations.

Since NACRE, many cross sections measure of astrophysical interest have been carried out, and many theoretical efforts have been investigated for better predictions of the concerned reaction rates. For instance, thermonuclear reaction rates of relevance to the BBN have been recomputed by means of the R-matrix method [22].

In parallel to these developments, an update and an extension of NACRE is published in Ref. [23]. The new version of NACRE II comprises 34 two-body reactions (15 particle transfer and 19 radiative capture reactions), and uses nuclear potential models to phenomenologically extrapolate resonant and nonresonant reaction cross sections to low energies of interest. NACRE II featured (1) detailed references to the works of the experimental data (and to some nuclear theoretical works); (2) the extrapolation of astrophysical S-factors to very low energies based on potential models; (3) a tabular presentation of the nuclear reaction rates in the \( 10^6 < T \leq 10^{10} \) K temperature range. (See [23] for more details).

In Table I of Ref. [23], the results for the 34 two-body exoergic reactions are summarized, of which 29 two-body reactions are implemented in the AlterBBN network of nuclear reactions. Specifically, the 29 nuclear reactions are the following nuclear reactions in Table 1: No. 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 39, 40, 41, 42, 45, 46, 49, 50, 53, 71, 72, 74, 75, 76, 77, 78, 87.

In this work, we apply these new thermonuclear reaction rates to calculate primordial abundances of the light elements generated by using the code AlterBBN. Our results are listed in Table 2. The new calculated abundances of \(^4\)He, \(^2\)H and \(^3\)He nuclides are almost the same compared with the old calculated results. However, compared to the previous numerical results, there is about 7.1 percent increase in the abundances of the lithium nuclides. Recent observational measurement of \(^7\)Li abundance is \(1.58^{+0.35}_{-0.28} \times 10^{-10} \) [18], which is almost three times smaller than that predicted by the BBN model. After using the updated thermonuclear reaction rates in the AlterBBN code, the calculated primordial abundance of \(^7\)Li is \(5.028 \times 10^{-10} \), which make the primordial Lithium problem much worse. Similar conclusions have been also observed by other work in literature [24].

Finally, we give some discussions and perspectives of this work. Our work presents calculations of the abundances of the light elements produced in BBN. This is an active...
Table 2  The abundances of the light elements using improved thermonuclear reaction rates

|                  | Observations       | Arbey (2012) [3] | This work |
|------------------|--------------------|------------------|-----------|
| $Y_p$            | $0.2453 \pm 0.0034$ [15] | 0.2476          | 0.2462    |
| $^2\text{H}/\text{H} \times 10^{-5}$ | $2.527 \pm 0.030$ [16] | 2.515          | 2.589     |
| $^3\text{He}/\text{H} \times 10^{-5}$ | $< 1.1 \pm 0.2$ [17] | 1.015          | 1.045     |
| $^7\text{Li}/\text{H} \times 10^{-10}$ | $1.58^{+0.35}_{-0.28}$ [18] | 4.694          | 5.028     |

domain that aims at better precision, in order to match the high precision reached by observations. However, we must emphasize that some of the nuclear reaction rates used in our network calculations are referred to publications before 1994, as shown in the Table 1. In fact, the nuclear reaction rates have been continually updated, more new nuclear reaction rates are reported in the Table 4 in literature [25]. Moreover, many important reactions of interest for the physics of BBN has been measured recently. For instance, One of the most relevant reactions for the $^7\text{Li}$ abundance is the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction, so the $^7\text{Be}(n, \alpha)^4\text{He}$ nuclear reaction cross section has been measured for the first time from 10 meV to 10 keV neutron energy [26]. In this report, the authors show that their results hint to a minor role of this reaction in BBN, leaving the long-standing primordial Lithium problem unsolved. Since new experimental data have become available, we would try to include the progress of these experiments in future theoretical calculations.

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Author Contributions  The independent author wrote the whole manuscript text and done all calculation. Based the AlterBBN software on the Eclipse platform, we involved the updated thermonuclear reaction rates in the early university and did some new calculations. If readers are interested, they can obtain the original calculation data through the communication email

Declarations

Conflict of interest  The authors declare no competing interests.

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