Primordial Nucleosynthesis

A Coc

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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 $^4$He, D, $^3$He and $^7$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 For this purpose, it is now superseded by the analysis of the Cosmic Microwave Background (CMB) radiation anisotropies.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 $\approx 3$, between the calculated and observed lithium primordial abundances, that has not been reduced, neither by recent nuclear physics experiments, nor by new observations. 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.

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 comes, indeed, from the primordial abundances of the “light elements”: $^4$He, D, $^3$He and $^7$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. (Besides the $^4$He, D, $^3$He and $^7$Li isotopes, only minute traces of $^6$Li, $^9$Be, $^{11}$B and CNO are produced by BBN.) 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 to 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 $\Omega_B h^2 = 3.65 \times 10^7 \eta$ with

$$\Omega_B h^2 = 0.02249 \pm 0.00062 \text{ and } \Omega_B = 0.04455 \pm 0.0027$$ (1)
 (“WMAP only Seven Year Mean” [5]) or

\[ \Omega_b h^2 = 0.00207 \pm 0.00033 \]  

(2)

according to the first release of the Planck mission collaboration [6]. The parameter \( h \) represents the Hubble constant \( (H_0) \) in units of 100 km/s/Mpc and \( \Omega_b \), the baryonic density relative to the critical density. These results are just slightly above the range of baryonic density provided by Wagoner [1] from BBN 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, \textit{a priori}, we know all the physics involved. Hence, departure from its predictions could provide hints or constraints on new physics or astrophysics.

2. The “light elements”: \( ^4\text{He}, \, ^3\text{He} \) and \( ^7\text{Li} \)

2.1. Abundances of the light 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 \textit{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 to extract them from observations of astrophysical sites which are thought to be non evolved and possibly 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 [7]. 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 [8] of:

\[ \text{Li/H} = (1.58 \pm 0.31) \times 10^{-10}. \]  

(3)

Note also that, observationally challenging, detections of \(^6\text{Li}\) had been reported [9] to a level of \( \sim 10^{-2} \) below the Spite plateau value, several orders of magnitude below the BBN predictions [10]. But the presence of a \(^6\text{Li}\) plateau is now excluded after improved modeling (now including 3-dimensions and non-local thermodynamic equilibrium) of these star atmospheres [11].

Contrary to \(^7\text{Li}\) 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:

\[ \text{D/H} = (3.02 \pm 0.23) \times 10^{-5}. \]  

(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] that:

$$Y_p = 0.2534 \pm 0.0083.$$  \hfill (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 [15]:

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

Consequently, comparison with $^3$He abundance from BBN is subject to caution [16].

### 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 (a few 100 keV). There are $\approx$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 (e.g. $^3$H(d,n)$^4$He and $^3$H(α,γ)$^7$Li) are now irrelevant at WMAP baryonic density. This can be deduced from the inspection of Table 1 of Ref. [17] which displays the sensitivity of the $^4$He, $D$, $^3$He and $^7$Li calculated abundances w.r.t. to a change in the 12 reaction rates by a constant factor.

The weak reactions involved in n→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$^{+0.8}$ 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$^{±1.1}$ s has been proposed [19] and is now used in BBN calculations.

The influence of the $^4$H(n,γ)$^2$H rate was unexpected: $^7$Li final abundance depends strongly on this reaction rate while other isotopes are little affected. Its cross section is obtained from Effective Field Theory whose results are estimated to be reliable to within 1% error [20]. Indeed, the few experimental informations available for this cross section at BBN energies are in very good agreement with theory (see Fig. 1 in Ref. [21]).

For the ten remaining reactions, $^2$H(p,γ)$^3$He, $^2$H(d,n)$^3$He, $^2$H(d,p)$^3$H, $^3$H(d,n)$^4$He, $^3$H(α,γ)$^7$Li, $^3$He(d,p)$^4$He, $^3$He(n,p)$^4$H, $^3$He(α,γ)$^7$Be, $^7$Li(p,α)$^4$He and $^7$Be(n,p)$^7$Li, the cross sections have been measured in the laboratory at the relevant energies. We used the reaction rates from the the evaluation performed by Descouvemont et al [22], supplemented by results from more recent experiments and analysis that have lead to improved reaction rates for a few important reactions.

At CMB deduced baryonic density, $^7$Li is produced indirectly by $^3$He(α,γ)$^7$Be, that will, much later decay to $^7$Li while it is destroyed by $^7$Be(n,p)$^7$Li(p,α)$^4$He. This is the, second to $^4$H(n,γ)$^2$H, most influential reaction for $^7$Li [17] as its final abundance is directly proportional to this rate. Its cross–section has long been a subject of debate because of systematic differences that were found according to the experimental technique: prompt or activation measurements. We refer to Di Leva [23] for a review of the most recent experimental data noting the relative scarcity of experimental data within the Gamow window. We use the Cyburt & Davids [24] calculated the S–factor, incorporating new data, which is significantly higher than the Descouvemont et al [22] R–matrix fit.
The $^2\text{H}(\text{d},\text{n})^3\text{He}$ reaction, also influential on $^7\text{Li}$, was re-measured [together with $^2\text{H}(\text{d},\text{p})^3\text{H}$] by Leonard et al [25], after the R-matrix analysis [22] was performed. The very precisely measured cross section is in perfect agreement with the R-matrix fit (see also [26]).

2.3. BBN primordial abundances compared to observations

Figure 1 shows the up to date abundances of $^4\text{He}$ (mass fraction), D, $^3\text{He}$ and $^7\text{Li}$ (in number of atoms relative to H) as a function of the baryonic density. The thicknesses of the curves reflect the nuclear uncertainties, obtained by a Monte-Carlo calculation using for the nuclear rates discussed in § 2.2. The horizontal lines represent the limits on the $^4\text{He}$, D and $^7\text{Li}$ primordial abundances deduced from spectroscopic observations § 2.1. The vertical stripes represent the baryonic density deduced from CMB observations [5, 6]. The concordance between BBN and observations is in good agreement for deuterium. Considering the large uncertainty associated with $^4\text{He}$ observations, the agreement with CMB+BBN is fair, but close to the observational lower limit. The calculated $^3\text{He}$ value is close to its galactic value showing that its abundance has little changed during galactic chemical evolution. On the contrary, the $^7\text{Li}$, CMB+BBN calculated abundance is significantly higher than the spectroscopic observations. Table 1 displays the corresponding numerical values deduced from the Monte–Carlo, at CMB deduced baryonic density, compared with those deduced from spectroscopic observations (§ 2.1). It emphasize the discrepancy of a factor of $\approx 3$ between lithium abundances deduced either from CMB+BBN or from spectroscopic observations. Table 1 shows that these results are stable when comparing the most recent result [27] with earlier work [17]. The small differences can be traced [27] to the evolutions of the baryonic density from the early WMAP results to the Planck ones, of the neutron lifetime and to the extension of the network.

The lithium discrepancy, has not yet found a satisfactory answer, and somewhat weakens the ability to use BBN as a probe of fundamental physics in the early Universe. Several ideas were addressed to try to explain this $^7\text{Li}$ problem. Some conceived the idea that the $^7\text{Li}$ deficit points toward physics beyond standard model such as decay of super-symmetric particles, mirror universe,... etc [28]. Others have suggested that the problem could due to $^7\text{Li}$ stellar destruction in the atmosphere of the halo stars [29] but a uniform destruction of $^7\text{Li}$ over the Spite-plateau region seems difficult. For a recent review of the latest Li observations and their different astrophysical aspects, see Refs. [30, 31, 32], and the proceedings of the 2012 Workshop Lithium in the Cosmos 1.

| Table 1. Primordial abundances. |
|----------------------------------|
|                                  |
|                                | [17]          | [27]          | Observations |
| $Y_p$                           | 0.2476±0.0004 | 0.2463±0.0003 | 0.2534 ± 0.0083 [14] |
| D/H ($\times 10^{-5}$)           | 2.68 ± 0.15   | 2.67±0.09     | 3.02 ± 0.23 [12]   |
| $^3\text{He}/\text{H}$ ($\times 10^{-5}$) | 1.05±0.04     | 1.05±0.03     | 1.1 ± 0.2 [15]     |
| $^7\text{Li}/\text{H}$ ($\times 10^{-10}$) | 5.14±0.50     | 4.89±0.41     | 1.58 ± 0.31 [8]    |

3. BBN with an extended network

3.1. Motivations and method

There are several reasons to increase the BBN network beyond the twelve or so “main reactions”.

1 http://www.iap.fr/lithiuminthecosmos2012/index.html, proceedings in Mem. S.A.It. 2012 22
Figure 1. 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 $\Omega_b h^2$). The vertical stripe corresponds to the Planck baryonic density [6] (dotted lines are from WMAP [5]) while the horizontal area represent the adopted primordial abundances.
First of all one needs to definitively exclude a direct or indirect “nuclear solution” to the lithium problem. A direct solution would be the destruction of $^7$Be (the $^7$Li progenitor) by a reaction that was not previously included in the network. An indirect one would be, again a previously neglected reaction, but that would modify the neutron abundance near the end of BBN. This is indeed the explanation for the unexpected effect of a lower $^1$H(n,$\gamma$)$^2$H rate (§ 2.2) that can be traced to the increased neutron abundance at $^7$Be formation time making its destruction by neutron capture, $^7$Be(n,p)$^7$Li(p,$\alpha$)$^4$He, more efficient (see Fig. 1 in [33]). Second, it allows to calculate the tiny BBN production of $^6$Li, $^9$Be and $^{11}$B, even though their direct detections seem highly unlikely with the present observational techniques. Third, hydrogen burning in the first generation of stars (“Population III”) proceeds through the slow p–p chains until they produce enough carbon, by the triple-alpha reaction, to activate the CNO cycle so that CNO production by BBN could affect their evolution.

The main difficulty in BBN calculations up to CNO is the extensive network needed, including n-, p-, $\alpha$-, but also d-, t- and $^3$He-induced reactions on targets in the A=1 to 20 range. 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. $^{10}$Be. A detailed analysis of all reaction rates and associated uncertainties would be desirable but is impractical for a network of $\approx$400 reactions. In a recent analysis [34], as a first approximation, the results from the TALYS code [35] were used, for rates that are not available in the literature, followed by sensitivity tests allowing each rate to be scaled by 0.01, 0.1, 10, 100 and 1000 factors and for the most influential reactions, was followed by dedicated rate re-evaluations.

3.2. Reactions that affect $^7$Li production

No new important reaction for $^7$Li+$^7$Be production was found besides those previously identified [36, 37]: essentially the $^7$Be(d,p)$2\alpha$ reaction. Indeed, if this reaction rate were significantly higher, $^7$Li abundance would be brought down to the observed level [36, 38]. However, subsequent experiments and analyses [39, 40, 41] ruled out this possibility [42].

Extending this search, very recent works [43, 44, 45] suggested the possibility of overlooked resonances in nuclear reactions involving $^7$Be. The most promising candidates were found to be in the $^7$Be+$^3$He→$^{10}$C [43], and $^7$Be+$^4$He→$^{11}$C [44, 45] channels. Indeed, the presence of a level close to the $^7$Be+$^3$He reaction threshold (Q=15.003 MeV) in $^{10}$C [43], or between 7.793 and 7.8936 MeV excitation energy in $^{11}$C [45] with favorable properties would help alleviate the lithium problem. However, a recent experiment was conducted at the Tandem of the Orsay ALTO facility to improve the $^{10}$C and $^{11}$C spectroscopy. The $^{10}$B($^3$He,t)$^{10}$C and $^{11}$B($^3$He,t)$^{11}$C reactions were investigated at a $^3$He beam energy of 35 MeV and the tritons analyzed by the Split-pole magnet. Only upper limits for the presence of new levels in $^{10}$C and $^{11}$C were obtained, too low to have an impact on $^7$Li production [46].

3.3. Reactions that affect $^6$Li, $^9$Be and $^{11}$B production

The most important reactions for $^6$Li, $^9$Be and $^{11}$B productions are $^4$He(d,$\gamma$)$^6$Li, $^7$Li(t,n)$^9$Be, $^7$Be(t,p)$^9$Be, $^7$Li(d,$\gamma$)$^9$Be and $^{11}$C(n,$\alpha$)$2\alpha$. However, some of them have been measured ($^4$He(d,$\gamma$)$^6$Li [10] and $^7$Li(t,n)$^9$Be [47, 48]) so that the uncertainties on their cross sections are small compared to the range explored in this sensitivity study. The BBN $^6$Li yield ($^6$Li/H≈10$^{-14}$) at CMB deduced baryonic density is about two orders of magnitude below the previously reported observations in some halo stars, that nevertheless were not confirmed.
3.4. Reactions that affect CNO production

The minimum value of the initial CNO abundance that would affect Population III stellar evolution is estimated to be as low as $10^{-13}$ (in number of atoms relative to hydrogen, CNO/H) for the less massive ones [49]. 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 [50]. Among the ≈400, only a few reactions were found to 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)$^4$He is unexpected and should be compared to the influence of $^1$H(n,$γ$)$^2$H on $^7$Li. Indeed, when increasing the $^7$Li(d,n)$^4$He reaction rate from [51] 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 [34]), an evolution followed by $^8$Li and CNO isotopes. Finally, the CNO Standard Big Bang Nucleosynthesis production is CNO/H $(0.5−3.3) \times 10^{-15}$ (with estimated uncertainties). These results are consistent with those of Iocco et al [50] and are too low to have an impact on Population III stellar evolution.

4. Some extensions of BBN

There are many extensions of the Standard Model of BBN and we refer to Iocco et al. [52] for an extensive review and to Fields [28] for non–Standard BBN solutions to the lithium problem. Note that these solutions quite systematically lead to an increased D production which is easier to cure than the lithium overproduction [12]. We will limit ourselves here in a few examples where nuclear physics is important.

4.1. Variation of constants

The possibility of the variation of “constants” is a key issue of modern physics (see Ref. [53] for a review). It is motivated by superstring theories and by observations of a possible [54, 55] variation of the fine structure constant in clouds at high redshift, on the line of sight of more distant quasars. Other tests of the variation of constants involve atomic clocks, the CMB and nuclear physics (Big Bang Nucleosynthesis, the triple–alpha reaction and stellar evolution, radioactivities in meteorites and the Oklo fossil reactor). They are all interesting because they probe variations on different cosmic time scale, BBN being the earliest one [56, 57, 58]. However, the impact of these variations on the (BBN) nuclear reaction rates is difficult to estimate, as in general, nuclear physics uses phenomenological models, whose parameters are not explicitly linked to fundamental constants. Key nuclear reactions, whose rate variations would be influential, in this context, are $n\leftrightarrow p$ (affecting $^4$He) and $n+p\rightarrow d+γ$ (affecting $^4$He, D, and strongly $^7$Li) but we will illustrate our purpose with the triple–alpha reaction: $^4$He($α,γ$)$^8$Be($α,γ$)$^{12}$C. Here, $^8$Be is normally slightly unbound and very short lived, acting as an intermediate state an the rate is boosted by the presence of a resonant (“Hoyle”) state in $^{12}$C. If constants were slightly different at BBN epoch, the rate would be much different because of the new position of the Hoyle state changes and even $^8$Be could become stable [59]. According to textbooks, a stable $^8$Be would allow the build–up of heavy elements, but this is not the case (Fig. 2): the C(NO) production remains ≈6 order of magnitude [34] lower than the Standard Big Bang Nucleosynthesis value (§ 3.4).
Figure 2. Left panel: the standard network up to \( A=7 \) (blue), \( A=12 \) (black) with in addition, the triple–alpha reaction (red). Right panel: \(^{12}\text{C}\) (solid black) and \(^{8}\text{Be}\) (red) mass fractions as a function of time, assuming \(^{8}\text{Be}\) is bound by 100, 50 and 10 keV (dotted lines correspond to thermal equilibrium) [57] compared to Standard BBN \(^{12}\text{C}\) production (dash) [34].

4.2. Exotic particles

There are various way, in which exotic particles can influence BBN [52]. The decay of a massive particle during or after BBN could affect the light element abundances and potentially lower the \(^7\text{Li}\) abundance (see e.g. [60]). Neutrons, protons or photons produced by these decays may be thermalized but more likely have a non-thermal high energy (\(\sim 1\) GeV) distributions. Interestingly, some nuclear cross–sections involved in these non-thermal processes are not known with a sufficient precision [61]. If they can be thermalized, it provides an extra source of neutrons that can alleviate the lithium problem [62, 63] as proposed in § 3. An other exotic source of thermalized neutrons could come from a “mirror world” [64] initially proposed to restore global parity symmetry. Long lived (relative to BBN time scale) negatively charged relic particles, 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. [65, 66, 67]). Even though exotics, the interaction of these electromagnetically bound states with other nuclei can be treated by conventional nuclear physics theory.

5. 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 and \(^4\text{He}\) primordial abundance deduced from 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. A possible 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 \(^7\text{Li}\) nucleosynthesis.
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.

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 [68], X–ray burst [69] or massive stars [70]. 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)$^4$He reaction on CNO.

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