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On the Determination of the ^{7}Be(n, α)^{4}He Reaction Cross Section at BBN Energies

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Abstract

^{7}Be destruction channels are currently a matter of study because of their influence on the ^{7}Li cosmological abundances. Here, we determine the cross section of the (n, α) reaction by using Trojan Horse experimental data for the ^{7}Li(p, α)^{4}He reaction and correcting for Coulomb effects. The deduced ^{7}Be(n, α)^{4}He data overlap with the Big Bang nucleosynthesis energies and the deduced reaction rate allows us to evaluate the corresponding cosmological implications.

Key words: nuclear reactions, nucleosynthesis, abundances – primordial nucleosynthesis

1. Introduction

The cosmological lithium problem is one of the most challenging open questions in astrophysics and cosmology, introducing inconsistencies in the framework given by the standard Big Bang nucleosynthesis (BBN) for which primordial abundances are described by means of the only free baryon-to-photon ratio $\eta = n_b/n_\gamma$ parameter (see, for instance, Bertulani & Kajino 2016). BBN aims at determining η, as well as other quantities, starting from the observed primordial abundances, thus probing the universe at the very early stage of ∼2–3 minutes after the Big Bang. During such an epoch, observable quantities of the light elements D, ^{3}He, ^{4}He, and ^{7}Li are produced and their primordial abundances are investigated today in properly selected astrophysical environments. On the other hand, standard BBN allows us to predict these primordial abundances by varying η parameter, once the neutron lifetime (τ_n), the number of neutrino families (N_ν), and the nuclear reaction network have been fixed. In turn, the η parameter is related to the baryon density of the universe as $\Omega_B h^2 = 3.65\times10^7\ \eta$. In addition, by studying the anisotropies of the cosmic microwave radiation (CMB), it is possible to independently determine η, mostly as because of the very recent *WMAP* and *PLANCK* missions (see, for instance, Komatsu et al. 2011; Planck Collaboration 2016). With respect to BBN, such η determinations refer to a later stage of the universe, corresponding to an age of about 0.3 Myr after the Big Bang.

The currently accepted picture is that the ^{7}Li cosmological abundance, deduced from $\eta = \eta_{CMB} = (6.07 \pm 0.07) \times 10^{-10}$ (Planck Collaboration 2016), corresponds to the value of $(\mathrm{Li/H})_{\mathrm{BBN}} \sim (4.56\text{–}5.34) \times 10^{-10}$ while the one obtained by metal-poor halo stars observations is $(\mathrm{Li/H})_{\mathrm{obs.}} = (1.58^{+0.35}_{-0.28}) \times 10^{-10}$ (Sbordone et al. 2010; Coc et al. 2012), thus implying a factor ∼3 lower than the one inferred from CMB observation.

Thanks to the precise LEP measurements for neutrino families, leading to the value of $N_\nu = 2.9840 \pm 0.0082$ (LEP Collaborations 2006), and to the neutron lifetime measurements, leading to the value of $\tau_n = 880.2 \pm 1.0$ s (Patrignani et al. 2016), the possible sources of uncertainties affecting the primordial BBN lithium abundances have been significantly reduced. Conversely, the search of nuclear physics solutions to this problem (Fields 2011) has been hampered in recent years mainly because of the role of the unstable ^{7}Be ($t_{1/2} = 53.22 \pm 0.06$ days) isotope (Coc et al. 2004; Chakraborty et al. 2011; Broggini et al. 2012). This could come into play in the BBN network with both (n, p) or (n, α) reactions. Although the (n, p) process is dominant (Broggini et al. 2012), the (n, α) reaction channel has been matter of very recent studies (Hou et al. 2015; Barbagallo et al. 2016; Kawabata et al. 2017).

In Hou et al. (2015), the authors extracted the experimental values of the ^{7}Be(n, α)^{4}He reaction cross section by applying the detailed-balance principle to the ^{4}He(α, n)^{7}Be data derived from ^{4}He(α, p)^{7}Li data of King et al. (1977), Slobodrian & Conzett (1975), and from the ^{7}Li(p, α)^{4}He data of Cassagnou et al. (1963). The investigation of Hou et al. (2015) focused only on the ^{7}Be ground state contribution, allowing one to measure the *p*-wave component of the ^{7}Be(n, α)^{4}He cross section because of the spin-parity selection rules in the outgoing channel.

The ^{7}Be(n, α)^{4}He cross-section measurement of Barbagallo et al. (2016) has been performed at the n_TOF facility by means of a neutron beam impinging on a radioactive ^{7}Be target, thus allowing for the study of the former reaction in the energy range 10 meV–10 keV. Their measurement is based on the coincidence detection of alpha particles coming from the reaction ^{7}Be(n, $\gamma\alpha$)^{4}He, thus it is only sensitive to the *s*-component of the ^{7}Be(n, α)^{4}He cross section (see Barbagallo et al. 2016 for details) at energies lower than 10 keV. To such a purpose, the authors investigated only the electromagnetic transition from the negative-parity ^{8}Be states, near the ^{7}Be+n threshold at about ∼19 MeV, to the decay channels having ∼8 MeV alpha particles in the exit channel, i.e., the 16.626 MeV and the 16.922 MeV excited levels. Starting from their partial cross-section measurements, they inferred the total direct radiative capture (DRC) reaction cross section at energies lower than 10 keV.

The most recent ^{7}Be(n, α)^{4}He cross-section measurement of Kawabata et al. (2017) is based again on the application of the detailed-balance principle to the time-reverse reaction ^{4}He(α, n)^{7}Be allowing for an investigation of the ^{7}Be–n interaction at energies of $E_{\mathrm{c.m.}} = 0.20$–0.81 MeV. As mentioned before, the authors investigated the p-wave component of the ^{7}Be(n, α)^{4}He reaction cross section, for which a dominant contribution has been found at BBN energies with respect to the s-wave component (Kawabata et al. 2017), showing an agreement with the data of Hou et al. (2015).

In this work, we derive the ^{7}Be(n, α)^{4}He reaction cross section in correspondence of the BBN Gamow energies by applying the charge symmetry method to the already available ^{7}Li(p, α)^{4}He experimental data studied via the Trojan Horse Method (THM) (Spitaleri et al. 2011, 2016; Tribble et al. 2014). Charge-symmetry hypothesis is still a largely debated topic in nuclear physics particularly for low-energy induced reactions. Although in the theoretical work of Kajino (1986) the authors found a charge-symmetry breaking (CSB) for the ^{3}He(α, γ)^{7}Be and ^{3}H(α, γ)^{7}Li reactions by deriving the corresponding S(0)-factors, charge symmetry has been found working in several other contexts. It has been found to be valid in the works of Shima et al. (1998) where the authors refer to the (γ, n) and (γ, p) cross-section measurements involving ^{4}He nuclei for testing charge-symmetry assumption. The cross-section values obtained for the two channels agree within the error bars, thus supporting the idea of no CSB. The same considerations apply to the work of Sagle et al. (1982). Additionally, a nice opportunity of testing charge symmetry has been given also by the recent THM d+d cross-section measurements discussed in Tumino et al. (2014) and aimed at measuring, with a single experiment, both the reaction channels d(d, p)t and d(d, n)^{3}He. The THM results support charge-symmetry evidence, even at extremely low energies of about 10 keV. Additionally, Barker (2006) proves the validity of charge symmetry by means of an R-matrix approach for the theoretical description of the ^{7}Be+p reaction of interest for astrophysics. The question about charge-symmetry universality, even for low-energy-induced nuclear reactions, is far from being achieved and further common efforts between experimentalist and theoretical physics are clearly necessary. In a review, Miller et al. (1990) give some examples of systems for which charge symmetry works and the corresponding evidence. Of course, the overview is far from being complete. In the end, one of the most recent impacts about the role of charge symmetry in nuclear astrophysics has been explored in Mukhamedzhanov (2012) together with Timofeyuk et al. (2003) in which the authors apply a charge-symmetry hypothesis to extract asymptotic normalization coefficients (ANC) for states of radioactive nuclei once the mirror stable one is known. This theoretical approach has been also strengthen by the experimental data of Trache et al. (2003) in which the authors found a value close to unity for the ANCs ^{8}B → ^{7}Be+p and ^{8}Li → ^{7}Li+n ratio with, as the authors claim, "an additional 3% uncertainty to account for possible CSB effects" (Trache et al. 2003).

2. Strategy

The THM allows the experimentalist to study a two-body reaction of interest for astrophysics, $A(x, c)C$, by properly selecting the quasi-free (QF) contribution of a suitable 2 → 3 reaction $a(A, cC)s$ induced at an entrance energy well above the Coulomb barrier. As explained in detail in the literature (see, for instance, Tribble et al. (2014) and references therein), nucleus a is chosen because of its dominant $x \oplus s$ cluster configuration, its low-binding energy, and a well-known momentum distribution for the x–s intercluster motion. Assuming the QF breakup of the nucleus a, s acts as spectator of the two-body reaction of interest (see Spitaleri et al. 2011, 2016; Tribble et al. 2014). Within the plane wave impulse approximation (PWIA), the $a(A, cC)s$ reaction cross section can be factorized as (Tribble et al. 2014; Spitaleri et al. 2016):

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto \mathrm{KF} \cdot |\Phi(\boldsymbol{p}_{xs})|^2 \cdot \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{cm}}^{\mathrm{HOES}}, \qquad (1)$$

where

1. KF represents the kinematical factor, depending on masses, momenta, and angles of the outgoing particles, that takes into account the final state phase space factor;
2. $|\Phi(\boldsymbol{p}_{xs})|^2$ gives the Fourier transform of the radial wave function describing the x–s intercluster motion, usually in terms of Hänkel, Eckart, or Hulthén functions depending on the x–s system.
3. $d\sigma/d\Omega|_{\mathrm{cm}}^{\mathrm{HOES}}$ is the half-off-energy-shell (HOES) differential cross section for the two-body reaction at the center-of-mass energy $E_{\mathrm{cm}} = E_{cC}$–Q, where Q represents the Q-value of the HOES $A(x, c)C$ reaction while E_{cC} represents the relative c–C energy measured in laboratory.

The THM has helped in investigation on several astrophysical scenario, such as lithium depletion (Lamia et al. 2013), AGB nucleosynthesis (Palmerini et al. 2013) or Novae nucleosynthesis (Cherubini et al. 2015). More advanced approaches have been introduced in later years, allowing us to justify and generalize Equation (1), releasing some approximations contained in it (see, for instance, La Cognata et al. 2010, 2013; Tribble et al. 2014; Spitaleri et al. 2016; Guardo et al. 2017).

Focusing on the aims of this work, ^{7}Li(p, α)^{4}He cross section has been largely studied with THM at astrophysical energies, i.e., lower than ~1 MeV (Spitaleri et al. 1999; Aliotta et al. 2000; Lattuada et al. 2001; Pizzone et al. 2003; Lamia et al. 2012). However, because we are interested in using the ones useful for the ^{7}Be(n, α)^{4}He analysis, only part of them will be considered in the forthcoming analysis; in particular, because of the difference in mass of the two entrance channels ^{7}Li+p and ^{7}Be+n, a difference of 1.644 MeV is present between the center-of-mass energies covered in the two cases. For such a reason, only ^{7}Li(p, α)^{4}He THM data covering a center-of-mass energy $E_{\mathrm{Li-p}} \geqslant 1.644$ MeV will be taken into account.

At such energies, only two THM data sets are available. The first one is discussed in Zadro et al. (1989) and relies on the THM application to the QF ^{2}H(^{7}Li, $\alpha\alpha$)n reaction, in which the emerging neutron acts as spectator. The second data set is reported in the work by Tumino et al. (2006) and refers to the ^{3}He QF breakup in which deuteron is seen as spectator in the ^{3}He(^{7}Li, $\alpha\alpha$)d interaction. The pictures of such QF-breakup processes are sketched in Figure 1. They represent the so-called *pole invariance* of THM for which the two-body reaction amplitude is not influenced by the upper poles of Figure 1 or, that is the same, the two-body reaction channel investigation is independent of the adopted TH-nucleus (Pizzone et al. 2011, 2013).

The THM cross-section values of Zadro et al. (1989) and Tumino et al. (2006) have been then converted into the

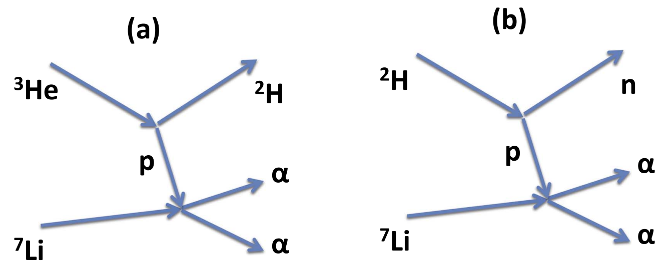

Figure 1. Polar diagrams for the ^{3}He(^{7}Li, $\alpha\alpha$)d (a) and ^{2}H(^{7}Li, $\alpha\alpha$)n (b) QF-breakup processes. Upper vertex describes the QF breakup of the TH-nucleus, while the lower one refers to the ^{7}Li(p, α)^{4}He reaction.

^{7}Be(n, α)^{4}He ones through the equation

$$\sigma_{\mathrm{n}\alpha} = \sigma_{\mathrm{p}\alpha} \cdot \frac{E_{\mathrm{Li-p}}}{E_{\mathrm{Li-p}} - 1.644} \cdot \frac{P^{n}_{l=1}(E_{\mathrm{Li-p}} - 1.644)}{P^{p}_{l=1}(E_{\mathrm{Li-p}})}, \quad (2)$$

where the hypothesis of the charge symmetry, largely studied in the past and experimentally verified (see, for instance, Sagle et al. 1982; Shima et al. 1998), for the ^{7}Li–p and ^{7}Be–n systems has been applied taking also advantage from the agreement between the data of Hou et al. (2015) and the more recent measurement of Kawabata et al. (2017).

The penetrability, P, has been evaluated through the standard formula

$$P_l(E,\, r) = \frac{kr}{F_l^2(E,\, r) + G_l^2(E,\, r)}, \quad (3)$$

where the channel radius is $r = r_0 \cdot (A_1^{1/3} + A_2^{1/3}) = 1.41(7^{1/3}+1)$ fm for both proton ($\mathrm{P^p}$) and neutron ($\mathrm{P^n}$) channels. In Equation (2), the use of a l = 1 penetrability is justified by parity conservation. In particular, while the two emerging alphas have a positive parity ($J^\pi = 0^+$), both the entrance channels ^{7}Li–p and ^{7}Be–n exhibit negative parities as for ^{7}Li (and ^{7}Be) $J^\pi = 3/2^-$. The discussion is limited here to the ground state contribution.

The result of such a procedure is shown in Figure 2, where the full black circles are the ^{7}Be(n, α) cross-section data as extracted from the ^{7}Li(p, α) measurement of Tumino et al. (2006), while the red ones refer to the investigation performed in Zadro et al. (1989). The ^{7}Be(n, α) cross-section data are then compared with those of Hou et al. (2015) and the most recent ones of Kawabata et al. (2017). Although THM data need a normalization procedure (Spitaleri et al. 2016), this does not represent an issue in the present case because the data used here were already available in absolute units thanks to the normalization procedure adopted in the two THM works. It is worth noting that the present investigation allows us to extract two experimental points at energies of ∼100 keV, well inside the energies of interest for the BBN scenario. The error bars shown in Figure 2 have been derived by means of the standard error propagation theory applied to Equation (2), taking into account the uncertainties in energy ($E_{\mathrm{Li-p}}$) and $\sigma_{\mathrm{p}\alpha}$ cross section from the two ^{7}Li(p, α)^{4}He THM investigations (about 20%–30%) and the choice of r_0 in the penetrability calculation (leading to a maximum variation of ∼7%, for r_0 values ranging from 1.2 fm up to 1.5 fm).

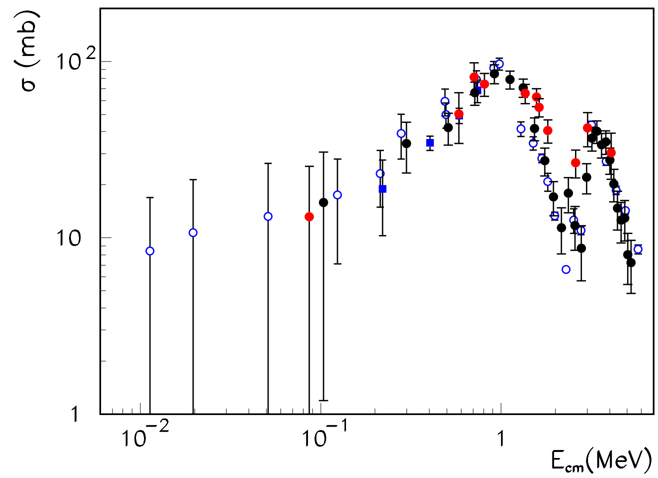

Figure 2. ^{7}Be(n, α)α cross section as derived here by using ^{2}H breakup data (full red circles) and ^{3}He breakup data (full black circles). They are compared with the data of Hou et al. (2015; empty blue circles) and those of Kawabata et al. (2017; full blue squares).

With respect to the recent data of Hou et al. (2015), the present THM investigation probes the p-wave contribution to the ^{7}Be(n, α)^{4}He cross section by only using a single experimental data set. With respect to the ^{4}He(α, n)^{7}Be cross-section measurements of Kawabata et al. (2017), the THM results do not suffer for the typical background problems or detection efficiency uncertainties typical of neutron-counting experiments, as our data have been derived from ^{7}Li(p, α)^{4}He THM experiments where high-energy alpha particles were detected (see Zadro et al. 1989; Tumino et al. 2006 for details). In addition, the THM data extracted here span a wide energy range, nicely overlapping both with the high-energy region as well as with the Gamow energies for BBN. Eventually, the application of THM allowed for studying the ^{7}Be–n induced reaction right at energies higher than 10 keV which represents the highest energy value reached in Barbagallo et al. (2016). This energy domain is of primary interest for BBN and, in this energy region, the s-wave component does not play a major role as it is does, in contrast, the p-wave (Kawabata et al. 2017) therefore also justifying the approach followed here.

3. Reaction Rate Calculation

Interpolating the THM data, it has been possible to determine the ^{7}Be(n, α) reaction rate at the effective energies of $E_0 = 0.086{\cdot}(1 + 1/2)T_9 \sim 0.08$–$0.1$ MeV by assuming a p-wave interaction at temperatures $T_9 = 0.6$–0.8 GK (Wagoner 1969) and by using the standard formula for the reaction rate calculation given in Rolfs & Rodney (1988):

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{N_A}{kT_9^{\frac{3}{2}}} \int_0^\infty E\sigma(E) e^{-\frac{E}{kT}} dE \quad (\mathrm{cm^3\ mol^{-1}\ s^{-1}}), \quad (4)$$

where the temperature, T_9, is expressed in units of 10^9 K and center-of-mass energy, E, in MeV. Our calculation leads to the values listed in Table 1. These values are one order of magnitude lower than the ones proposed in the Wagoner (1969) reaction rate usually taken as reference, confirming the

Table 1
The Upper, Lower, and Adopted THM Reaction Rate Extracted here for the ^{7}Be(n, α)^{4}He Reaction Compared with the Most Recent One of Hou et al. (2015)

T_9	Lower	Adopted	Upper	Hou et al. (2015)
0.1	3.88×10^5	7.51×10^5	1.21×10^6	9.6×10^5
0.2	7.75×10^5	1.48×10^6	2.35×10^6	1.7×10^6
0.3	1.10×10^6	2.05×10^6	3.23×10^6	2.3×10^6
0.4	1.42×10^6	2.60×10^6	4.04×10^6	2.9×10^6
0.5	1.75×10^6	3.14×10^6	4.82×10^6	3.5×10^6
1	3.85×10^6	6.24×10^6	8.95×10^6	7.2×10^6
1.5	6.80×10^6	9.71×10^6	1.36×10^6	1.2×10^7
2	1.04×10^7	1.32×10^7	1.85×10^6	1.7×10^7
2.5	1.41×10^7	1.66×10^7	2.32×10^6	2.1×10^7
3	1.77×10^7	2.01×10^7	2.75×10^6	2.5×10^7
4	2.37×10^7	2.71×10^7	3.42×10^6	3.2×10^7
5	2.78×10^7	3.40×10^7	3.87×10^6	3.5×10^7

Note. Both reaction rate calculations are expressed in cm^3 mol^{-1} s^{-1}.

conclusions reached in the most recent ^{7}Be(n, α)^{4}He works (Hou et al. 2015; Barbagallo et al. 2016; Kawabata et al. 2017). Figure 3 shows the ratio between the reaction rate extracted here and the one deduced in the work of Hou et al. (2015). The red area of Figure 3 reflects the uncertainty on the present THM reaction rate as from the experimental data in Figure 2. The central value of the present THM reaction rate is ~13% lower than the one proposed in the recent work of Hou et al. (2015), even if they agree within the experimental errors.

Additionally, the THM reaction rate has been fitted via the following formula,

$$N_A\langle\sigma v\rangle = \exp\left[a_1 + \frac{a_2}{T_9} + \frac{a_3}{T_9^{1/3}} + a_4 T_9^{1/3} + a_5 T_9 + a_6 T_9^{5/3} + a_7 \ln T_9\right], \quad (5)$$

where the a_i coefficients have been left as free parameters. In Equation (5), the temperature T_9 is expressed in units of 10^9 K and the final reaction rate is given in (cm^3 mol^{-1} s^{-1}). The resulting a_i coefficients are listed in Table 2. A maximum variation of ±3% has been found between the calculated and the fitted THM reaction rates, thus confirming the goodness of the adopted procedure.

4. Conclusions

By considering the conclusions made by Broggini et al. (2012), for which an increase of a factor ~60 of the ^{7}Be(n, α)^{4}He reaction rate with respect the one of Wagoner (1969) is required to reduce the ^{7}Li cosmological abundance by a factor of two, it seems unlikely that the solution of the ^{7}Li cosmological problem could be found in the ^{7}Be–neutron interaction, also taking into account the present THM results for which the ^{7}Be(n, α) reaction rate is lower by a factor ~10 with respect the one of Wagoner (1969). In detail, primordial nucleosynthesis calculations, performed via the BBN code described in Pizzone et al. (2014) evolved from an original code by Kawano (1988), show that a change in the ^{7}Be(n, α) reaction rate as calculated in the present work yields a ^{7}Li/H ratio of 2.845×10^{-11} and to a ^{7}Be/H ratio of 4.156×10^{-10}. Thus, the calculated cosmological lithium abundance is 4.441×10^{-10}, as pointed out in Coc et al. (2012), which leaves essentially unchanged astrophysical consequences for BBN if compared to the observed value of 1.58×10^{-10} in metal-poor halo stars (Sbordone et al. 2010). Additionally, a further ^{7}Li/H primordial abundance calculation has been performed by only varying the ^{7}Be(n, p)^{7}Li reaction rate until the calculated primordial lithium abundance matches the observed one. In this case, a change of a factor of four with respect to the ^{7}Be(n, p)^{7}Li reaction rate by Smith et al. (1993) would be necessary (see Table 3).

However, because the ^{7}Be(n, α) cross-section measurements derived here and those of Kawabata et al. (2017) only partially cover the BBN energy range, further measurements are strongly needed to assess completely the nuclear input for the cosmological lithium problem.

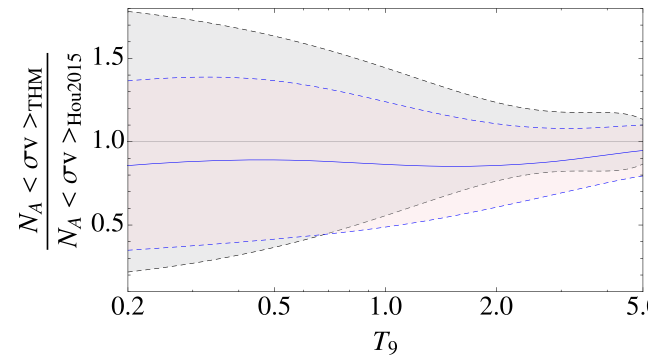

Figure 3. Ratio (blue line) between the ^{7}Be(n, α)α reaction rate extracted here and the one published by Hou et al. (2015). The red area reflects the uncertainty on the THM reaction rate as deduced from the fit of the THM experimental data, while the gray area represents the one derived by Hou et al. (2015).

Table 2
Reaction Rate Parameters Intervening in Equation (5) for the ^{7}Be(n, α)^{4}He THM Investigation

Parameter a_i	Fitting Value
a_1	−9.9039
a_2	0.1070
a_3	−16.3045
a_4	45.1375
a_5	−3.6269
a_6	0.2370
a_7	−16.0161

Table 3
Primordial Lithium Abundances Calculated Via the BBN Code Developed by Pizzone et al. (2014) and Kawano (1988) (Labeled as Pizz2014)

Reaction Rate	^{7}Li/H	^{7}Be/H	(^{7}Li/H+^{7}Be/H)
Pizz2014+ Hou2015	2.840×10^{-11}	4.149×10^{-10}	4.433×10^{-10}
Pizz2014 +Present work	2.845×10^{-11}	4.156×10^{-10}	4.441×10^{-10}
Pizz2014+Present work +4 × Smith1993	3.971×10^{-11}	1.155×10^{-10}	1.552×10^{-10}

Note. The first two rows refer to the abundances calculated by only varying the ^{7}Be(n, α) reaction rate reported in Hou et al. (2015; Hou2015) and in the present work, respectively. The last row refers to the ^{7}Li abundance calculated with the present ^{7}Be(n, α) reaction rate and only varying the ^{7}Be(n, p) one within a factor 4 to approach the observed one (1.58×10^{-10}).

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