

Big-Bang Nucleosynthesis with updated nuclear data

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Abstract. Primordial nucleosynthesis 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 ^4He , D , ^3He and ^7Li deduced from observations and calculated 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 For this purpose, it is now superseded by the analysis of the Cosmic Microwave Background (CMB) radiation anisotropies. Big-Bang nucleosynthesis remains, nevertheless, a valuable tool to probe the physics of the early Universe. However, the yet unexplained, discrepancy between the calculated and observed lithium primordial abundances, has not been reduced, neither by recent nuclear physics experiments, nor by new observations.

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 from the primordial abundances of the “light elements”: ^4He , D , ^3He and ^7Li . They are produced during the first ≈ 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. The number of free parameters in Standard BBN have decreased with time. The number of light neutrino families is known from the measurement of the Z^0 width by LEP experiments at CERN: $N_\nu = 2.9840 \pm 0.0082$ [1]. The lifetime of the neutron (entering in weak reaction rate calculations) $\tau_n = 885.7 \pm 0.8$ s [2] and the nuclear reaction rates have been measured in nuclear physics laboratories. The last parameter to have been independently determined is the baryonic density of the Universe, which is now deduced from the observations of the anisotropies of the CMB radiation. It is usual to introduce η , the number of photons per baryon which remains constant during the expansion, and is directly related to Ω_b by $\Omega_b \cdot h^2 = 3.65 \times 10^{-7} \eta$ with $\Omega_b \cdot h^2 = 0.02273 \pm 0.00062$ and $\Omega_b = 0.0441 \pm 0.0030$ (“WMAP only” [15]). The parameter h represents the Hubble constant in units of 100 km/s/Mpc (i.e. $h = 0.719$).

2. Nuclear reactions

Unlike in other sectors of nuclear astrophysics, nuclear cross sections have usually been directly measured at BBN energies (~ 100 keV). There are 12 nuclear reactions responsible for the production of ^4He , D, ^3He and ^7Li 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 [13] come from the standard theory of the weak interaction, normalized to the experimental neutron lifetime [2]. The $^1\text{H}(n, \gamma)^2\text{H}$ cross section is also obtained from theory [3] 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. Formerly, we used the reaction rates from the the evaluation performed by Descouvemont *et al* . [12] . 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 $i = ^4\text{He}$, D, ^3He and ^7Li) w.r.t. to a change in the 12 reaction rates by a constant factor. We define the sensitivity as $\partial \log Y / \partial \log \langle \sigma v \rangle$, 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.

Table 1. Abundance sensitivity: $\partial \log Y / \partial \log \langle \sigma v \rangle$ at WMAP baryonic density.

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

This table can be used as a guide for further experimental efforts. We see for instance that *at WMAP baryonic density*, the $^3\text{H}(\alpha, \gamma)^7\text{Li}$ and $^7\text{Li}(p, \alpha)^4\text{He}$ reactions play a negligible role. 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 a sufficient precision. The influence of the $^1\text{H}(n, \gamma)^2\text{H}$ rate is unexpected. The ^7Li 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 ^7Be formation time for a low $^1\text{H}(n, \gamma)^2\text{H}$ rate making

its destruction by neutron capture, ${}^7\text{Be}(n,p){}^7\text{Li}(p,\alpha){}^4\text{He}$, more efficient. 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[3]. The next most important reaction (Table 1) is ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ as it is the path for the formation of ${}^7\text{Li}$ at high 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 according to the experimental technique : prompt or activation measurements. Thanks to the recent experimental efforts [6], 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 [10] calculated the S-factor which is significantly higher than the Descouvemont *et al* one [12]. The ${}^2\text{H}(d,p){}^3\text{H}$ reaction, also influential on ${}^7\text{Li}$ was re-measured [together with ${}^2\text{H}(d,n){}^3\text{He}$] by Leonard *et al* [20] and the very precisely measured cross section is in perfect agreement with the R-matrix fit[12] used.

3. 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* (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. 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 24 metal poor halo stars [25] have led to a relative primordial abundance of $\text{Li}/\text{H} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (95% c.l.), obtained by extrapolation to zero metallicity. New observations of a subset of these stars, followed by an improved analysis, have reduced the uncertainty to $\text{Li}/\text{H} = (1.10 \pm 0.1) \times 10^{-10}$ [18]. Note also that observationally challenging detections of ${}^6\text{Li}$ has been reported[4] to a level of $\sim 10^{-2}$ below the Spite plateau value. The presence of such a ${}^6\text{Li}$ plateau should, however, be taken with caution.

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, a very fragile isotope, can only be destroyed after BBN. Its most primitive abundance is determined from the observation of clouds at high redshift, on the line of sight of distant quasars. Very few observations of these cosmological clouds [19] are available and the adopted primordial D abundance is given by the average value $(2.78^{+0.44}_{-0.38}) \times 10^{-5}$ of D/H. However, new observations [24] have confirmed the convergence of the D/H observed values towards an improved mean of $(2.82^{+0.20}_{-0.19}) \times 10^{-5}$.

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. The primordial ${}^4\text{He}$ abundance Y_p (${}^4\text{He}$ mass fraction) is given by the extrapolation to zero metallicity but is affected by systematic uncertainties [22, 16] such as plasma temperature or stellar absorption. As the most recent determinations, based on almost the same set of observations, but different atomic physics, lead to a large scatter of values, here, we will use a safe interval, $0.232 < Y_p < 0.258$ [22], to account for systematic uncertainties.

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, ${}^3\text{He}/\text{H} = (1.1 \pm 0.2) \times 10^{-5}$ [5]. Consequently, the baryometric status of ${}^3\text{He}$ [27] is not firmly established.

Table 2. Yields at WMAP baryonic density.

	Cyburt et al 2008[11]	This work	Observations	Factor
${}^4\text{He}$	0.2486 ± 0.0002	0.2476 ± 0.0004	$0.232\text{--}0.258$ [22]	$\times 10^0$
D/H	2.49 ± 0.17	2.68 ± 0.15	$2.82^{+0.20}_{-0.19}$ [24]	$\times 10^{-5}$
${}^3\text{He}/\text{H}$	1.00 ± 0.07	1.05 ± 0.04	$(0.9\text{--}1.3)$ [5]	$\times 10^{-5}$
${}^7\text{Li}/\text{H}$	$5.24^{+0.71}_{-0.67}$	5.14 ± 0.50	1.1 ± 0.1 [18]	$\times 10^{-10}$

4. BBN primordial abundances compared to observations

Table 2 displays the comparison between BBN abundances deduced from the WMAP results and the spectroscopic observations. Figure 1 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 reflects the nuclear uncertainties. They were obtained by a Monte-Carlo calculation using for the nuclear rate uncertainties those obtained by [12] with the notable exception of ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ [10] and ${}^1\text{H}(\text{n}, \gamma){}^2\text{H}$ [3]. (The dashed curves [7] do not include these two new rates.) The horizontal lines represent the limits on the ${}^4\text{He}$, D and ${}^7\text{Li}$ primordial abundances deduced from spectroscopic observations. The vertical stripe represents the baryonic density deduced from CMB observations by [15]. 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 : from a factor of ≈ 3 [7] when using the Descouvemont et al. library[12] only and the Ryan et al. observations [25], to a factor of ≈ 5 [11] when using the new rates and Li observations [18]. The origin of this discrepancy between CMB+BBN and spectroscopic observations remains an open question. For ${}^6\text{Li}$, now that an increased ${}^2\text{H}(\alpha, \gamma){}^6\text{Li}$ cross section is excluded[17], 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.

5. BBN as a probe of the early Universe

As the baryonic density of the Universe is now deduced from the observations of the anisotropies of the CMB radiation with a precision that cannot be matched by BBN, one may wonder whether primordial nucleosynthesis studies are still useful. In the Report by the ESA-ESO Working Group on Fundamental Cosmology [23] it is shown that two of the most important issues in cosmology are modified gravity and varying constants. Since, except for the baryonic density, BBN parameters have *all been determined by laboratory measurements*, BBN can be used to test these two important issues within the first minutes of the Universe.

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. The effect of the scalar field on BBN is to modify the rate of expansion. Constraints from BBN [8] can then put limits on the implied parameters (initial scalar field value, attraction strength towards GR,...).

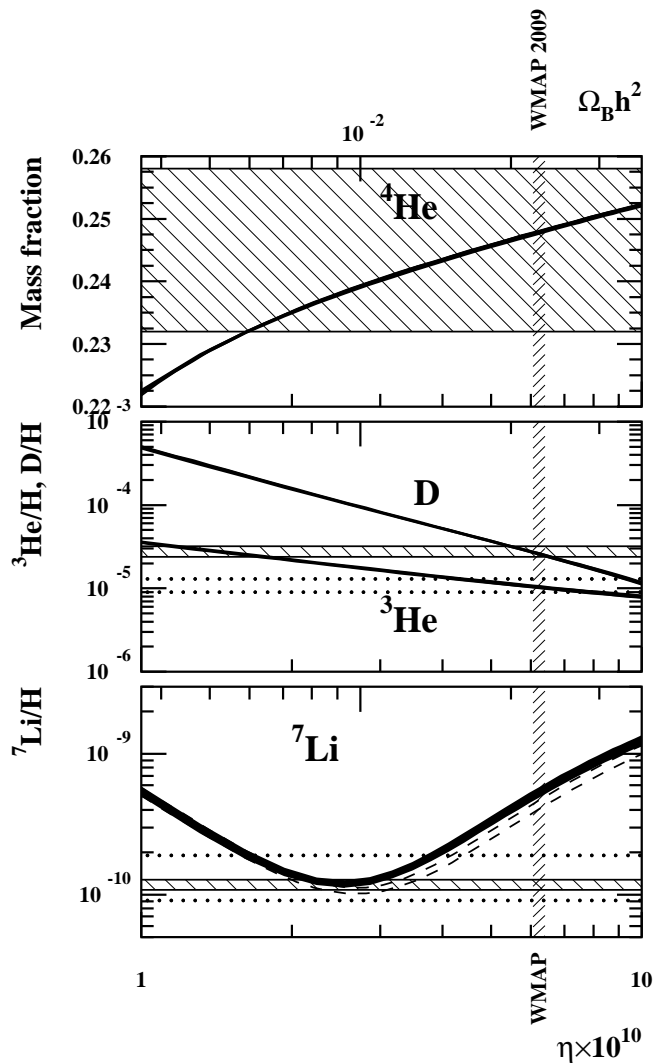


Figure 1. Abundances of ${}^4\text{He}$ (mass fraction), D, ${}^3\text{He}$ and ${}^7\text{Li}$ (by number relative to H) as a function of the baryon over photon ratio η (or $\Omega_b h^2$) showing the effect of nuclear uncertainties. The dashed curves (only discernable for Li) correspond to an earlier calculation [7] with older rates for ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ and ${}^1\text{H}(\text{n}, \gamma){}^2\text{H}$. The hatched bands represent the primordial abundances deduced from observations. (For lithium, the former observational limits are shown by dotted lines.) The vertical stripe is the WMAP baryonic density.

Coupled variation of the fundamental couplings is also motivated by superstring theories (see Ref. [26] for a review). Hence, this should induce variations of the masses of the particles, the energy scale of the strong interaction, Λ_{QCD} , the Fermi constant of the weak interactions.... The impact of these variations on the nuclear reaction rates is very difficult to estimate, as in general, nuclear physics uses phenomenological models whose parameters are not explicitly linked to fundamental constants. However, it is possible to estimate the variation of Q_{np} (neutron-proton mass difference), τ_n (lifetime of the neutron), B_D (binding energy of deuterium) and consequently the variation of the weak and ${}^1\text{H}(\text{n}, \gamma){}^2\text{H}$ rates. In particular, a relatively small ($\approx 4\%$) change of B_D at BBN epoch would induce a larger variation [14] of the ${}^1\text{H}(\text{n}, \gamma){}^2\text{H}$ reaction rate sufficient to reconcile all primordial abundances deduced from observations with BBN calculations [9] including ${}^7\text{Li}$.

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 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 most 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 ${}^7\text{Li}$ nucleosynthesis (Table 1). It is for instance surprising that for ${}^2\text{H}(p,\gamma){}^3\text{He}$ and ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ a larger number of experimental data is available at low energies than at BBN energies. (For ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$, see also Mohr 2009 [21].)

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.

7. References

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