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Big–Bang nucleosynthesis after WMAP

Alain Coc*
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM), CNRS/IN2P3, Université Paris Sud, UMR 8609, Bâtiment 104, F–91405 Orsay Campus, France
E-mail: coc@csnsm.in2p3.fr

The observations of the anisotropies of the Cosmic Microwave Background (CMB) radiation, by the WMAP satellite, has provided a determination of the baryonic density of the Universe ($\Omega_b{\cdot}h^2$) with an unprecedented precision. Using this value, the primordial abundances of the light elements can be calculated in the framework of the Standard Big–Bang Nucleosynthesis model (SBBN). While the agreement is excellent for D and good for ^4He, there is a difference of a factor of $\approx$3 for ^7Li. In addition, in a few halo stars, ^6Li has also been observed at a level well above SBBN predictions. To enable a more reliable calculation of these ^7Li and ^6Li yields, two nuclear reactions important for the nucleosynthesis of ^7Li and ^6Li have been studied experimentally: D$(\alpha,\gamma)^6$Li and ^{7}Be(d,p)2α. We also investigate the inportance of the np$\to$dγ reaction in SBBN. Even though, the lithium primordial production is not well understood, BBN can be used to constrain theories beyond the standard model.

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1. Introduction

Standard Big–Bang Nucleosynthesis (SBBN) can now be considered as a parameter free model now that the nuclear reaction rates, the number of neutrino families and the baryonic density of the Universe have been independently determined. In particular, the value $\Omega_b{\cdot}h^2$=0.0223±0.0008 has been extracted from the observations of the anisotropies of the Cosmic Microwave Background (CMB) radiation, by the WMAP satellite[36]. With this very precise value of the baryonic density and the main nuclear reaction rates under control, it should be possible to calculate precisely the abundance of the light isotopes. When compared to primordial abundances deduced from observations, the agreement is excellent for D, good for ^4He but there is a discrepancy of a factor of ≈3 for lithium and of orders of magnitude for ^6Li. Nevertheless, considering only ^4He and D, BBN can be used to constrain non-standard models.

2. Primordial abundances

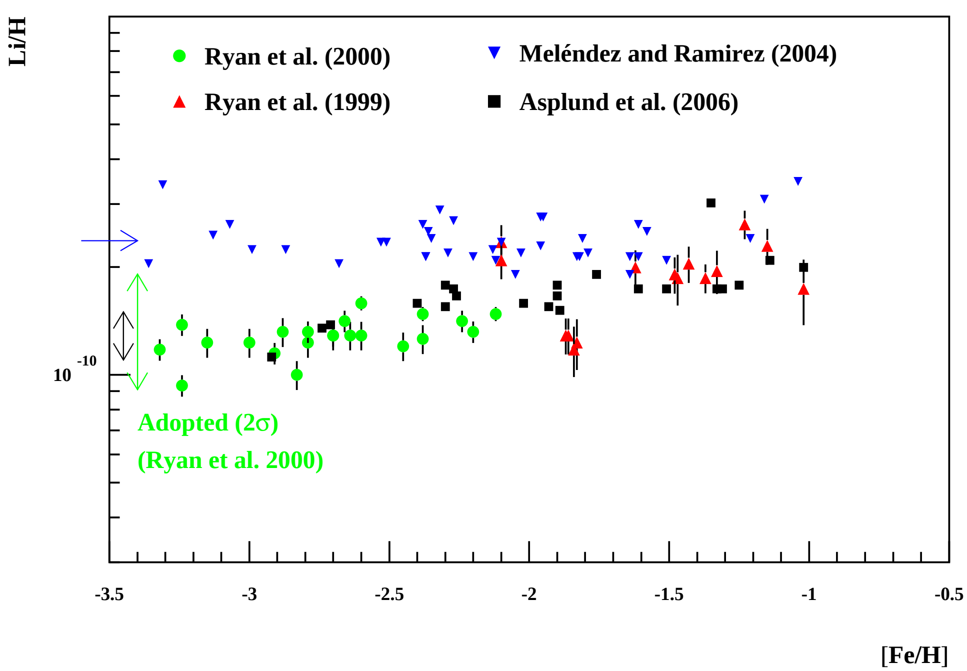

Figure 1: Recent lithium observations in halo stars [33, 34, 25, 5]: lithium abundances as a function of metallicity. The arrows represent the corresponding primordial abundances obtained by extrapolation to zero metallicity.

Figure 1 shows the most recent observations of lithium in metal poor halo stars, displaying a plateau as a function of metallicity. Assuming that lithium has not been much depleted at the surface of these stars, the presently observed abundance reflects to the primordial one[37]. From their observations, Ryan et al.[34] have obtained a relative primordial abundance of Li/H =

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$(1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (95% c.l.) by extrapolation to zero metallicity (Fe/H=0). Their quoted uncertainty takes into account systematic uncertainties including stellar depletion. The observations by Asplund et al.[5] confirm these data, showing also a small increase in lithium abundance as a function of metallicity, leading to Li/H = $(1.1-1.5) \times 10^{-10}$ at Fe/H=0. The observations by Meléndez and Ramírez[25] do not show the same tendency and lead to a slightly higher primordial abundance Li/H = $\approx 2.34 \times 10^{-10}$ due to a different value of adopted effective temperature for the extraction of the abundances. We assume that the presence of a plateau is an indication that depletion should not have been very effective and adopt the Ryan et al. value.

Contrary to ^7Li which can be both produced and destroyed, deuterium, a very fragile isotope, can only be destroyed after BBN. Clouds at high redshift on the line of sight of even more distant quasars are thought to be the best candidates for the determination of its primordial abundance. We adopt the average $(2.78^{+0.44}_{-0.38}) \times 10^{-5}$ of the observed D/H values in these cosmological clouds as calculated by Kirkman et al[23].

^4He primordial abundance is deduced from observations in HII regions of compact blue galaxies, considered as most primitive, and extrapolated to zero metallicity. Unfortunately, these abundances are affected by systematic uncertainties: values of $Y_p = 0.242 \pm 0.0021$[19] and $Y_p = 0.25 \pm 0.001$[20] were obtained from the same set of HII regions but different atomic physics input. Hence, we prefer to use the safe interval of 0.232< Y_p <0.258[29].

Contrary to ^4He, ^3He is both produced and destroyed in stars so that the evolution of its abundance as a function of time is not well known. Because of the difficulties of helium observations and the small ^{3}He/^{4}He ratio, ^3He has only been observed in our galaxy. The ^3He abundances observed in galactic HII regions display a plateau as a function of the galactic radius and in a limited range of metallicities: -0.6 < [Fe/H] < 0.1 [6]. It is however difficult to extrapolate this galactic value (spanning only a limited range of Fe/H) to zero metallicity so that ^3He is not usually used to constrain BBN. An upper limit on ^3He primordial abundance is given by Bania et al. [6]: ^{3}He/H = $(1.1 \pm 0.2) \times 10^{-5}$, based on their best observed source.

To these four isotopes whose origin is at least partially due to SBBN, one is tempted to add now ^6Li, which has been observed[28, 7, 3, 5] in a few low metallicity halo stars; i.e. the same stars that exhibit a lithium (^7Li+^6Li) plateau. In particular, Asplund et al.[5] report the detection at a 2–σ level of ^6Li in nine halo stars. These observations [28, 7, 3, 5] seems to indicate a plateau as a function of metallicity at a level of ^{6}Li/^{7}Li $\sim$0.05. The origin of ^6Li in these halo stars is not known but to compare ^6Li observed abundances with SBBN, we will assume, based on these observations, the approximate range: $10^{-12} <$ ^{6}Li/H $< 10^{-11}$.

3. Nuclear data

Even though many more reactions can be considered, there are only 12 nuclear reactions that govern ^4He, D, ^3He and ^7Li primordial nucleosynthesis: p$\leftrightarrow$n, n(p,γ)D, D(p,γ)^{3}He, D(d,n)^{3}He, D(d,p)^{3}H, T(d,n)^{3}He, T(α,γ)^{7}Li, ^{3}He(n,p)^{3}H, ^{3}He(d,p)^{4}He, ^{3}He(α,γ)^{7}Be, ^{7}Li(p,α)^{4}He and ^{7}Be(n,p)^{7}Li.

The $\nu_e + n \to e^- + p$ and $\bar{\nu}_e + p \to e^+ + n$ rates are calculated within standard weak interaction theory (with small corrections[15]) using Fermi distributions for the neutrinos and the neu-

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tron lifetime (885.7±0.8 s world average[16]) for normalization. Note, however, that a recent measurement[35] gives a significantly different value for the neutron lifetime 878.5±0.7 ± 0.3 s.

The np→dγ rate cannot be obtained from first principles but Chen and Savage [8] and Rupak [32] have used “Effective Field Theory" (EFT) to derive the cross section. They give also the theoretical uncertainty by estimating the magnitude of the first neglected term in their expansion: 4% [8] and 1% [32] repectively. In our previous calculations, we have used the Chen and Savage theoretical rate.

The rates from for the ten remaining reactions are obtained from experimental data. Because they are high enough, the cross sections can be measured *at the energies relevant for BBN*. Compilations and analysis of these experimental data have been done by Descouvemont et al.[14]. Using the R–matrix formalism to fit the experimental data, they provide reaction rates and associated uncertainties. Other rates for the ≈20 remaining reactions connecting ^4He, D, ^3He and ^7Li come from various sources including the NACRE compilation[1] but their impact on BBN were found to be negligible. An extended network (≈100 reactions) is used for ^6Li, ^9Be, ^{10}B and ^{11}B production.

More recent experiments, at BBN energies, have slightly reduced the uncertainties for the D(d,p)T and D(d,n)^{3}He[24], ^{3}He$(\alpha,\gamma)^7$Be[27] and other reactions (see § 5).

4. SBBN primordial abundances compared to observations

Figure 2 summarizes the concordance between the primordial abundances deduced from observations (§ 2) or from primordial nucleosynthesis and the baryonic density provided by WMAP within the ΛCDM model[36]. The Monte–Carlo calculations[9] were performed using the reaction rates and uncertainties provided by Descouvemont et al.[14] or from theory for the twelve most important reactions. It shows that the agreement is perfect for deuterium: when using the WMAP baryonic density, SBBN gives D/H = $(2.60^{+0.19}_{-0.17}) \times 10^{-5}$ to be compared with the average value $(2.78^{+0.44}_{-0.38}) \times 10^{-5}$ of D/H observations in cosmological clouds[23]. The exact convergence between these two independent methods is claimed to reinforce the confidence in the deduced $\Omega_b{\cdot}h^2$ value. The conservative limits on ^4He abundances accommodate easily the SBBN calculated one. The calculated ^3He abundance corresponds to the upper limit deduced from the Bania et al. observations[6]: an indication that ^3He has not much evolved since BBN.

On the contrary, the SBBN calculated ^7Li abundance, is a factor of 3.4 higher than the primordial abundance deduced from their observations by Ryan et al[33, 34]: Li/H = $(1.23^{+0.68}_{-0.32}) \times 10^{-10}$. These authors have extensively studied and quantified the various sources of uncertainty: extrapolation, stellar depletion and stellar atmosphere parameters. Nuclear uncertainties on the twelve important reactions, reflected by the width of the ^7Li curve does not alleviate significantly the discrepancy. They are taken into account, together with the uncertainty on the baryonic density in the calculation of the SBBN range Li/H = $4.15^{+0.49}_{-0.45} \times 10^{-10}$. It is surprising that the major discrepancy affects ^7Li since it could a priori lead to a more reliable primordial value than deuterium, because of much higher observational statistics, small scatter, and an easier extrapolation to primordial values. Note that other SBBN calculations[13, 12] using other sources for the reaction rates also display a similar discrepancy for ^7Li. Non nuclear depletion of lithium[31] have been invoked to solve this discrepancy but it is also important to exclude any nuclear solution.

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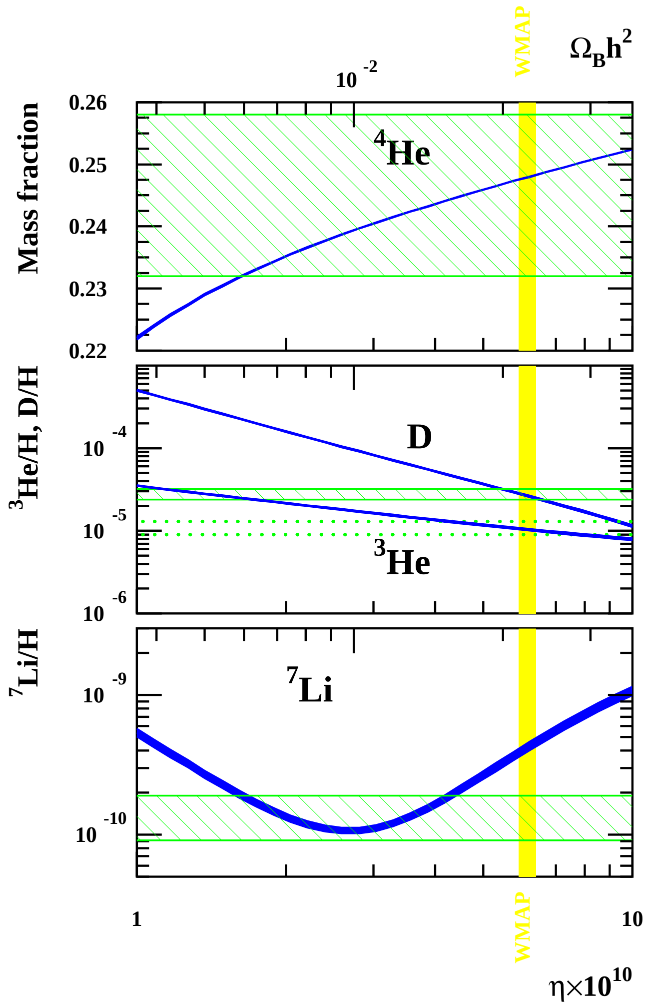

Figure 2: Abundances of ^4He (mass fraction), D, ^3He and ^7Li (by number relative to H) as a function of the baryon over photon ratio η or $\Omega_b{\cdot}h^2$. Limits (1-σ) are obtained from Monte Carlo calculations[9]. Horizontal lines represent primordial ^4He, D and ^7Li abundances deduced from observational data (see text). The vertical stripe represent the (68% c.l.) $\Omega_b{\cdot}h^2$ limits provided by WMAP[36].

The calculation of ^6Li BBN production was plagued by the nuclear uncertainty affecting the cross-section of the $\mathrm{D}(\alpha,\gamma)^6\mathrm{Li}$ reaction. When using the NACRE[1] rate limits one obtained a factor of 20 uncertainty on ^6Li yield: $2.3 \times 10^{-15} < {}^6\mathrm{Li/H} < 3.7 \times 10^{-14}$, more than two orders of below the observed values!

5. New experiments concerning SBBN lithium production

It is well known that the valley shaped curve representing Li/H as a function of $\Omega_b{\cdot}h^2$ is due to two modes of ^7Li production. One, at low baryonic density produces ^7Li directly via ^{3}H$(\alpha,\gamma)^7$Li while ^7Li destruction comes from ^{7}Li(p,α)^{4}He. The other one, at high density, leads to the formation of ^{7}Be through ^{3}He$(\alpha,\gamma)^7$Be while ^{7}Be destruction by ^{7}Be(n,p)^{7}Li is inefficient because of the lower neutron abundance at high density. Since the WMAP results point toward the high $\Omega_b{\cdot}h^2$ region, a particular attention should be paid to ^{7}Be synthesis that will later decay to ^7Li. In particular, the ^{7}Be+d reactions could have been an alternative to ^{7}Be(n,p)^{7}Li for the destruction of ^7Be, by compensating for the scarcity of neutrons at high $\Omega_b{\cdot}h^2$. An increase of the ^{7}Be(d,p)2^{4}He reaction rate by factors of 100 would alleviate the discrepancy[9]. The rate for this reaction can be traced to an estimate by Parker[30] based on the single experimental data available[21] above the energies relevant to Big Bang nucleosynthesis. An experiment[2] was performed using a ^{7}Be radioactive beam at the Louvain-la-Neuve (Belgium) facility down to the 0.15–0.38 MeV energy range comparable to the Gamow peak (0.15–0.56 MeV) at 1 GK. The cross section at BBN energy was found to be *lower*[2] than the Parker estimate ruling out this nuclear solution to the ^7Li discrepancy.

The D$(\alpha,\gamma)^6$Li reaction used to be the main source of uncertainty (a factor of ≈20[40, 18]) in ^6Li production when using the NACRE[1] rates. Despite these large uncertainties both in SBBN yields and primordial abundance determinations, there is a huge difference between them. However, before proceeding any further, it is important to clarify the nuclear physics aspects. The D$(\alpha,\gamma)^6$Li reaction is the main path for ^6Li SBBN production while destruction proceeds from the ^{6}Li(p,α)^{3}He. Both rates are available in the NACRE[1] compilation. While the latter reaction rate is reasonably known at BBN energies, the former suffers from an uncertainty of more than one order of magnitude. This is due to the difference between the only D$(\alpha,\gamma)^6$Li data available at BBN energies, measured indirectly via the Coulomb dissociation technique[22], on the one hand and theoretical extrapolations from higher energies where direct measurements have been performed on the other hand. The upper and lower rates found in NACRE originate from this difference between theory and experiment. A new Coulomb dissociation experiment was performed recently at GSI[18] that provided data over a wide energy range from the high energy region where direct measurements are available down to the BBN region. With a preliminary rate obtained by a R–matrix fit to the D$(\alpha,\gamma)^6$Li data (see Ref. [18] for details) we obtained an upper limit for the ^6Li yield of ^{6}Li/H$\lesssim 1.5\times10^{-14}$ at WMAP baryonic density, i.e. two orders of magnitudes below observed values. The calculated uncertainty should now also include those on the ^{6}Li(p,α)^{3}He reaction rate that were negligible before. Other potentially ^6Li producing reactions have a negligible contribution because they have negative Q-value (^{7}Li(p,d)^{6}Li and ^{4}He(t,n)^{6}Li) or a too low cross section (^{3}He(t,γ)^{6}Li). For instance, multiplying the ^{3}He(t,γ)^{6}Li reaction rate[17] by a factor of 1000 would only increase the ^6Li yield by a factor of ≈7 at WMAP baryonic density. Using a more realistic factor would not affect significantly ^6Li production as shown by Fukujita and Kajino[17].

6. The theoretical reaction rates in SBBN

While various cross-sections have been reevaluated, one can wonder whether all nuclear physics

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has been explored in depth enough for the purpose of BBN. Our purpose is not to argue that current nuclear data or theory cannot been trusted, we want to quantify to which extent BBN computations are sensitive to these data and whether the ^7Li problem can find a solution in this sector. In our previous works[9], we have used the Chen and Savage theoretical np→dγ rate with their associated uncertainties which were found to be negligible for BBN applications. However, one would prefer that this rate come, as the ten others, from experimental data at BBN energies. To evaluate the impact of a change in the np→dγ rate we multiplied it by a constant factor. Surprisingly, ^7Li is the most sensitive isotope to such a change while, for instance, D is little affected. In particular, a value of the rate smaller by 30% enables to re-concile ^7Li abundance, computed assuming WMAP determination of the baryon density and spectroscopic observations. This can be explained by an increased neutron abundance leading to a higher ^{7}Be destruction by ^{7}Be(n,p), the dominant destruction mechanism. It is thus important to investigate the np→dγ cross section.

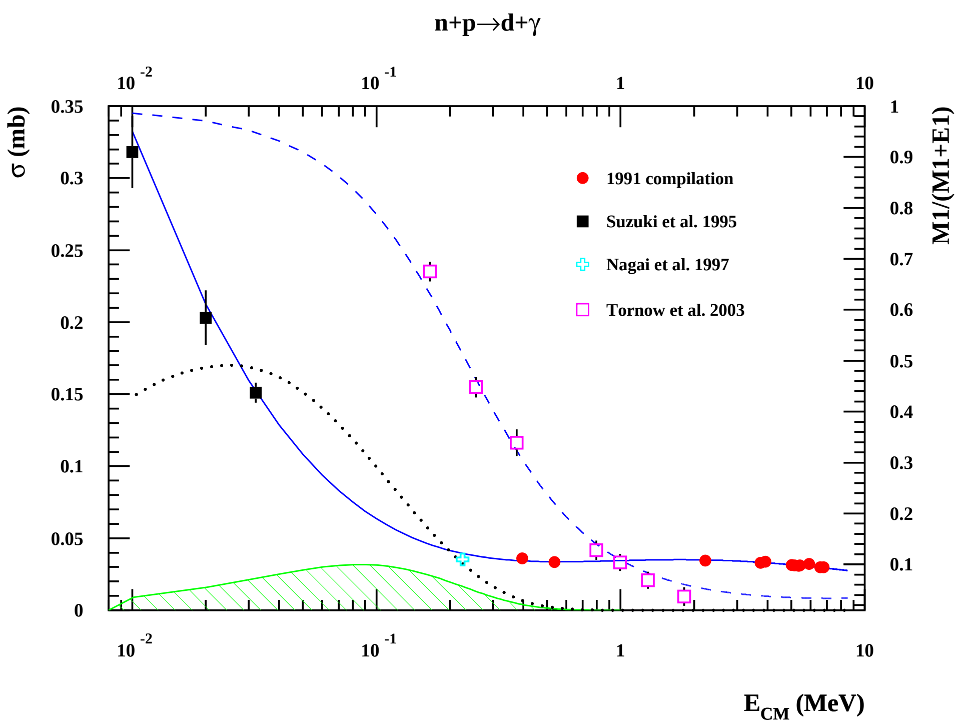

Figure 3: Theoretical np→dγ cross section compared to experiments. The solid line represents the total cross section (left axis) while the dashed line corresponds to the relative M1 contribution to the total cross section (right axis) as calculated by Chen and Savage[8]. The hatched area represents the Boltzmann factor at a typical themperature (arbitrary units). The dotted line is its product with the total cross section showing by its maximum that the main contribution of the cross section to the rate should lie around 25 keV.

In Fig. 3 is represented the total np→dγ cross section calculated by using the Chen and Savage[8] prescription. Chen and Savage[8] and Rupak[32] compared their theoretical results with the seven experimental data points from Ref.[4]. The agreement between theory and experiment was very good but verified mostly outside of the region of interest where the cross section is rather flat. On the same figure, is shown the product of the total cross section. with the Boltz-

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mann factor $E\exp(-E/\mathrm{k}_B T)$ for a temperature of 10^9 K. With the steep rise of the cross section at low energy, the maximum of the product, and hence the dominant contribution to the rate, occurs around $E_{CM} \approx$25 keV, much below the lowest experimental data point at $E_{CM} \approx$400 keV reported in Ref.[4]. An other experimental check of the EFT calculations is provided by the work of Tornow et al.[39] at the Duke Free–Electron Laser Laboratory. With their polarized gamma ray beam, they were able to determine the M1 versus E1 contribution in the d$\gamma \rightarrow$np inverse reaction down to $E_{CM} \approx$170 keV. However, the energy range experimentally reached still remains too high and while the data shows a good agreement for the *relative* contributions to the cross section, they do not constrain its *absolute* value. Fortunately there exist low energy experimental data[38, 26] since the last review[4] that span the SBBN energy range (Fig. 3). It shows the excellent agreement between EFT theory and experiment down to BBN energies excluding the 30% change that would reduce the ^7Li yield to the observed one.

7. Conclusions and perspectives

Even though, the lithium primordial production is not well understood, BBN together with ^4He and D observations can be used to constrain theories beyond the standard model. As an example, we can mention scalar-tensor theories of gravity. These theories are motivated by high-energy theories trying to unifying gravity with other interactions which generically involve a scalar field in the gravitational sector, in particular, in superstring theories (see Ref. [10] for a recent investigation of BBN within this framework). An other example is the study of the possible variation of the fundamental coupling constants, between BBN time and now, that would affect, in particular, affect the np$\rightarrow$dγ rate and alleviate the ^7Li discrepancy[11].

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