

## PRIMORDIAL NUCLEOSYNTHESIS\*

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Primordial Nucleosynthesis, or Big-Bang Nucleosynthesis (BBN), is one of the three items of evidence 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 For this purpose, it is now superseded by the analysis of the Cosmic Microwave Background (CMB) radiation anisotropies.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 remains, 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.

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## 1. Introduction

There are presently three items of evidence for the Big-Bang Model: the universal expansion, the Cosmic Microwave Background (CMB) radiation and Primordial or Big-Bang Nucleosynthesis (BBN). This third evidence comes from the primordial abundances of the “light elements”:  $^4\text{He}$ , D,  $^3\text{He}$  and  $^7\text{Li}$  which were produced during the first  $\approx 20$  minutes of the Universe. Their calculated abundances can be compared to those deduced from 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,  $\rho_B = (1 - 3) \times 10^{-31} \text{ g/cm}^3$  [1], and to first give an upper limit on the number neutrino families  $N_\nu \leq 3$  [2],

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in both cases 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 (normalized to the experimental value for the lifetime of the neutron). 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  $\Omega_b = 3.65 \times 10^{-7} \eta$  with  $\Omega_b h^2 = 0.02249 \pm 0.00062$  (“WMAP only Seven Year Mean” [4]). The parameter  $h$  represents the Hubble constant in units of 100 km/s/Mpc and  $\Omega_b$  is the baryonic density relative to the *critical density*, which corresponds to a flat (*i.e.* Euclidean) space. This results in a baryonic density which is just slightly above the range were 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 appear 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  $\text{D}$ , 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.

## 2. Primordial abundances from observations

During the evolution of the Galaxy, complex nucleosynthesis takes place, mainly in massive stars which release matter enriched in heavy elements (globally called “metals”) into the interstellar medium when they explode as supernovae. 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 [5]. This constant Li abundance is interpreted as corresponding to the BBN  $^7\text{Li}$  yield. Astronomical observations of metal poor halo stars have led to a relative primordial abundance [6] of

$$\text{Li}/\text{H} = (1.58 \pm 0.31) \times 10^{-10}. \quad (1)$$

Deuterium 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 [7] (and references therein) of this data yields a D/H abundance of

$$\text{D/H} = (3.02 \pm 0.23) \times 10^{-5}. \quad (2)$$

After BBN,  ${}^4\text{He}$  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. Using the data compiled in Ref. [8], it was found [9] that

$$Y_p = 0.2534 \pm 0.0083. \quad (3)$$

Contrary to  ${}^4\text{He}$ ,  ${}^3\text{He}$  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 [10]. Consequently, comparison with  ${}^3\text{He}$  abundance from BBN is subject to caution.

### 3. Nuclear reactions

Unlike 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  ${}^4\text{He}$ , D,  ${}^3\text{He}$  and  ${}^7\text{Li}$  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.

The weak reactions involved in  $n \leftrightarrow p$  equilibrium are an exception; their rates [11] come from the standard theory of the weak interaction, normalized to the experimental neutron lifetime. While it has not yet been possible to solve the discrepancy on its precise value [12], a reevaluation of the recommended value:  $880.1 \pm 1.1$  s has been proposed [13], awaiting experimental confirmation. The  ${}^1\text{H}(n, \gamma)\text{D}$  cross section is also obtained from theory [14] but in the framework of Effective Field Theory. For the ten remaining reactions,  ${}^2\text{H}(p, \gamma){}^3\text{He}$ ,  ${}^2\text{H}(d, n){}^3\text{He}$ ,  ${}^2\text{H}(d, p){}^3\text{H}$ ,  ${}^3\text{H}(d, n){}^4\text{He}$ ,  ${}^3\text{H}(\alpha, \gamma){}^7\text{Li}$ ,  ${}^3\text{He}(d, p){}^4\text{He}$ ,  ${}^3\text{He}(n, p){}^3\text{H}$ ,  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ ,  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  and  ${}^7\text{Be}(n, p){}^7\text{Li}$ , the cross sections have been measured in the laboratory at the relevant energies. We use the reaction rates from the evaluation performed by Descouvemont *et al.* [15] updated with the results of a few more recent experiments and analysis.

As we will see in the following, primordial abundances of the light elements are well reproduced by theory, except for  ${}^7\text{Li}$ . Hence, it is essential to scrutinize the nuclear reactions that affect its production or destruction.

(At WMAP baryonic density,  ${}^7\text{Li}$  is produced indirectly by  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ , that will, much later decay to  ${}^7\text{Li}$ .) The sensitivity of the abundances ( $Y_i$  with  $i = {}^4\text{He}$ , D,  ${}^3\text{He}$  and  ${}^7\text{Li}$ ) w.r.t. to a change in the 12 reaction rates by a constant factor have been calculated [18]. The relative uncertainty on  $\tau_n$  only affects  ${}^4\text{He}$  abundance but by a factor of ten lower than the observational uncertainty. The influence of the  ${}^1\text{H}(n, \gamma)\text{D}$  rate was unexpected. The  ${}^7\text{Li}$  final abundance depends strongly on the rate of this reaction while other isotopes are little affected. This effect can be traced to the increased neutron abundance at  ${}^7\text{Be}$  formation time for a low  ${}^1\text{H}(n, \gamma)\text{D}$  rate making its destruction by neutron capture,  ${}^7\text{Be}(n, p){}^7\text{Li}(p, \alpha){}^4\text{He}$ , more efficient (see Fig. 1 in [19]). However, the few experimental informations available for this cross section at BBN energies are in good agreement with the calculations (Fig. 1) estimated to be reliable to within 1% uncertainty [14].

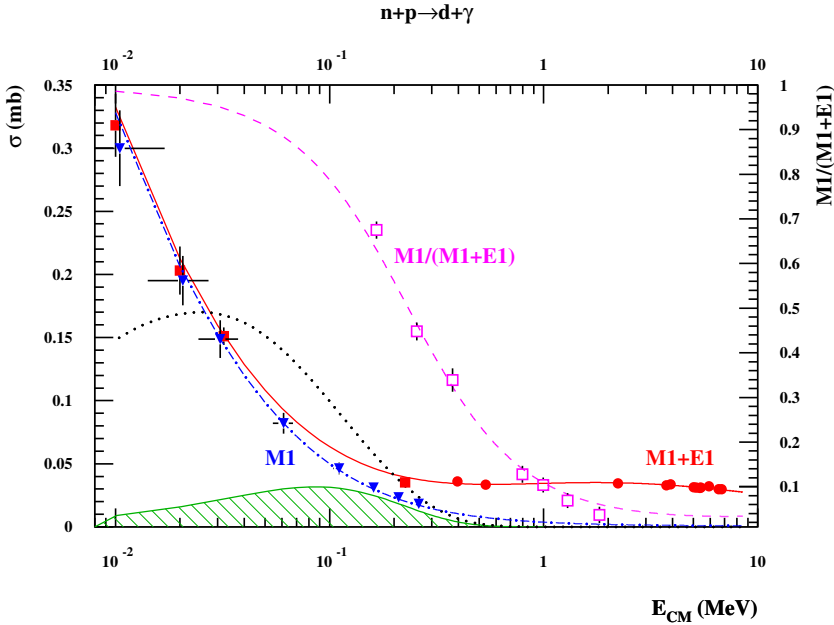


Fig. 1. Comparison between theory [16] and experiments [17] for the  ${}^1\text{H}(n, \gamma)\text{D}$  cross section (left axis) and the  $M1/(M1 + E1)$  ratio (right axis). Dashed area represents the Boltzmann distribution at 1 GK and its product times the cross section reaching a maximum around 20 keV.

The next most important reaction [18] is  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  as it is the path for the formation of  ${}^7\text{Li}$  at WMAP density. Hence, the  ${}^7\text{Li}$  abundance is directly proportional to this rate, which has long been a subject of debate. Systematic differences in the measured cross section were found depending on the experimental technique: prompt or activation measurements. Thanks

to the recent experimental efforts [20], the two methods provide now results in agreement with each other. With this new experimental data, Cyburt and Davids [21] calculated the  $S$ -factor which is significantly higher than the Descouvemont *et al.* [15] R-matrix fit, done before these new data were available. 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.* [22], obtained by a third technique, the recoil mass separation, deviate from both fits (see Ref. [23]). Theoretical explanations are available [24], but this should not affect the  $S$ -factor at BBN energies.

#### 4. BBN primordial abundances compared to observations

Figure 2 shows the 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 thickness of the curves reflect the nuclear uncertainties. They were ob-

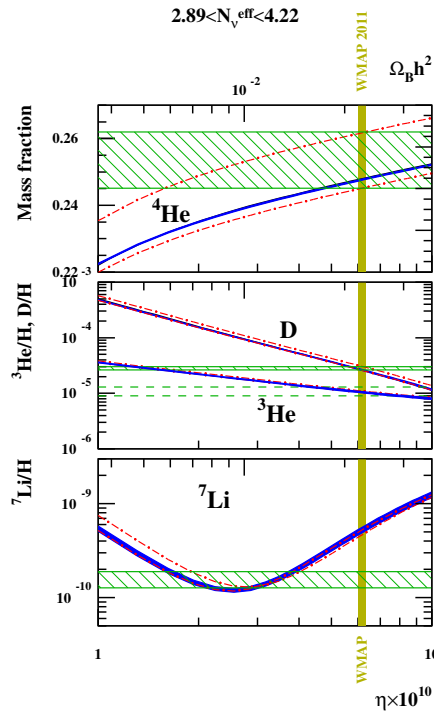


Fig. 2. Abundances of  ${}^4\text{He}$  (mass fraction), D,  ${}^3\text{He}$  and  ${}^7\text{Li}$  (by number relative to H) as a function of the baryon over photon ratio  $\eta$ . Showing the effect of nuclear uncertainties [18]. The dot-dashed lines corresponds to the extreme values of the *effective* neutrino families compatible with  ${}^4\text{He}$  observations.

tained [18] by a Monte-Carlo calculation using for the nuclear rate uncertainties those obtained by [15] with the notable exception of  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  [21] and  ${}^1\text{H}(n, \gamma){}^2\text{H}$  [14] (see Sec. 3). The horizontal lines represent the limits on the  ${}^4\text{He}$ , D,  ${}^3\text{He}$  and  ${}^7\text{Li}$  primordial abundances deduced from spectroscopic observations (see Sec. 2). The vertical stripe represents the baryonic density deduced from CMB observations [4]. The concordance between BBN and observations is in perfect agreement for deuterium. Considering the large uncertainty associated with  ${}^4\text{He}$  observations, the agreement with CMB + BBN is fair. 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 by a factor of  $\approx 3$ .

The origin of this lithium discrepancy remains an open question. One possible explanation is lithium stellar depletion, but the larger needed depletion factor is hardly compatible with the thin observed plateau [25]. New physics solutions to this “lithium problem” include variation of the fundamental couplings, decay of a massive particles during or after BBN, negatively charged relic particle forming bound states with nuclei, ... (see *e.g.* [26] for a review). Note that solutions involving a change in the rate of expansion of the Universe do not help as shown in Fig. 2 as it only significantly affects  ${}^4\text{He}$ . (A change in the expansion rate is simulated by changing the *effective* number of neutrino families within the range  $2.89 < N_{\text{eff}} < 4.22$  allowed by  ${}^4\text{He}$  observations.) In the following section, we will limit ourselves to tentative solutions in the nuclear sector.

## 5. Other nuclear reactions

We have seen (Sec. 3) that, among the 12 main reactions,  ${}^1\text{H}(n, \gamma)\text{D}$  was the most influential on  ${}^7\text{Li}$  production. A reduction of its cross section by 30% around 25 keV, would be needed [19] but this is not allowed by experiment (Fig. 1). The experimental nuclear data concerning the other main reactions (even  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ ) are sufficient to exclude a solution in this sector, so that one has to extend the network to up to now neglected reactions. For instance, it was found [27] that if the  ${}^7\text{Be}(d, p)2\alpha$  reaction rate were higher by a factor of  $\sim 100$ ,  ${}^7\text{Li}$  abundance would be brought down to the observed level [27], but an experiment, performed at Louvain-la-Neuve did not find such an enhancement [28]. Afterwards, Cyburt and Pospelov [29] proposed a resonance enhancement of the cross section that could have been left undetected by this experiment. Later, a dedicated experiment at Oak Ridge [30] did not find such a resonance, in the  ${}^7\text{Be} + d$  channel. Then, Kirsebom and Davids [31] pointed out that the properties of the corresponding  ${}^9\text{B}$  level had been measured [32]. When used in the reaction rate and subsequent BBN calculation, the  ${}^7\text{Li}$  depletion was found

insignificant [31] ( $< 4\%$ ). The  ${}^7\text{Be} + {}^3\text{He}$  channel was found promising by Chakraborty *et al.* [33] 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 Brogini *et al.* [34]. In addition, “missing”  ${}^{10}\text{C}$  levels, were not found in a dedicated experiment, recently carried out in Orsay (F. Hammache, private communication).

However, an other nuclear solution would be a more efficient  ${}^7\text{Be}$  destruction by the  ${}^7\text{Be}(n, p){}^7\text{Li}(p, \alpha){}^4\text{He}$  reaction with an increased late time neutron abundance (see Sec. 3). The neutron over proton number ratio is 0.13 at the onset of nucleosynthesis but it drops by many orders of magnitude when neutrons become trapped in  ${}^4\text{He}$ . As shown in Fig. 3, a constant injection at a rate of a few  $10^{-8} \text{ s}^{-1}$  (of neutron mass fraction) is sufficient to reconcile  ${}^7\text{Li}$  production with observations. It is at the expense of D, whose overproduction can more easily be compensated by destruction, in the course of conventional galactic chemical evolution [7]. If we do not con-

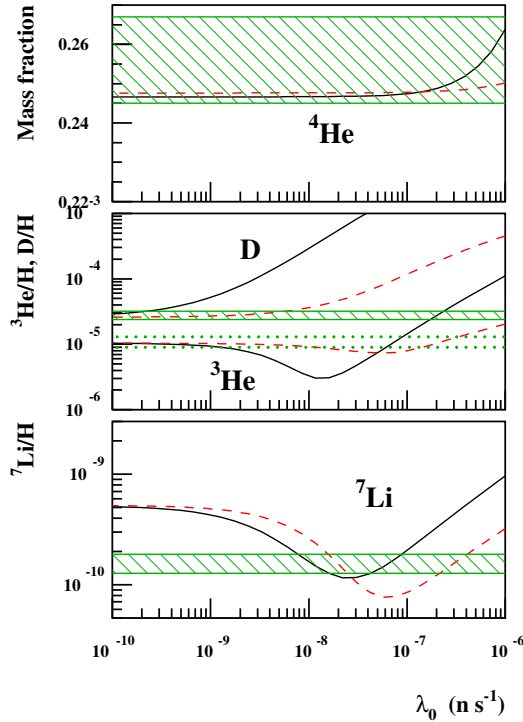


Fig. 3. Abundances as a function of constant neutron injection (solid) or following the decay of non-baryonic dark matter as in Ref. [35] but with a  $\tau_x = 30 \text{ mn}$  decay constant (dashed).

sider here exotic scenarios (*e.g.* dark matter decay [35] also shown in Fig. 3), one would need an extra nuclear reaction that would affect late time neutron abundance like the  ${}^1\text{H}(n, \gamma)\text{D}$  reaction.

This was one of the motivations of our work [36] in which we extended our BBN network to  $\approx 400$  reactions up to CNO, but no extra source of neutron nor new influential reactions on  ${}^7\text{Li}$  production was found. The second motivation was to calculate the CNO production by BBN which was found to be in the range of  $(0.5\text{--}3.) \times 10^{-15}$  (in number of atoms relative to H). This primordial CNO is not sufficient to affect the evolution of the first stars born shortly after the Big Bang. However, surprisingly, we found that CNO production is sensitive to the  ${}^7\text{Li}(d, n){}^24\text{He}$  reaction rate; it can be compared to the unexpected influence of  ${}^1\text{H}(n, \gamma){}^2\text{H}$  on  ${}^7\text{Li}$  (Sec. 3). This is why, even though it seems, that the possibility of a nuclear solution to the lithium problem, has been ruled out, it is worth continuing the search.

## 6. 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,  ${}^4\text{He}$  and  ${}^3\text{He}$  primordial abundances deduced from observations. However, it disagrees with lithium observations in halo stars by a factor of  $\approx 3$ . This *lithium problem* has not found yet a satisfactory solution.

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. Even in the simple context of BBN without the complexity (*e.g.* mixing) of stellar nucleosynthesis, it would have been very unlikely to predict the influence of the  ${}^1\text{H}(n, \gamma){}^2\text{H}$  reaction on  ${}^7\text{Li}$  nor of the  ${}^7\text{Li}(d, n){}^24\text{He}$  reaction on CNO.

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