Primordial Nucleosynthesis

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Abstract. Primordial nucleosynthesis, or Big Bang Nucleosynthesis (BBN), is one of the three evidences for the Big-Bang model, together with the expansion of the Universe and the Cosmic Microwave Background. There is a good global agreement over a range of nine orders of magnitude between abundances of $^4\text{He}$, D, $^3\text{He}$ and $^7\text{Li}$ deduced from observations, and calculated in primordial nucleosynthesis. This comparison was used to determine the baryonic density of the Universe. For this purpose, it is now superseded by the analysis of the Cosmic Microwave Background (CMB) radiation anisotropies. However, there remain, a yet unexplained, discrepancy of a factor 3–5, between the calculated and observed lithium primordial abundances, that has not been reduced, neither by recent nuclear physics experiments, nor by new observations. We review here the nuclear physics aspects of BBN for the production of $^4\text{He}$, D, $^3\text{He}$ and $^7\text{Li}$, but also $^6\text{Li}$, $^9\text{Be}$, $^{11}\text{B}$ and up to CNO isotopes. These are, for instance, important for the initial composition of the matter at the origin of the first stars. Big-Bang nucleosynthesis, that has been used, to first constrain the baryonic density, and the number of neutrino families, remains, a valuable tool to probe the physics of the early Universe, like variation of "constants" or alternative theories of gravity.

1. Introduction

There are presently three evidences for the Big-Bang Model: the universal expansion, the Cosmic Microwave Background (CMB) radiation and Primordial or Big-Bang Nucleosynthesis (BBN). The third evidence for a hot Big-Bang comes, indeed, from the primordial abundances of the “light elements”: $^4\text{He}$, D, $^3\text{He}$ and $^7\text{Li}$. They were produced during the first $\approx 20$ minutes of the Universe when it was dense and hot enough for nuclear reactions to take place. These primordial abundances are compared to astronomical observations in primitive astrophysical sites. It is worth reminding that Big Bang Nucleosynthesis has been essential in the past, to first estimate the baryonic density of the Universe, $\rho_B = (1 - 3) \times 10^{-31}$ g/cm$^3$ [1], and give an upper limit on the number neutrino families $N_\nu \leq 3$[2], both in the seventies. The number of light neutrino families is now known from the measurement of the Z$^0$ width by LEP experiments at CERN: $N_\nu = 2.9840 \pm 0.0082$ [3]. The nuclear reaction rates have all been measured in nuclear physics laboratories or can be calculated from the standard theory of weak interactions. In that case, they are normalized to the experimental value for the lifetime of the neutron. Its precise value is still a matter of debate [4] $\tau_n = 880-884$ s, but its uncertainty has only marginal effect on BBN. The last parameter to have been independently determined is the precise value of baryonic density of the Universe, which is now deduced from the observations of the anisotropies of the CMB radiation. It is usual to introduce $\eta$, the number of photons per baryon which remains...
constant during the expansion, and is directly related to $\Omega_b$ by $\Omega_b \cdot h^2 = 3.65 \times 10^7 \eta$ with

$$\Omega_b \cdot h^2 = 0.02249 \pm 0.00062 \text{ and } \Omega_b = 0.04455 \pm 0.0027$$

(“WMAP only Seven Year Mean” [5]). The parameter $h$ represents the Hubble constant ($H_0$) in units of 100 km/s/Mpc (i.e. $h = 0.704$ [5]) and $\Omega_b \equiv \rho_b / \rho_{0,C}$ the baryonic density relative to the critical density, $\rho_{0,C}$, which corresponds to a flat (i.e. Euclidean) space. It is given by:

$$\rho_{0,C} = \frac{3H_0^2}{8\pi G} = 1.88 \, h^2 \times 10^{-29} \text{ g/cm}^3 \text{ or } 2.9 \, h^2 \times 10^{11} \text{ M}_\odot / \text{Mpc}^3$$

where $G$ is the gravitational constant. It corresponds to a density of a few hydrogen atoms per cubic meter or one typical galaxy per cubic megaparsec (Mpc). This results (Eqs. 1–2) in a baryonic density which is just slightly above the range provided by Wagoner [1] in 1973!

Hence, the number of free parameters in Standard Big Bang Nucleosynthesis has now been reduced to zero, and the calculated primordial abundances are in principle only affected by the moderate uncertainties in some nuclear cross-sections. It may appears that Big Bang Nucleosynthesis studies are now useless, but this is certainly not the case. First, even though the agreement with observations is good or very good for $^4\text{He}$, $^3\text{He}$ and D, there is a tantalizing discrepancy for $^7\text{Li}$ that has not yet found a consensual explanation. Second, when we look back in time, it is the ultimate process for which, a priori, we know all the physics involved. Hence, departure from its predictions could provide hints or constraints on new physics or astrophysics.

Besides the $^4\text{He}$, D, $^3\text{He}$ and $^7\text{Li}$ isotopes, some minute traces of $^6\text{Li}$, $^9\text{Be}$, $^{11}\text{B}$ and CNO are produced by BBN. Observations of $^6\text{Li}$ in a few halo stars have renewed the interest for this isotope and the nuclear uncertainties concerning its production. The evolution of the first generation (Population III) of stars could be influenced by the amount of primordial CNO elements, as hydrogen burning can proceed either through the slow p–p chain, or through the more efficient CNO cycle. We will hence review the nuclear aspects of the primordial production of element up to oxygen.

2. The cosmological elements $^4\text{He}$, D, $^3\text{He}$ and $^7\text{Li}$

2.1. Abundances of the cosmological elements

During the evolution of the Galaxy, complex nucleosynthesis takes place, mainly in massive stars which release matter enriched in heavy elements into the interstellar medium when they explode as supernovae. Accordingly, the abundance of heavy elements in the gas, at the origin of star formation, increases with time. The observed abundance of metals (in astrophysics, the chemical elements beyond helium) is hence an indication of its age: the oldest stars have the lowest metallicity. To derive the most primitive abundances one has first, to extract them from observations of astrophysical sites which are thought to be non evolved and second, extrapolate them to zero metallicity.

Primordial lithium abundance is deduced from observations of low metallicity stars in the halo of our Galaxy where the lithium abundance is almost independent of metallicity, displaying a plateau [6]. This constant Li abundance is interpreted as corresponding to the BBN $^7\text{Li}$ yield. This interpretation assumes that lithium has not been depleted at the surface of these stars so that the presently observed abundance is supposed to be equal to the initial one. The small scatter of values around the “Spite plateau” is an indication that depletion may not have been very effective. Astronomical observations of metal poor halo stars have led to a relative primordial abundance [7] of:

$$\text{Li/H} = (1.58 \pm 0.31) \times 10^{-10}.$$
Note also that observationally challenging detections of $^6$Li has been reported [8] to a level of $\sim 10^{-2}$ below the Spite plateau value. The presence of a $^6$Li plateau is however not confirmed as only few (2-3) stars seem to present significant $^6$Li abundances on their surfaces [9]. For a recent review of the latest Li observations and their different astrophysical aspects, see Refs. [10, 11], and the proceedings of the 2012 Workshop Lithium in the Cosmos\(^1\).

Contrary to $^7$Li which can be both produced (spallation, asymptotic giant branch (AGB) stars, novae) and destroyed (in the interior of stars), deuterium is a very fragile isotope, that can only be destroyed after BBN. Its most primitive abundance is determined from the observation of absorption lines in clouds at high redshift, on the line of sight of more distant quasars. Very few observations of these cosmological clouds are available and a weighted mean [12] (and references therein) of this data yields a $D/H$ abundance of:

$$D/H = (3.02 \pm 0.23) \times 10^{-5}. \quad (4)$$

After BBN, $^4$He is produced by stars. Its primitive abundance is deduced from observations in HII (ionized hydrogen) regions of compact blue galaxies. Galaxies are thought to be formed by the agglomeration of such dwarf galaxies which are hence considered as more primitive. The primordial $^4$He abundance $Y_p$ ($^4$He mass fraction) is given by the extrapolation to zero metallicity but is affected by systematic uncertainties such as plasma temperature or stellar absorption. Using the data compiled in Ref. [13], it was found [14, 15] that:

$$Y_p = 0.2534 \pm 0.0083. \quad (5)$$

Contrary to $^4$He, $^3$He is both produced and destroyed in stars so that the evolution of its abundance as a function of time is not well known, and has only been observed in our Galaxy [16]:

$$^3\text{He}/H = (1.1 \pm 0.2) \times 10^{-5}. \quad (6)$$

Consequently, comparison with $^3$He abundance from BBN is subject to caution [17].

2.2. Nuclear reactions for $^4$He, D, $^3$He and $^7$Li nucleosynthesis

Unlike in other sectors of nuclear astrophysics, nuclear cross sections have usually been directly measured at BBN energies ($\sim 100$ keV). There are 12 nuclear reactions responsible for the production of $^4$He, D, $^3$He and $^7$Li in Standard BBN. There are many other reactions connecting these isotopes, but their cross sections are too small and/or reactants too scarce to have any significant effect. Even among these 12 reactions, a few of them are now irrelevant (see below) at WMAP baryonic density.

The weak reactions involved in $n \leftrightarrow p$ equilibrium are an exception; their rates [18] come from the standard theory of the weak interaction, normalized to the experimental neutron lifetime. Until very recently, the averaged value of 885.7\pm0.8 s was recommended by the Particle Data Group, but new measurement lead to significantly lower values. While it has not yet been possible to solve this discrepancy [4], a reevaluation of the recommended value: 880.1\pm1.1 s has been proposed [19], awaiting experimental clarification.

The $^1\text{H}(n,\gamma)^2\text{H}$ cross section is also obtained from theory [20] but in the framework of Effective Field Theory.

For the ten remaining reactions, $^2\text{H}(p,\gamma)^3\text{He}$, $^2\text{H}(d,n)^3\text{He}$, $^2\text{H}(d,p)^3\text{H}$, $^3\text{H}(d,n)^4\text{He}$, $^3\text{H}(d,p)^4\text{He}$, $^3\text{He}(n,p)^4\text{He}$, $^3\text{He}(\alpha,\gamma)^7\text{Li}$, $^7\text{Li}(p,\alpha)^4\text{He}$ and $^7\text{Be}(n,p)^7\text{Li}$, the cross sections have been measured in the laboratory at the relevant energies. Formerly, we used

\(^1\) [http://www.iap.fr/lithiuminthecosmos2012/index.html], proceedings will appear in Memorie della Società Astronomica Italiana Supplementi.
Table 1. Abundance sensitivity to reaction rates: $\partial \log Y / \partial \log \sigma_v$ at WMAP baryonic density.

| Reaction                  | $^4$He | D   | $^3$He | $^7$Li | $E_0(\Delta E_0/2)$ (MeV) |
|---------------------------|--------|-----|--------|-------|--------------------------|
| n→p ($\tau_n^{-1}$)      | -0.73  | 0.42| 0.15   | 0.40  |                          |
| $^1$H(n,γ)$^2$H          | 0      | -0.20| 0.08   | 1.33  |                          |
| $^2$H(p,γ)$^3$He         | 0      | -0.32| 0.37   | 0.57  | 0.11(0.11)               |
| $^2$H(d,n)$^3$He         | 0      | -0.54| 0.21   | 0.69  | 0.12(0.12)               |
| $^2$H(d,p)$^3$H          | 0      | -0.46| -0.26  | 0.05  | 0.12(0.12)               |
| $^3$H(d,n)$^4$He         | 0      | 0    | -0.01  | -0.02 | 0.13(0.12)               |
| $^3$H(α,γ)$^7$Li         | 0      | 0    | 0.03   | 0.23  | 0.17(0.17)               |
| $^3$He(n,p)$^3$H         | 0      | 0.02 | -0.17  | -0.27 |                          |
| $^3$He(d,p)$^4$He        | 0      | 0.01 | -0.75  | -0.75 | 0.21(0.15)               |
| $^3$He(α,γ)$^7$Be        | 0      | 0    | 0      | 0.97  | 0.37(0.21)               |
| $^7$Li(p,α)$^4$He        | 0      | 0    | 0      | -0.05 | 0.24(0.17)               |
| $^7$Be(n,p)$^7$Li        | 0      | 0    | 0      | -0.71 |                          |

the reaction rates from the the evaluation performed by Descouvemont et al. [21]. However, more recent experiments and analysis have lead to improved reaction rates for several important reactions.

To point out the most important reactions, we display in Table 1 the sensitivity of the calculated abundances ($Y_i$ with $i = ^4$He, D, $^3$He and $^7$Li) w.r.t. to a change in the 12 reaction rates by a constant factor. We define the sensitivity as $\partial \log Y / \partial \log \sigma_v$, based on the assumption that the nuclear cross section uncertainties are now dominated by systematic uncertainties that affect their normalization rather than by statistics. These values were obtained, at the WMAP baryonic density, by a parabolic fit of $\Delta Y_i / Y_i$ for $\pm 15\%$ variations of the reaction rates. The last column represents the Gamow window at BBN typical temperatures.

This table can be used as a guide for further experimental efforts. We see for instance that at WMAP baryonic density, the $^3$H(α,γ)$^7$Li and $^7$Li(p,α)$^4$He reactions play a negligible role. At WMAP baryonic density, $^7$Li is produced indirectly by $^3$He(α,γ)$^7$Be, that will, much later decay to $^7$Li.

The sensitivity to the weak rates is high but (within standard theory), the uncertainty is governed by the neutron lifetime which is now known with reasonable precision. Indeed, the relative uncertainty on $\tau_n$, is of the order of $5 \times 10^{-3}$ [4] affects $^4$He abundance by (Table 1) $-0.73 \times 5 \times 10^{-3}$, a factor of ten lower than the observational uncertainty (Eq. 5).

The influence of the $^1$H(n,γ)$^2$H rate was unexpected. The $^7$Li final abundance depends strongly on the rate of this reaction while other isotopes are little affected. This unexpected effect can be traced to the increased neutron abundance at $^7$Be formation time for a low $^1$H(n,γ)$^2$H rate making its destruction by neutron capture, $^7$Be(n,p)$^7$Li(p,α)$^4$He, more efficient (see Fig. 1 in [22]). However, the few experimental informations available for this cross section at BBN energies are in good agreement with the calculations estimated to be reliable to within 1% error[20].

The next most important reaction (Table 1) is $^3$He(α,γ)$^7$Be as it is the path for the formation of $^7$Li at high density. Hence, the $^7$Li abundance is directly proportional to this rate, which has long been a subject of debate. Systematic differences in the measured cross section were found according to the experimental technique: prompt or activation measurements. Thanks to the
Figure 1. Astrophysical S–factor for the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction, adapted from Fig. 3 in Di Leva et al. [24]. The data are from Refs. [23, 24], the dot–dashed and solid curves are respectively the previously used Descouvemont et al. [21] (anterior to the displayed data [23, 24]) or the adopted Cyburt & Davids [25] (including recent data [23]) fits. The dashed vertical lines represent the Gamow window at 1 GK.

recent experimental efforts [23, 24], in particular at LUNA at the Laboratori Nazionali del Gran Sasso, the two methods provide now results in agreement, within each others error bars. With this new experimental data, Cyburt & Davids [25] calculated the S–factor which is significantly higher than the Descouvemont et al. [21] R–matrix fit, done before these new data were available (Fig. 1). This explains the higher $^7\text{Li}$ primordial abundance obtained in recent calculations. At high energy, the recent experimental data, in particular of Di Leva et al. [24], obtained by a third technique, the recoil mass separation, deviate from both fits. Theoretical explanations are available [26], but this should not affect the S–factor at BBN energies. Nevertheless, one may note the relative scarcity of experimental data within the Gamow window (Fig. 1).

The $^2\text{H}(d,n)^3\text{He}$ reaction, also influential on $^7\text{Li}$, was re-measured [together with $^2\text{H}(d,p)^3\text{H}$] by Leonard et al [27], after the R-matrix analysis [21] was performed. The very precisely measured cross section is in perfect agreement with the R-matrix fit (Fig. 2).
2.3. BBN primordial abundances compared to observations

Figure 3 shows the abundances of $^{4}$He (mass fraction), D, $^{3}$He and $^{7}$Li (in number of atoms relative to H) as a function of the baryonic density. The thickness of the curves reflect the nuclear uncertainties. They were obtained by a Monte-Carlo calculation using for the nuclear rate uncertainties those obtained by [21] with the notable exception of $^{3}$He(α, γ)$^{7}$Be [25] and $^{1}$H(n,γ)$^{2}$H [20]. The horizontal lines represent the limits on the $^{4}$He, D and $^{7}$Li primordial abundances deduced from spectroscopic observations. The vertical stripe represents the baryonic density deduced from CMB observations [5]. The concordance between BBN and observations is in perfect agreement for deuterium. Considering the large uncertainty associated with $^{4}$He observations, the agreement with CMB+BBN is fair. The calculated $^{3}$He value is close to its galactic value showing that its abundance has little changed during galactic chemical evolution. On the contrary, the $^{7}$Li, CMB+BBN calculated abundance is significantly higher than the spectroscopic observations: from a factor of ≈3 [29] when using the Descouvemont et al. library [21] only and the Ryan et al. observations [30] (dotted lines in lower panel of Fig. 3), to a factor of ≈5 [28, 31] when using the new rates and Li observations [7]. Table 2 displays the comparison between BBN abundances deduced from the WMAP results and the spectroscopic
observations. The origin of this lithium discrepancy between CMB+BBN and spectroscopic observations remains an open question. Note also that with the new determination of the \(^{4}\text{He}\) primordial abundances \([14, 15]\), the agreement for \(^{4}\text{He}\) becomes marginal. As shown on the figure, an increase of the rate of expansion of the universe during BBN (simulated by an additional effective neutrino family) would improve the situation.

### Table 2. Yields at WMAP baryonic density compared to observations.

|          | Cyburt el al 2008\([28]\) | CV10 \([31]\) | Observations | Factor |
|----------|-----------------------------|--------------|--------------|--------|
| \(^{4}\text{He}\) | 0.2486\(\pm\)0.0002        | 0.2476\(\pm\)0.0004 | 0.2534\(\pm\)0.0083\([15]\) | \(\times10^{0}\) |
| D/H      | 2.49\(\pm\)0.17             | 2.68\(\pm\)0.15          | 3.02 \(\pm\)0.23 \([12]\) | \(\times10^{-5}\) |
| \(^{3}\text{He}/\text{H}\) | 1.00\(\pm\)0.07             | 1.05\(\pm\)0.04          | 1.1 \(\pm\)0.2\([16]\) | \(\times10^{-5}\) |
| \(^{7}\text{Li}/\text{H}\) | 5.24\(^{+0.71}_{-0.67}\) | 5.14\(\pm\)0.50          | 1.58\(\pm\)0.31\([7]\) | \(\times10^{-10}\) |

### 3. BBN production of heavier elements

Even though the direct detection of primordial CNO isotopes seems highly unlikely with the present observational techniques at high redshift, it is important to better estimate their Standard Big Bang Nucleosynthesis production. Hydrogen burning in the first generation of stars (Pop III stars) proceeds through the slow p-p chains until enough carbon is produced (through the triple-alpha reaction) to activate the CNO cycle. The minimum value of the initial CNO abundance that would affect Pop III stellar evolution is estimated to be as low as \(10^{-15}\) (in number of atoms relative to hydrogen, CNO/H) for the less massive ones \([32]\). This is only two orders of magnitude above the Standard Big Bang Nucleosynthesis CNO yield, using the current nuclear reaction rate evaluations of Iocco et al. \([33]\). In addition, it has been shown that Pop III stars evolution is sensitive to the triple-alpha \((^{12}\text{C} \text{ producing})\) reaction and can be used to constrain the possible variation of the fundamental constants \([34]\). This reaction rate is very sensitive to the position of the Hoyle state, which in turn is sensitive to the values of the fundamental constants. The same mechanism could also increase the amount of CNO \((^{12}\text{C})\) produced in BBN. In the same context of the variations of the fundamental constants, \(^{8}\text{Be}\) (which decays to two alpha particles within \(\sim 10^{-16}\) s) could become stable if these constants were only slightly different. At BBN time, this would possibly allow to bridge the “A=8 gap” and produce excess CNO \([35]\). To determine how significant would be this excess, one needs to know the standard BBN production of the CNO elements.

The production of CNO isotopes has been studied in the context of standard and inhomogeneous BBN. The most relevant analysis comes from Iocco et al. \([33]\) who included more than 100 nuclear reactions and predicted a CNO/H abundance ratio of approximately \(6 \times 10^{-16}\), with an upper limit of \(10^{-10}\).

The main difficulty in BBN calculations up to CNO is the extensive network needed, including \(n-, p-, \alpha-\), but also \(d-, t-\) and \(^{3}\text{He}\)-induced reactions. Most of the corresponding cross sections cannot be extracted from experimental data only. This is especially true for radioactive tritium-induced reactions, or for those involving radioactive targets like e.g. \(^{10}\text{Be}\). For some reactions, experimental data, including spectroscopic data of the compound nuclei, are just nonexistent. Hence, for many reactions, one has to rely on theory to estimate the reaction rates. Previous studies lack documentation on the origin of the reaction rates, but have apparently extensively used old and unreliable prescriptions to estimate many of them. A detailed analysis of all
Figure 3. Abundances of $^4\text{He}$ (mass fraction), D, $^3\text{He}$ and $^7\text{Li}$ (by number relative to H) as a function of the baryon over photon ratio $\eta$ (or $\Omega_b h^2$.) showing the effect of nuclear uncertainties [31]. The vertical stripe corresponds to the WMAP baryonic density [5] while the horizontal area represent the adopted primordial abundances (dotted lines those adopted in CV10 [31]). The dashed curves represent previous calculations [29] before the re-evaluation [25] of the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ rate. The dot-dashed lines corresponds, to 4 effective neutrino families.
reaction rates and associated uncertainties would be desirable but is impractical for a network of ≈400 reactions. So we first performed a sensitivity study to identify the most important reactions, followed by dedicated re-evaluations. For this purpose, we used, as a first guess, the more reliable reaction rate estimates provided by the TALYS code [36].

3.1. Sensitivity study

To extend our BBN network, we need the neutron, proton, deuterium, tritium, 3He and α-particle capture cross sections on targets in the A=1 to 20 range. As a first approximation, we used the results from TALYS for rates that are not available in the literature (the full list of references can be found in Ref. [37]). By comparing TALYS results with experimentally determined reaction rates [38, 39], we observed that, even for very light elements like Li, TALYS globally provides predictions, "accurate" within 3 orders of magnitude, in the temperature range of interest here. Hence variations of these theoretical rates by up to three orders of magnitude can in a first step be used in our sensitivity analysis. Sensitivity studies have already been performed for the reactions involved in 4He, D, 3He and 7Li production [40, 41, 29] but here, we will concentrate on the C, N and O isotopes production. To estimate the impact of the reaction rate uncertainties on Standard Big Bang Nucleosynthesis, we perform for each reaction six additional calculations, changing its rate by factors of 0.001, 0.01, 0.1, 10, 100 and 1000, and calculate the relative change in CNO abundances. (Mass fractions of isotopes with A ≥ 12 are added together into CNO.) Tables 3 to 6 display, for each reaction, the fractional change in CNO abundances, and the reference for the origin of the reaction rate used for the sensitivity study (the TALYS rates are available electronically [42]); i.e. before reaction rate re-evaluation (next section).

| Reaction | Factors | Fractional change in CNO | Ref. |
|----------|---------|--------------------------|------|
| 4Li(d,γ)8Be | 1.00 | 1.00 | 1.00 | 1.11 | 2.10 | TALYS |
| 7Li(d,n)2α | 1.66 | 1.65 | 1.55 | 0.28 | 0.06 | 0.02 | [43] |
| 7Li(t,n)9Be | 0.99 | 0.99 | 0.99 | 1.10 | 2.14 | 11.7 | [44] |
| 7Li(t,2n)2α | 1.00 | 1.00 | 1.00 | 0.99 | 0.91 | 0.53 | [45] |
| 8Li(n,γ)9Li | 1.00 | 1.00 | 1.00 | 1.01 | 1.06 | 1.62 | [46] |
| 8Li(t,n)10Be | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 | 1.23 | TALYS |
| 8Li(α,γ)12B | 1.00 | 1.00 | 1.00 | 1.01 | 1.11 | 2.15 | TALYS |
| 8Li(α,n)11B | 0.89 | 0.89 | 0.90 | 1.97 | 11.2 | 78.1 | [47] |
| 9Li(α,n)12B | 1.00 | 1.00 | 1.00 | 1.01 | 1.08 | 1.73 | TALYS |
| 10Be(α,n)13C | 1.00 | 1.00 | 1.00 | 1.03 | 1.28 | TALYS |
| 11B(n,γ)12B | 0.91 | 0.91 | 0.92 | 1.81 | 9.91 | 87.7 | [46] |
| 11B(d,n)12C | 0.70 | 0.71 | 0.73 | 3.67 | 30.2 | 280. | TALYS |
| 11B(d,p)12B | 0.99 | 0.99 | 0.99 | 1.08 | 1.83 | 9.33 | TALYS |
| 11B(t,n)13C | 1.00 | 1.00 | 1.00 | 1.01 | 1.12 | 2.17 | TALYS |
| 11C(n,γ)12C | 1.00 | 1.00 | 1.00 | 1.01 | 1.08 | 1.75 | [46] |
| 11C(d,p)12C | 0.99 | 0.99 | 0.99 | 1.05 | 1.55 | 5.67 | TALYS |
| 12C(t,α)11B | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.75 | TALYS |
| 13C(d,α)11B | 1.00 | 1.00 | 1.00 | 0.96 | 0.84 | 0.75 | TALYS |

Table 3. Sensitivity of the most important reactions for CNO production in BBN, to reaction rate variations around initial test rates from references (last column).
The examination of Table 3 shows that, among the ≈400, only a few reactions have a strong impact on the CNO final abundance. The CNO production is significantly sensitive (more than by a factor of about 2) to several reaction rates. In particular, these include: $^7$Li(d,n)$^4$He, $^7$Li(t,n)$^9$Be, $^8$Li(α,n)$^{11}$B, $^{11}$B(n,γ)$^{12}$C, $^{11}$B(d,n)$^{12}$C, $^{11}$B(d,p)$^{12}$B and $^{11}$C(d,p)$^{12}$C. The impact of $^7$Li(d,n)$^2^4$He is unexpected and should be compared to the influence of $^1$H(n,γ)$^2$H on $^7$Li (see [22]). Indeed, when increasing the $^7$Li(d,n)$^2^4$He reaction rate by a factor of 1000, even though the $^4$He, D, $^3$He and $^7$Li final abundances are left unchanged, the peak $^7$Li abundance at $t \approx 200$ s is reduced by a factor of about 100 (see Fig. 15 in [37]), an evolution followed by $^8$Li and CNO isotopes. From this table, we can deduce that the main nuclear paths to CNO (see also [33]) proceeds from the $^7$Li(α,γ)$^{11}$B reaction followed by $^{11}$B(p,γ)$^{12}$C, $^{11}$B(d,n)$^{12}$C, $^{11}$B(d,p)$^{12}$B and $^{11}$B(n,γ)$^{12}$B reactions. Another nucleosynthesis path starts with $^7$Li(n,γ)$^8$Li(α,n)$^{11}$B. (Note that primordial $^{11}$B is produced by a different path: the late decay of $^{11}$C.)

The examination of Tables 4 to 6 show that the most important reactions for $^6$Li, $^9$Be and $^{11}$B productions are $^4$He(d,γ)$^6$Li, $^7$Li(t,n)$^9$Be, $^7$Be(t,p)$^9$Be, $^7$Li(γ)$^9$Be and $^{11}$C(n,α)2α. However, some of them have been measured ($^4$He(d,γ)$^6$Li [49] and $^7$Li(t,n)$^9$Be [44, 51]) so that the uncertainties on their cross sections are small compared to the range explored in this sensitivity study. Considering the tiny production of these isotopes in Standard BBN (next section), compared to present day observational techniques, these uncertainties are not important.

Our sensitivity study, with the extended network, also included $^4$He, D, $^3$He and $^7$Li but no new important reaction was found besides those previously identified [29, 41], essentially the $^7$Be(d,p)2α reaction. Indeed, if this reaction rate were higher by a factor of ~100, $^7$Li abundance would be brought down to the observed level [29]. An experiment, performed at Louvain-la-
Figure 4. Abundances in number of atoms relative to H for $^6$Li, $^9$Be, $^{10}$B, $^{11}$B and CNO isotopes. For CNO, the hatched area represent the present estimated uncertainty. For $^6$Li, the dotted lines shows the uncertainty related to the $^4$He(d,$\gamma$)$^6$Li reaction before the GSI experiment [49] (solid line )and the hatched area shows the most significant $^6$Li detection in HD 84937 star [60, 9].
Neuve did not find such an enhancement in the cross-section \textit{integrated over} the Gamow window [52]. Afterwards, Cyburt & Pospelov [53] proposed a resonance enhancement of the cross section that could have been left undetected by this experiment. Later, a dedicated experiment at Oak Ridge [54] did not find such a resonance, in the $^7\text{Be}+d$ channel. Then, Kirsebom & Davids [55] pointed out that the properties of the corresponding $^9\text{B}$ level had been measured [56]. When used in the reaction rate and subsequent BBN calculation, the $^7\text{Li}$ depletion was found insignificant [55] (<4%). The $^7\text{Be}+^3\text{He}$ channel was found promising by Chakraborty et al. [57] since the spectroscopy of the compound nucleus $^{10}\text{C}$ is deficient in the Gamow window. But as in the $^7\text{Be}+d$ channel, the required level properties are at the fringe of standard nuclear physics, as shown by Broggini et al. [58]. In addition, “missing” $^{10}\text{C}$ levels, were not found in a dedicated experiment, recently carried out in Orsay [59]. It seems, then that the possibility of a nuclear solution to the lithium problem, has been ruled out.

3.2. Results

For the few reactions that were identified to have an impact on Standard Big Bang Nucleosynthesis, we (re-)evaluated the rates issued from TALYS, or other sources whose references are listed in the last columns of Table 3 to Table 6. We were able to collect sufficient experimental data, or theoretical constraints, to derive new reaction rates with associated uncertainties, much reduced with respect to our initial three orders of magnitude variation. In some cases these new rates differ from the previous ones by large factors but changes compensate each other (e.g. $^{11}\text{B}(d,n)^{12}\text{C}$ and $^{11}\text{B}(d,p)^{12}\text{B}$). In the meantime, the important $^8\text{Li}(\alpha,n)^{11}\text{B}$ reaction rate, was independently re-evaluated by La Cognata & Del Zoppo [61], but it affects CNO production by less than 2%\textsuperscript{2}, when compared to our own re-evaluation. We hence confirm that the CNO Standard Big Bang Nucleosynthesis production is CNO/H $\approx 0.7 \times 10^{-15}$ (number of atoms relative to H). Our present analysis does not allow us to precisely quantify the uncertainty on this result, but from the inspection of Table 3, and assuming a factor of ten uncertainty on the re-evaluated reaction rates, we can estimate the range of CNO/H values to $(0.5 – 3.) \times 10^{-15}$. These results are consistent with those of Iocco et al. [33] but slightly lower than those of Vonlanthen et al. [62]. Detailed CNO, B and Be isotopic abundances, compared with those from Iocco et al. [33] can be found in Table 7, together with H, He and Li isotopic abundances compared with our previous work. As expected, the extension of the network does not alleviate the $^7\text{Li}$ discrepancy between calculations and observations. No uncertainty is available yet for the extended network result but, for $^4\text{He}$, D, $^3\text{He}$ and $^7\text{Li}$, they are within the reduced network uncertainties [31]. The differences in the central values are essentially caused by the small evolution of the baryonic density, following the progress in WMAP data reduction over the years.

For $^6\text{Li}$, now that an increased $^2\text{H}(\alpha,\gamma)^6\text{Li}$ cross section is excluded[49], the BBN $^6\text{Li}$ yield ($^6\text{Li}/\text{H} \approx 10^{-14}$) at WMAP baryonic density is about two orders of magnitude below the reported observations in some halo stars, that nevertheless have to be confirmed.

The CNO Standard Big Bang Nucleosynthesis production is found to be little sensitive to the baryonic density of the Universe as shown on Figure 4 where the $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$ and $^{11}\text{B}$ abundances, results of our calculations, are also depicted. Even when considering our estimated uncertainty, the primordial CNO abundance is too low to have an impact on Pop III stellar evolution. Those first stars having high masses and consequently short lifetimes are not observed today. The high C and O abundances observed in extremely low metallicity Pop II stars are expected to have been synthesized by massive Pop III stars making the determination of primordial CNO abundances from observations presently out of reach.

\textsuperscript{2} 1.4% indeed, and not a factor of 1.4 (a typo in [37]).
Table 7. Primordial abundances at (slightly evolving) WMAP baryonic density, with an extended network and after reaction rate re-evaluations, compared to previous works.

|              | CV10 [31]       | CGXSV [37]    |
|--------------|----------------|---------------|
| $Y_p$        | 0.2476±0.0004  | 0.2476        |
| D/H ($\times 10^{-5}$) | 2.68 ± 0.15  | 2.59          |
| $^3$He/H ($\times 10^{-5}$) | 1.05±0.04  | 1.04          |
| $^7$Li/H ($\times 10^{-10}$) | 5.14±0.50  | 5.24          |
| $^6$Li/H ($\times 10^{-14}$) | 1.3[49]  | 1.23          |
| $^9$Be/H ($\times 10^{-19}$) | 2.5   | 9.60          |
| $^{10}$B/H ($\times 10^{-21}$) | 3.00  |               |
| $^{11}$B/H ($\times 10^{-16}$) | 3.9   | 3.05          |
| $^{12}$C/H ($\times 10^{-16}$) | 4.6   | 5.34          |
| $^{13}$C/H ($\times 10^{-16}$) | 0.90  | 1.41          |
| $^{14}$C/H ($\times 10^{-21}$) | 13000. | 1.62          |
| $^{14}$N/H ($\times 10^{-17}$) | 3.7   | 6.76          |
| $^{15}$N/H ($\times 10^{-20}$) | 2.25  |               |
| $^{16}$O/H ($\times 10^{-20}$) | 2.7   | 9.13          |
| CNO/H ($\times 10^{-16}$) | 6.00  | 7.43          |

4. Conclusions

The baryonic density of the Universe as determined by the analysis of the CMB anisotropies is in very good agreement with Standard BBN compared to D primordial abundance deduced from cosmological cloud observations. However, it disagrees with lithium observations in halo stars by a factor that has increased with the availability of improved nuclear data and astronomical observations. Presently, the favored explanation is lithium stellar depletion, but the larger needed depletion factor is hardly compatible with the thin observed plateau. It is hence essential to determine precisely the absolute cross sections important for $^7$Li nucleosynthesis (Table 1).

Nevertheless, primordial nucleosynthesis remains an invaluable tool for probing the physics of the early Universe. When we look back in time, it is the ultimate process for which we, a priori, know all the physics involved. Hence, departure from its predictions provide hints for new physics or astrophysics. Gravity could differ from its general relativistic description, for instance a scalar field, in addition to the tensor field of general relativity (GR), appears naturally in superstring theories. That would affect the rate of expansion of the universe and hence BBN (see [64] and Ref. [63] for a review). Coupled variation of the fundamental couplings is also motivated by superstring theories (see Ref. [65] for a review). However, the impact of these variations on the nuclear reaction rates is difficult to estimate, as in general, nuclear physics uses phenomenological models, whose parameters are not explicitly linked to fundamental constants. The decay of a massive particle during or after BBN could affect the light element abundances and potentially lower the $^7$Li abundance (see e.g. [66]). Negatively charged relic particle, like the supersymmetric partner of the tau lepton, could form bound states with nuclei, lowering the Coulomb barrier and hence leading to the catalysis of nuclear reactions (see e.g. [67, 68]). Annihilation of dark matter during BBN, e.g. injecting extra neutrons, could also modify the primordial abundances [69, 70].

We have extended our network up to the CNO region and performed a sensitivity study to identify the few reactions that could affect the $A\geq7$ isotope yields and re-evaluated their rates. The CNO isotope production was found to be in the range $\text{CNO/H} = (0.5 - 3.) \times 10^{-15}$, not sufficient to have an impact on the evolution of the first stars. It is nevertheless a reference
value for comparison with non-Standard Big Bang Nucleosynthesis CNO production e.g. in the context of varying constants. In this particular case, even with a faster triple–alpha reaction rate or a stable \(^{8}\)Be, the C(NO) production remains \(\approx 6\) order of magnitude [37] lower than the Standard Big Bang Nucleosynthesis value reported here.

Last but not least, we stress here the importance of sensitivity studies in nuclear astrophysics that have been done, e.g. in the context of novae [71], X–ray burst [72] or massive stars [73]. Even in the simpler context of BBN without the complexity (e.g. mixing) of stellar nucleosynthesis, it would have been very unlikely to predict the influence of the \(^{1}\)H(n,\(\gamma\))\(^{2}\)H reaction on \(^{7}\)Li nor of the \(^{7}\)Li(d,n)\(^{2}\)He reaction on CNO.

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References
[1] Wagoner R V 1973 Astrophys. J. 179 343–60
[2] Yang J, Schramm D, Steigman G and Rood R T 1979 Astrophys. J. 227 697–704
[3] The ALEPH Collaboration and The DELPHI Collaboration and the L3 Collaboration and The OPAL collaboration and The SLD Collaboration and the LEP Electroweak Working Group and the SLD Electroweak and Heavy Flavour Groups, 2006 Phys. Rep. 427 257
[4] Wietfeldt F E and Greene G L 2011 Rev. Mod. Phys. 83 1173– 92
[5] Komatsu E et al. [WMAP Collaboration] 2011 Astrophys. J. Supp. 192 18–47 (Preprint astro-ph/1001.4538)
[6] Spite F and Spite M 1982 Astron. Astrophys. 115 357
[7] Shordone L et al., 2010 à 522 26
[8] Asplund M, Lambert D L, Nissen P E, Primas F & Smith V V 2006 Astrophys. J. 644 220
[9] Steffen M, Cayrel R, Caffau E, Bonifacio P, Ludwig H G and Spite M 2012, Proc. “Lithium in the Cosmos” (Paris), Mem. S.A.R. 75 282 (Preprint astro-ph/1206.2239)
[10] Spite F and Spite M Proc. IAU Symposium No. 268, “Light Elements in the Universe” (Geneva), Eds. C. Charbonnel, M. Tosi, F. Primas & C. Chiappini (Cambridge University Press, 2010) p. 221.
[11] Iocco F 2012 Mem. S.A.R. 22 19 Proceedings Lithium in the Cosmos (Paris) (Preprint astro-ph/1206.2396)
[12] Olive K A, Petitjean P, Vangioni E and Silk J 2012 to appear in Mon. Not. R. Astron. Soc. (Preprint astro-ph/1203.5701)
[13] Izotov Y I, Thuan T X and Stasińska G 2007 Astrophys. J. 662 15 (astro-ph/0702072)
[14] Aver E, Olive K A and Skillman E D 2011 JCAP 1103, 043 (astro-ph/1012.2385)
[15] Aver E, Olive K A and Skillman E D 2012 JCAP 1204 004 (astro-ph/1112.3713)
[16] Bania T, Rood R and Balser D 2002 Nature 415 54
[17] Vangioni-Flam E et al. 2003 Astrophys. J. 585 611
[18] Dicus D, Kolb E, Gleeson A, Sudarshan E, Teplitz V and Turner M 1982 Phys. Rev. D 26 2694
[19] Beringer J et al. (Particle Data Group) 2012 Phys. Rev. D 86 010001 (URL: http://pdg.lbl.gov)
[20] Ando S, Cyburt R H, Hong S W and Hyun C H 2006 Phys. Rev. C 74 025809
[21] Descouvemont P, Adahchour A, Angulo C, Coc A and Vangioni-Flam E 2004 Atomic Data and Nuclear Data Tables 88 203
[22] Coc A, Nunes N J, Olive K A, Uzan J-P and E. Vangioni 2007 Phys. Rev. D 76 023511
[23] Brown T A D et al 2007 Phys. Rev. C 76 055801; Confortola F et al 2007 Phys. Rev. C 75 065803; Gyürky G et al 2007 Phys. Rev. C 75 065805; Nara Singh B S et al 2004 Phys. Rev. Lett. 93 262503; Costantini H et al 2008 Nucl. Phys. A 814 144
[24] Di Leva A et al. 2009 Phys. Rev. Lett. 102 232502; erratum Di Leva A et al. 2009 Phys. Rev. Lett. 103 159930
[25] Cyburt R H and Davids B 2008 Phys. Rev. C 78 064614
[26] Nell T 2011 Phys. Rev. Lett. 106 042502
[27] Leonard D S, Karwowski H J, Brune C R, Fisher B M and Ludwig E J 2006 Phys. Rev. C 73 045801
[28] Cyburt R H, Fields B D and Olive K A 2008 JCAP 11 12
[29] Coc A, Vangioni-Flam E, Descouvemont P, Adahchour A and Angulo C 2004 Astrophys. J. 600 544
[30] Ryan S G, Beers T C, Olive K A, Fields B D and Norris J E 2000 Astrophys. J. 530 L57
[31] Coc A and Vangioni E 2010, Journal of Physics Conference Series 202 012001
