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Nuclear aspects of Primordial Nucleosynthesis related to Lithium production

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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 ^{4}He, D, ^{3}He and ^{7}Li 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 For this purpose, it is now superseded by the analysis of the Cosmic Microwave Background (CMB) radiation anisotropies.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 robust probe of the physics of the early Universe. However, the yet unexplained, discrepancy between the calculated and observed lithium primordial abundances, has not been reduced by recent nuclear physics experiments. We extended the nuclear network to more than 400 reactions, until sodium, to evaluate the primordial ^{6}Li, B, Be and CNO abundances and search for extra source of neutrons could solve the lithium problem by destroying ^{7}Be. We performed a sensitivity study of this extended network to identify new important reactions but noted the stability of Big Bang nucleosynthesis results from ^{4}He, D, ^{3}He and ^{7}Li to CNO. Other sources of extra neutrons could be found in more exotic scenarios, for instance the decays or annihilation of dark matter particles.

Key words. Cosmology: early Universe ; Nuclear reactions, nucleosynthesis, abundances

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": ^{4}He, D, ^{3}He and ^{7}Li. 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_ν = 2.984±0.008 (Nakamura et al. 2012). The lifetime of the neutron (entering in weak reaction rate calculations) 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 $\Omega_b \cdot h^2 = 0.02249^{+0.00056}_{-0.00057}$ (Komatsu et al. 2011) or $\eta = 6.16 \pm 0.15 \times 10^{-10}$, the number of baryons per photon which remains constant during the expansion. Comparison between theoretical and observational abundances shows a very good overall agreement except for the ^{7}Li.

2. Abundances of the cosmological elements

Deuterium, a very fragile isotope, is 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 are available and the adopted primordial D abundance is given by the average value (Olive et al. 2012, and references therein):

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

After BBN, ^{4}He is still 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 (mass fraction) is given by the extrapolation to zero metallicity but is affected by systematic uncertainties such as plasma temperature or stellar absorption. These most recent determinations based on almost the same set of observations lead to (Aver et al. 2012; Skillman, Aver & Olive 2012):

$Y_p = 0.2534 \pm 0.0083$.

Contrary to ^{4}He , ^{3}He is both produced and destroyed in stars so that the evolution of its abundance as a function is subject to large uncertainties and has only been observed in our Galaxy (Bania et al. 2002):

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

Consequently, the baryometric status of ^{3}He is not firmly established (Vangioni-Flam et al. 2003).

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, the so-called Spite plateau (Spite & Spite 1982). 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. We leave this discussion to other contributions to this workshop and use here the recent analysis by Sbordone et al. (2010) for our comparison with theory:

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

In 2006, high-resolution observations of Li absorption lines in some very old halo stars have also claimed evidence for a large primitive abundance of the weakly-bound isotope ^{6}Li (Asplund et al. 2006). Again we refer to contributions in these proceedings to confirm or not ^{6}Li detection but, as in Hammache et al. (2010), we use for comparison the range:

$4.4 \times 10^{-12} < {}^6\text{Li/H} < 1.4 \times 10^{-11}$,

where the highest value corresponds to the observational data from Spite & Spite (2010) while the lower one corresponds to the value observed in HD 84937 star (Steffen et al. 2010, and references therein, see also Steffen et al. 2012)

3. 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 ^{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.

The weak reactions involved in n↔p equilibrium are an exception; their rates (Dicus et al. 1982) come from the standard theory of the weak interaction, normalized to the experimental neutron lifetime. We used $\tau_n = 881.5 \pm 1.5$ s, but this value is still debated (Nakamura et al. 2012; Wietfeldt & Greene 2011) due to experimental systematic uncertainties. The ^{1}H(n,γ)^{2}H cross section is also obtained from theory (Ando et al. 2006) but in the framework of Effective Field Theory. 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)^{3}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. Formerly, we used the reaction rates from the the evaluation performed by Descouvemont et al. (2004). However, more recent experiments and analysis have lead to improved reaction rates for several important reactions.

To point out the most important reactions for ^{7}Li nucleosynthesis, we recall the sensitivity of its calculated abundance w.r.t. to a change in the 12 reaction rates by a constant factor (Coc & Vangioni 2010): $\partial\log Y_{7Li}/\partial\log\langle\sigma v\rangle$, at WMAP baryonic density. This is based on the assumption that the nuclear cross section uncertainties are now dominated by systematic uncertainties that affect their normalization rather than by statistics. We obtained sensitivities of 0.40, 1.33, 0.57, 0.69, 0.05, -0.02, 0.03, -0.27, -0.75, 0.97, -0.05, -0.71 to variations of the n$\leftrightarrow$p, ^{1}H(n,γ)^{2}H, ^{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(n,p)^{3}H, ^{3}He(d,p)^{4}He, ^{3}He(α,γ)^{7}Be, ^{7}Li(p,α)^{4}He, ^{7}Be(n,p)^{7}Li reaction rates, respectively.

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. The sensitivity to the weak rates (0.4) is high but (within standard theory), the uncertainty is governed by the neutron lifetime which is within the 880 to 884 s range (Wietfeldt & Greene 2011) and hence does not affect ^{7}Li yield significantly. The influence of the ^{1}H(n,γ)^{2}H rate is unexpected. The ^{7}Li final abundance depends strongly on the rate of this reaction (sensitivity 1.33) 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. 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 a few percent error (Ando et al. 2006). The next most important reaction (sensitivity 0.97) 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 recent experimental efforts (Brown et al. 2007; Confortola et al. 2007; Gyürky et al. 2007; Nara Singh al. 2004; Costantini et al. 2008; Di Leva et al. 2009), 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 (2008) calculated the S–factor which is significantly higher than the Descouvemont et al. (2004) one. The ^{2}H(d,p)^{3}H reaction, also influential on ^{7}Li was re-measured [together with ^{2}H(d,n)^{3}He] by Leonard et al. (2006) and the very precisely measured cross section is in perfect agreement with the R-matrix fit (Descouvemont et al. 2004).

4. BBN primordial abundances compared to observations

Figure 1 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 reflects the nuclear uncertainties. They were obtained by a Monte-Carlo calculation using for the nuclear rate uncertainties those obtained by Descouvemont et al. (2004) with the notable exception of ^{3}He(α,γ)^{7}Be (Cyburt & Davids 2008) and ^{1}H(n,γ)^{2}H (Ando et al. 2006) (§ 3). 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 by Komatsu et al. (2011). The concordance between BBN and observations is in good 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 sig-

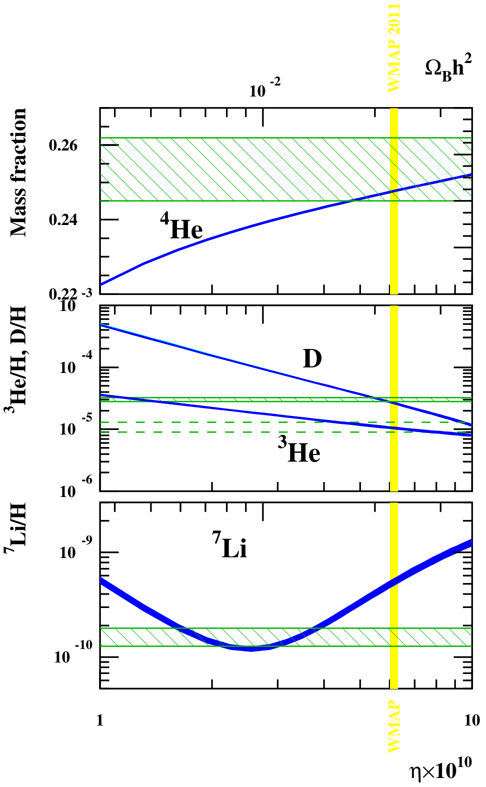

Fig. 1. Abundances of ^{4}He (mass fraction), D, ^{3}He and ^{7}Li (by number relative to H) as a function of the baryon over photon ratio η (or $\Omega_b \cdot h^2$) showing the effect of nuclear uncertainties. The hatched bands represent the primordial abundances deduced from observations. The vertical stripe is the WMAP baryonic density.

nificantly higher than the spectroscopic observations: a factor of ≈ 3 (Cyburt et al. 2008; Coc & Vangioni 2010) when using the new rates and Li observations (Sbordone et al. 2010). Table 1 displays the comparison between BBN abundances deduced from the WMAP results and the spectroscopic observations. The origin of this discrepancy between CMB+BBN and spectroscopic observations remains an open question.

5. Extending the BBN network

A motivation for extending our BBN network is the above mentioned dichotomy concerning the Li abundance. At WMAP baryonic density, ^{7}Li is produced as ^{7}Be that later decays. Nuclear ways to destroy this ^{7}Be have been explored. An increased ^{7}Be(d,p)2α cross section has been proposed by Coc et al. (2004) but was not confirmed by experiment described in Angulo et al. (2005) unless a new resonance is present (Cyburt & Pospelov 2012) with very peculiar properties. However, no resonance was found in a recent ORNL experiment (O'Malley et al. 2011) and the corresponding ^{9}B level does not fill the required conditions (Kirsebom & Davids 2011; Scholl et al. 2011). Other ^{7}Be destruction channels have recently been proposed by Chakraborty et al. (2011) and (Broggini et al. 2012a,b) but do not seem to be supported by a very recent Orsay experiment (Hammache et al. 2012).

Another scenario would be to take advantage of an increased late time neutron abundance. This is exactly what happens (in the context of varying constants) when the ^{1}H(n,γ)^{2}H rate is decreased. The neutron late time abundance is increased (with no effect on ^{4}He) so that more ^{7}Be is destroyed by ^{7}Be(n,p)^{7}Li(p,α)α. (see in Coc et al. 2007, Fig. 1). Examples of exotic solutions are presented in § 6 but first, one needs to explore nuclear sources of neutrons by extending our network up to CNO and including all n-, p-, α-, but also d-, t- and ^{3}He-induced reactions on targets from A=1 to 16. In this process, we also obtain the ^{6}Li, ^{9}Be, ^{10}B, ^{11}B and CNO primordial abundances.

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 pp 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

Table 1. Primordial abundances of H, He and Li isotopes at WMAP baryonic density.

	CD08	CV10	CGXSV12	Observations
Nb. reactions		13 (+2)	424	(See text)
Y_p	0.2486±0.0002	0.2476±0.0004	0.2475	0.2561 ± 0.0108
D/H ($\times10^{-5}$)	2.49±0.17	2.68 ± 0.15	2.59	2.82±0.2
^{3}He/H ($\times10^{-5}$)	1.00±0.07	1.05±0.04	1.04	1.1 ±0.2
^{7}Li/H ($\times10^{-10}$)	$5.24^{+0.71}_{-0.62}$	5.14±0.50	5.24	1.58±0.31
^{6}Li/H ($\times10^{-14}$)		1.3†	1.23	∼1000 (?)
CNO/H ($\times10^{-16}$)	6.00‡		7.43	

CD08: Cyburt & Davids (2008); CV10: Coc & Vangioni (2010); CGXSV12: Coc et al. (2102)
‡Iocco et al. (2007); †Hammache et al. (2010)

10^{-11} (Cassisi & Castellani 1993) or even as low as 10^{-13} (in number of atoms relative to hydrogen, CNO/H) for the less massive ones Ekström et al. (2008). 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. (2007). 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. (2007) who included more than 100 nuclear reactions and predicted a CNO/H abundance ratio of approximately 6×10^{-16}, with an upper limit of 10^{-10}. In addition, it has been shown that Pop III stars evolution is sensitive to the triple-alpha (^{12}C producing) reaction and can be used to constrain the possible variation of the fundamental constants (Ekström et al. 2010). 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}C) produced in BBN. In the same context of the variations of the fundamental constants, ^{8}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. To determine how significant would be this excess, one needs to know the standard BBN production of the CNO elements.

The main difficulty in BBN calculations with such an extensive network (≈400 reactions.), including n-, p-, α-, but also d-, t- and ^{3}He-induced reactions, is that 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. 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. As a first approximation, we used theoretical reaction rates calculated with the TALYS nuclear reaction code (Goriely et al. 2008) for those that are not available in the literature (the full list of references can be found in Coc et al. (2102).

By comparing TALYS results with experimentally determined reaction rates we observed that TALYS globally provides predictions within 3 orders of magnitude in the temperature range of interest here, even for very light elements like Li. Hence variations of these theoretical rates by three orders of magnitude can in a first step be used in our sensitivity analysis for the BBN abundance calculation. 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 abundances. (Mass fractions of isotopes with A≥12 are added together for CNO.)

Note that even with a factor 10^3 rate increase or decrease, we have found no ^{7}Li or ^{7}Be *n*-, *p*-, *d*-, ^{3}He- or α-induced reactions that would significantly directly reduce the ^{7}Li+^{7}Be abundance as suggested by Chakraborty et al. (2011) and Broggini et al. (2012a), except for the ^{7}Be(d,p) reaction already considered by Coc et al. (2004); Angulo et al. (2005); Cyburt & Pospelov (2012) or indirectly through neutron injection.

Reactions affecting the ^{6}Li nucleosynthesis are ^{4}He(d,γ)^{6}Li and to a much lower extent ^{3}He(t,γ)^{6}Li. The rate of the latter has been calculated by Fukugita & Kajino (1990) without providing an estimate of the associated uncertainty that should, in any case, be much lower that the factor of 1000 needed. But the key BBN ^{6}Li production mechanism is the former, ^{4}He(d,γ)^{6}Li reaction, at energies in the range of 50 keV $\leq E_{cm} \leq$ 400 keV (Serpico et al. 2004). This reaction has very recently been reinvestigated by Hammache et al. (2010) with the Coulomb breakup method. The rate uncertainty has consequently been reduced from a factor of $\approx$20 to $\approx$40% at BBN energies, confirming the previous result that Standard Big-Bang Nucleosynthesis cannot produce ^{6}Li at the required level. In addition, a further confirmation should come from a direct measurement of the cross-section is currently underway at the LUNA Gran Sasso underground laboratory (Anders, Bemmerer & Gustavino 2012).

The ^{9}Be nucleosynthesis is sensitive to the ^{7}Li(t,n)^{9}Be reaction but also to the ^{7}Li(d,γ)^{9}Be, ^{7}Be(t,p)^{9}Be reactions and to a lower extent to the ^{7}Li(^{3}He,p)^{9}Be.

The ^{11}B production could be drastically reduced if the ^{11}C(n,α)2^{4}He reaction rate was higher.

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)2^{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 § 3). 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$200 s is reduced by a factor of about 100 (see Fig. 15 in Coc et al. 2102), an evolution followed by ^{8}Li and CNO isotopes. Hence, the main nuclear path to CNO (see also Iocco et al. 2007) proceeds from the ^{7}Li$(\alpha,\gamma)^{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.) With our extended network, we confirm the results of Iocco et al. (2007) that the CNO Standard Big-Bang Nucleosynthesis production is CNO/H $\approx 0.7 \times 10^{-15}$ (number of atoms relative to H) and estimate the range of CNO/H values to lie within $(0.5 - 3.) \times 10^{-15}$. Even when considering our estimated uncertainty, the primordial CNO abundance is too low to have an impact on Pop III stellar evolution.

6. Neutron injection to alleviate the ^{7}Li problem

A more exotic option for neutron injection that would help reduce the ^{7}Li BBN production by destroying ^{7}Be, is hadronic decays of exotic unstable particles. For example, a metastable stop NLSP decaying into a gravitino LSP (dark matter candidate) and a top quark injects energetic protons and neutrons during nucleosynthesis (Kohri & Santoso 2009). There are many earlier variations on this approach, pioneered by Dimopoulos et al. (1988), and refined by Jedamzik (2006), Cumberbatch et al. (2007) and Cyburt et al. (2010), among others. In these models, neutron injection provides the primary impact on BBN and Li production.

Here, we use a different approach: a parametrized study of the effect of free neutron injection where both the rate and the timescale of injection are varied. This is expected to give hints regarding the possible injection mechanism: including possible nuclear reaction uncertainties, fundamental constant variations and exotic particle decays or annihilations.

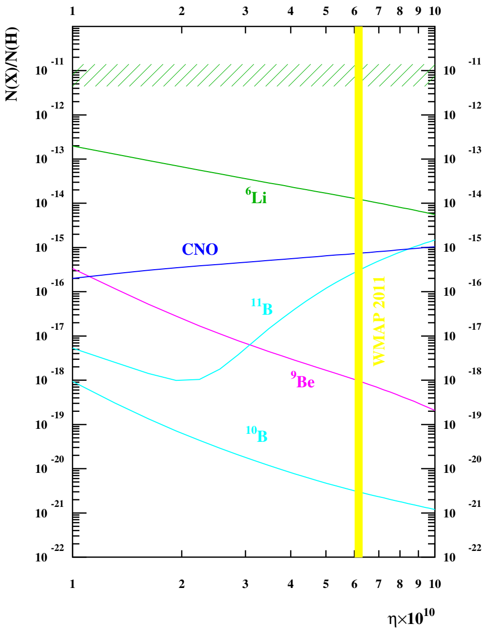

Fig. 2. Abundances in number of atoms relative to H for ^{6}Li, ^{9}Be, ^{10}B, ^{11}B and CNO. The hatched area represent the approximate range of ^{6}Li observations (see text).

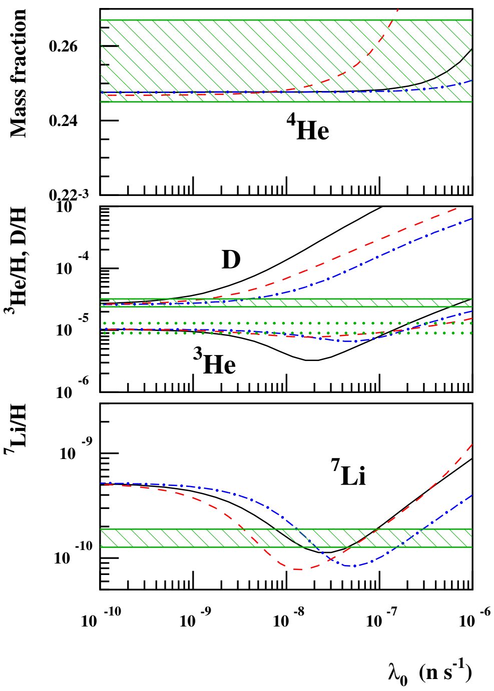

Fig. 3. ^{4}He, D, ^{3}He and ^{7}Li abundances as a function of neutron injection rate for case (4) i.e. decay, with τ_x = 40 mn (solid) and case (5) i.e. annihilation with T_c = 0.3 GK (dash).

Including an additional neutron injection in our SBBN code is straightforward. We allow protons to decay to neutrons with a lifetime of $\lambda^{-1}(t)$. As we are considering very low injection rates, this has no consequence on the high proton abundance. To illustrate the consequences of early or late injection, we consider the following cases:

1. $\lambda(t) = \lambda_0$
2. $\lambda(t) = \lambda_0 \exp(-t/\tau_x)$
3. $\lambda(t) = \lambda_0 \left(\frac{T}{T_c}\right)^3$

where λ_0, τ_x and T_c are constant, while t and T are respectively the time and temperature. Since the proton abundance remains essentially constant (Y_p ≈0.5 to 0.7) during BBN the rate of injection $Y_p(t)\lambda(t)$ is constant in case (1). Cases (2) and (3) represent more physical situations where neutrons come from the decay of an hypothetical particle X of lifetime τ_x decaying to $X \rightarrow n$ + ... with a branching ratio B_n, or as a product of the annihilation of dark matter particles.

Figure 6 shows that, within the three scenarios, for some values of the parameters λ_0, τ_x and T_c, ^{7}Li abundance becomes compatible with observations at the expense of D overproduction. This is, indeed, a frequent consequence of models aiming at reconciling ^{7}Li primordial production with observations that deuterium production increases above the range favored by observations (Olive et al. 2012) and may even require additional deuterium depletion (T. Kajino, talk at this conference).

7. Conclusion

The baryonic density of the Universe as determined by the analysis of the CMB anisotropies is in good agreement with Standard BBN compared to D primordial abundance deduced from cosmological cloud observations. The BBN calculated ^{4}He abundance is still compatible with the latest evaluation of its primordial abundance deduced from HII observations in blue compact galaxies but is close to the lower limit, suggesting the need for extra relativistic degrees of freedom. 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. The origin of this discrepancy remains an open question but a nuclear solution seems highly unlikely.

We have used an extensive network of more than 400 nuclear reactions, up to CNO, and performed a sensitivity study by varying uncertain reaction rates by factors of up to 1000 and down to 0.001. On the basis of these new evaluations the CNO isotope production was found to be in the range CNO/H $= (0.5-3.)\times 10^{-15}$, but as expected, the extension of the network does not alleviate the ^{7}Li discrepancy between calculations and observations. However, we stress here the importance of sensitivity studies in nuclear astrophysics: 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,γ)^{2}H reaction on ^{7}Li nor of the ^{7}Li(d,n)2^{4}He reaction on CNO.

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. (Olive 2012 and T. Kajino's talk at this conference)

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