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How to best reconcile Big Bang Nucleosynthesis with Li abundance determinations?: Exotic BBN

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Abstract. Non-standard model solutions to the ^{7}Li problem are discussed. Particular attention is given to the possibility of a relatively long lived gravitino decay affecting the light element abundances. Gravitinos with masses between 4-5 TeV could significantly reduce the final ^{7}Li abundance. Alternatively, a possible variation in the fundamental constants may also affect the ^{7}Li abundance. In both cases, reduced ^{7}Li is accompanied by an increased D/H abundance. This may have implications for the chemical evolution in quasar absorption systems.

Key words. big bang nucleosynthesis, supersymmetry, fundamental constants

1. Introduction

It is widely recognized that there is a significant mismatch between the predicted standard big bang nucleosynthesis (SBBN) abundance of ^{7}Li at the WMAP value of the baryon-to-photon ratio, η, and observationally determined abundances seen on the Spite plateau (Cyburt et al. 2008). Indeed, that this one of the primary issues addressed at this workshop. Specifically, for $\eta = 6.16 \times 10^{-10}$ (Komatsu et al. 2011), the BBN prediction for ^{7}Li/H is found to be $(5.07^{+0.71}_{-0.62}) \times 10^{-10}$ in Cyburt et al. (2008) and 5.24×10^{-10} in Coc et al. (2012) with an estimated error bar of 0.5, which is considerably higher than almost all observational determinations. The value found in Ryan et al. (2000) was ^{7}Li/H = $(1.23^{+0.34}_{-0.16}) \times 10^{-10}$. Similarly, the recent analysis of Sbordone et al. (2010) found ^{7}Li/H = $(1.58 \pm 0.31) \times 10^{-10}$. Li observations have also been performed in some globular clusters. For example, González Hernández et al. (2009) found $(2.34 \pm 0.05) \times 10^{-10}$ in NGC 6397, significantly higher than the result for field stars.

Without question, it makes sense to first explore thoroughly the possibility that the discrepancy is due some more or less standard process which has not been included in the so-called standard model calculation. For example, it is important to exhaust all nuclear possibilities such as the nuclear reaction rates used in BBN calculations (Coc et al. 2004; Angulo et al. 2005; Cyburt et al. 2004; Boyd et al. 2010), or considering additional resonance reactions (Cyburt & Pospelov 2009; Chakraborty et al. 2011; Broggini et al. 2012). These were reviewed here by A. Coc.

The possibility that depletion plays a role has been discussed at length (Vauclair & Charbonnel 1998; Pinsonneault et al. 1998, 2002; Richard, Michaud & Richer 2005; Korn et al. 2006; García Peréz et al. 2008) and covered here by O. Richard, A. Korn, and K. Lind. The temperature scale used in the ^{7}Li abundance determination has also been considered

(Meléndez & Ramírez 2004; Hosford et al. 2009, 2010) and discussed here by S. Ryan.

Since none of the above possibilities are perfectly acceptable (if there were, there would be no problem), the next step is to consider more exotic possibilities and that is the subject of this contribution. In the next section, I will describe the possibility of reducing the ^{7}Li abundance through the decays of some massive yet relatively long lived particle, and in section 3, I will discuss the effect of a possible variation in the fine-structure constant, α. However, I do note here another possibility raised recently is that of an axion condensate which cools the photon background leading to lower value of η at the time of BBN relative to that determined by WMAP (Erken et al. 2012; Kusakabe et al. 2012).

2. Decaying particles

The decay of a massive particle during or after BBN could affect the light element abundances and potentially lower the ^{7}Li abundance (Jedamzik 2004; Kawasaki et al. 2005; Feng et al. 2004; Ellis et al. 2005; Jedamzik et al. 2006; Cyburt et al. 2006; Kusakabe et al. 2007; Cumberbatch et al. 2007; Kawasaki et al. 2008; Pospelov et al. 2008; Jittoh et al. 2008; Jedamzik & Pospelov 2009; Cyburt et al. 2009; Kusakabe et al. 2008, 2010; Jedamzik 2008a,b; Bailly et al. 2009; Pospelov & Pradler 2010a,b; Cyburt et al. 2010; Jittoh et al. 2010; Kawasaki & Kusakabe 2011). In general, the effect on the light element abundances will depend on three quantities: the abundance of the decaying particle parameterized by $\zeta_X = n_X m_X/n_\gamma$, where n_X/n_γ is the abundance of X relative to photons and m_X which is a second independent parameter; and thirdly, the particle lifetime, τ_X. Given a theory behind X, the decay produces a non-thermal injection spectrum which can be tracked with cascade software such as Pythia. One must then evolve the element abundances including both the thermal (BBN) and non-thermal processes.

One example, is that of gravitino decay. The gravitino, which is present in supersymmetric extensions of the Standard Model based on supergravity, can decay into lighter supersymmetric states and their Standard Model partners. Because the gravitino only couples to matter through gravitation, its decay rate is proportional to Newton's constant, G_N, and its lifetime is relatively long. Here, I will consider a constrained version of the minimal supersymmetric model which is described by four parameters: a universal gaugino mass, $m_{1/2}$; a universal scalar mass, m_0; a universal trilinear term, A_0; and the ratio of the two Higgs expectation values, $\tan\beta$. In addition, we must specify the sign of the Higgs mixing parameter, μ, which is taken to be positive, and the gravitino mass (see e.g. Ellis & Olive 2010).

In these models, the gravitino has the following two-body decay modes: $\widetilde{G} \to \tilde{f} f$, $\widetilde{G} \to \tilde{\chi}^+ W^-(H^-)$, $\widetilde{G} \to \tilde{\chi}^0_i \gamma(Z)$, $\widetilde{G} \to \tilde{\chi}^0_i H^0_i$ and $\widetilde{G} \to \tilde{g} g$, where f is a Standard Model fermion and $\tilde{f}$ is its supersymmetric partner, $\tilde{\chi}^0_i(\tilde{\chi}^+)$ represent the neutralinos (charginos), and $H^-(H^0)$ are the charged (neutral) Higgs bosons. The lightest neutralino is generally assumed to be a stable dark matter candidate. The decay products then cascade producing non-thermal neutrons and protons.

It was observed (Jedamzik 2004; Kawasaki et al. 2005) that for a sufficiently high abundance of decaying particles with a lifetime of about $\tau_X \sim 10^2 - 10^3$ sec, there a narrow "valley" emerges in which ^{7}Li/H is significantly reduced. This effect is due to injected neutrons by first destroying ^{7}Be. Thermalized and non-thermalized (Cyburt et al. 2009) neutrons can destroy ^{7}Be via ^{7}Be$(n,p)^7$Li which is followed by ^{7}Li$(p,\alpha)^4$He. This "valley" is seen in Fig. 1 (Cyburt et al. 2009, 2010). Notice that the left side of the "valley" coincides almost exactly with the constraint from D/H, so that we find D/H > 3.2×10^{-5} in essentially the entire region where ^{7}Li/H $< 2.75 \times 10^{-10}$. However, along the left side of the "valley" in Fig. 1, there may be a marginal solution to the ^{7}Li problem.

The valley also manifests itself in supersymmetric models with a large gravitino mass. For example, let us consider a particular supersymmetric model (keeping the gravitino mass free) based on benchmark point C (Battaglia et al. 2001, 2004; de Roeck et al. 2007) which is defined by $(m_{1/2}, m_0, A_0, \tan\beta)$

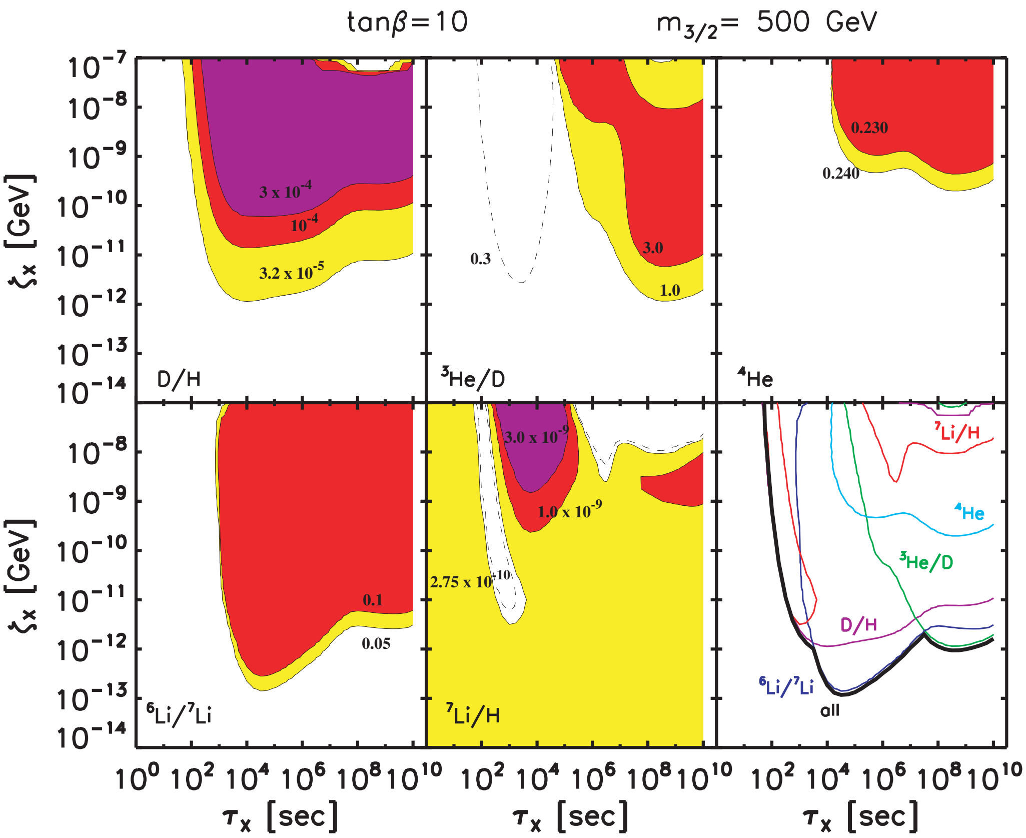

Fig. 1. Plots of abundance versus lifetime for metastable particles X with lifetimes τ_X between 1 and 10^{10} sec, assuming the decay spectra calculated for a supersymmetric model with $(m_{1/2}, m_{3/2}, \tan\beta)$ = (300 GeV, 500 GeV, 10). The white regions in each panel are those allowed by the ranges of the observed light-element abundances, whilst the yellow, red and magenta regions correspond to progressively larger deviations from the central values of the abundances.

= (400,90,0,10), as shown in Fig. 2 (Cyburt et al. 2010). The lightest neutralino mass is about 165 GeV for this point, and for gravitino masses larger than this we have neutralino dark matter with an unstable massive gravitino. In the lower right panel, we see marginal compatibility between the ^{7}Li constraint (light blue) and the other constraints for $m_{3/2} \gtrsim 3$ TeV.

This marginal compatibility can be quantified by defining a χ^2

$$\chi^2 \equiv \left(\frac{Y_p - 0.256}{0.011}\right)^2 + \left(\frac{\frac{D}{H} - 2.82\times10^{-5}}{0.27\times10^{-5}}\right)^2 + \left(\frac{\frac{^7\mathrm{Li}}{H} - 1.23\times10^{-10}}{0.71\times10^{-10}}\right)^2 + \sum_i s_i^2, \qquad (1)$$

The uncertainties used in the denominators is obtaining using both BBN theory and observational uncertainties (added in quadrature). The s_i are nuisance parameters involving the uncertainties in the nuclear rates. We can then focus on the this region and the resulting χ^2 contours in the $m_{3/2}, \zeta_{3/2}$ plane are shown in the left panel of Fig. 3 (Cyburt et al. 2010).

In the limit of large $m_{3/2}$ and/or small $\zeta_{3/2}$, the value of the χ^2 function approaches ~ 31.7, corresponding to its standard BBN value. This large value of χ^2 is effectively a manifesta-

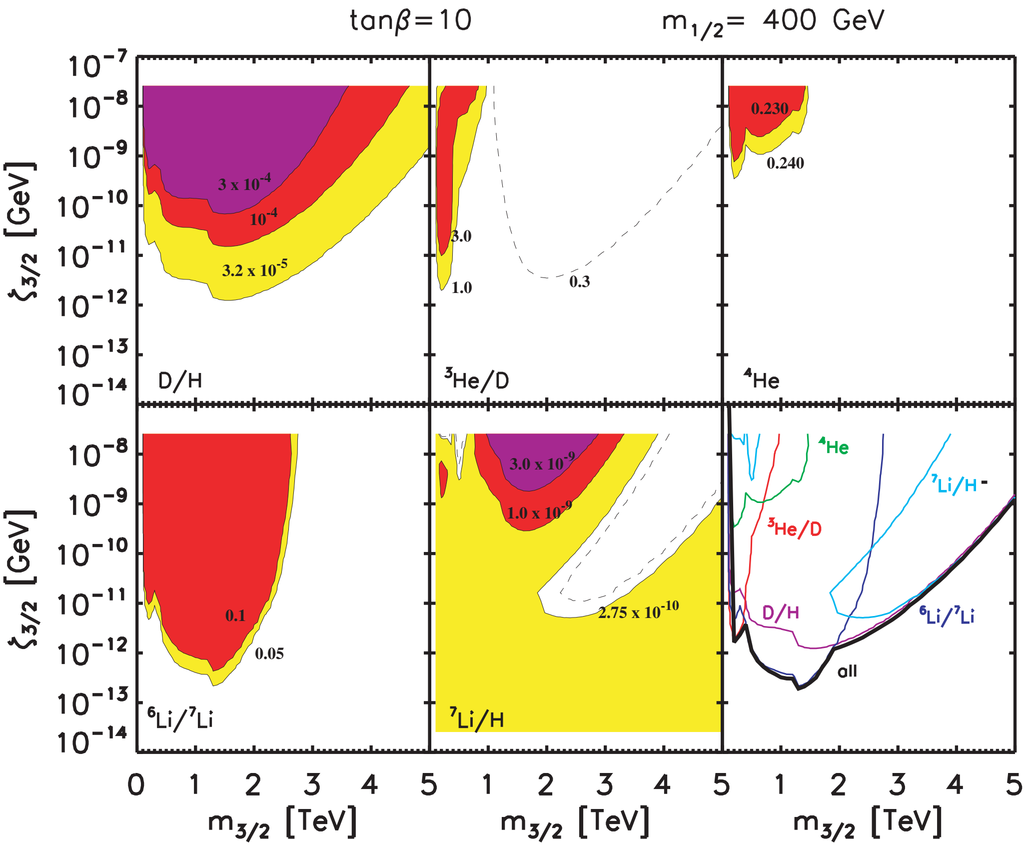

Fig. 2. The effects of the decays of a gravitino with mass $m_{3/2}$ on the different light-element abundances for a specific point (benchmark C of Battaglia et al. 2001) with $m_{1/2}$ = 400 GeV on the WMAP coannihilation strip for a CMSSM scenario with $\tan\beta = 10, A_0 = 0$. Shading is the same as in the previous figure.

tion of the ^{7}Li problem. We see that there is a 'trough' of much lower χ^2 with a minimum at $\sim$ 5.5, shown by a cross. The contours of χ^2 = 6 and 9.2, correspond to the 95 and 99% CLs for fitting to two parameters. Also shown are the higher χ^2 contours of 32 (corresponding to the BBN value) and 50.

In Table 1, the various abundances and χ^2 contributions for each of the three light elements for the standard BBN result and the best-fit point is shown for benchmark point C as well as three other benchmark points discussed in Cyburt et al. (2010). It is interesting to note the tension between D and ^{7}Li. At each of the best fit points, there is a considerable reduction in ^{7}Li, approaching the observational value. The minimum value $\chi^2 \sim 5.5$ certainly amounts to a mitigation of the ^{7}Li problem, but not a solution, in the sense that since we are fitting two parameters ($m_{3/2}$ and $\zeta_{3/2}$) and using 3 measurements, we have effectively only one degree of freedom and χ^2/d.o.f. $\sim$ 5.5. However, this improvement in ^{7}Li comes at the expense of D/H, which at this point begins to make a more significant contribution to the total χ^2. On the other hand, the ^{4}He abundance Y_p does not contribute significantly to the likelihood at any point in the parameter space. At the minimum, the deuterium abundance contributes $\Delta\chi^2 \sim 1.5$, whereas the ^{7}Li abundance contributes $\Delta\chi^2 \sim 3.4$. Thus the previous 4- or 5-σ ^{7}Li problem is reduced to a $\lesssim$ 2-σ problem.

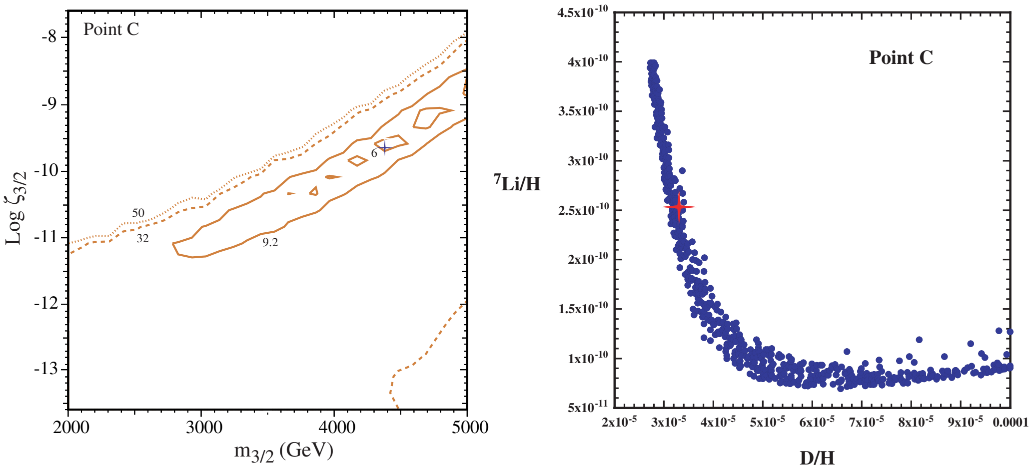

Fig. 3. Left: Contours of the χ^2 function in the $(m_{3/2}, \zeta_{3/2})$ planes for the benchmark CMSSM scenarios C incorporating the uncertainties in the nuclear rates Cyburt et al. (2010). Right: The resulting ^{7}Li abundance as a function of the resulting D/H abundance due to the late decays of a massive gravitino (Olive et al. 2012).

As noted earlier, it is known that there is a systematic difference in the ^{7}Li abundances determined in globular clusters (González Hernández et al. 2009). Using abundance of ^{7}Li seen in NGC6397 results in a lower χ^2 as seen for benchmark points C and M in the second set of results shown in the Table. The best-fit χ^2 values drop considerably in this case, with values of 2.0 and 2.7 for points C and M respectively. Thus a massive ($\gtrsim$ 4 TeV) gravitino can provide a potential solution of the lithium problem if globular cluster data is assumed to represent the primordial ^{7}Li abundance.

It is important to keep in mind that the deuterium abundances also carry considerable (systematic) uncertainty. Indeed, the sample variance is much larger than than the error in the weighted mean of the deuterium abundance determinations. Using the larger uncertainty, one can obtain solutions with χ^2 = 2.8 and a best-fit point with a ^{7}Li/H abundance of 1.81×10^{-10} coming at the expense of a higher D/H abundance of 3.56×10^{-5}. When the globular cluster value of ^{7}Li/H is used together with the higher D/H uncertainty, we can even find a best-fit solution with χ^2 = 1.1: D/H = 3.20×10^{-5} and ^{7}Li/H = 2.45×10^{-10}. These solutions are shown in the final two rows of the Table.

As can be ascertained from the above discussion, the optimum solution involves a trade-off between lower Li and higher D. This correlation is seen in the right panel of Fig. 3 (Olive et al. 2012). The resulting D/H and ^{7}Li abundances are shown for gravitino masses in the range 2-5 TeV with abundances $\zeta_{3/2}$ = $2.4 \times 10^{-14} - 2.4 \times 10^{-8}$ GeV with cuts: ^{7}Li/H $< 4 \times 10^{-10}$ and D/H $< 10^{-4}$. The best fit point is shown by a (red) star. It should be noted that the D/H abundance is already relatively high at the best fit points with respect to the weighted mean of D/H as determined from observations of quasar absorption systems.

Since the deuterium abundance is a monotonically decreasing function of time, the ultimate solution to the ^{7}Li problem may require a relatively high initial D/H abundance and a Lithium abundance which is in agreement with observations. In Fig. 4 (Olive et al. 2012), the evolution of the the D/H abundance as a function of redshift and the Li/H abundance (A = $\log Li/H + 12$) as a function of Fe/H is shown for three sets of initial conditions based on a model of cosmic chemical evolution (Daigne et al. 2004, 2006). As one can see, the evo-

Table 1. Results for the best-fit points for CMSSM benchmarks C, E, L and M. The second set of results for C and M correspond to the globular cluster value for primordial ^{7}Li/H. The third and fourth entries for point C correspond to the higher adopted uncertainty for D/H in field stars and to the globular cluster ^{7}Li abundances, respectively.

	$m_{3/2}$[GeV]	$\mathrm{Log}_{10}(\zeta_{3/2}/[\mathrm{GeV}])$	Y_p	D/H ($\times 10^{-5}$)	^{7}Li/H ($\times 10^{-10}$)	$\sum s_i^2$	χ^2
BBN	——	——	0.2487	2.52	5.12	——	31.7
C	4380	−9.69	0.2487	3.15	2.53	0.26	5.5
E	4850	−9.27	0.2487	3.20	2.42	0.29	5.5
L	4380	−9.69	0.2487	3.21	2.37	0.26	5.4
M	4860	−10.29	0.2487	3.23	2.51	1.06	7.0
C	4680	−9.39	0.2487	3.06	2.85	0.08	2.0
M	4850	−10.47	0.2487	3.11	2.97	0.09	2.7
C	3900	−10.05	0.2487	3.56	1.81	0.02	2.8
C	4660	−9.27	0.2487	3.20	2.45	0.16	1.1

lutionary history which best agrees with the Li abundance is in agreement with the highest D/H abundances observed as well as the local interstellar medium value at $z = 0$. It can not, however, explain the dispersion seen in the narrow redshift range of the data. The dispersion may be a consequence of different star formation histories in the galaxies associated with the damped Lyman alpha absorbers.

3. Variable constants

A still more exotic solution to the Li problem is the possibility of a variation in the fundamental constants (Dmitriev et al. 2004; Coc et al. 2007; Berengut et al. 2010). The success of BBN relies on a fine balance between the overall expansion rate of the Universe and the weak interaction rates

$$G_F^2 T_f^5 \sim \Gamma_{wk}(T_f) \sim H(T_f) \sim \sqrt{G_N N} T_f^2, \qquad (2)$$

where T_f is the freeze out temperature defined by this equation. This balance controls the relative number of neutrons to protons at the onset of nucleosynthesis. Changes in the expansion rate, characterized by the Hubble parameter H which is proportional to $\sqrt{G_N N}$ where N is the number of relativistic particles, or changes in the weak rates, which may result from changes in fundamental parameters, affect the neutron-to-proton ratio and ultimately the ^{4}He abundance, Y. Thus one can use the concordance between the theory and the observational determination of the light element abundances to constrain new physics (Cyburt et al. 2005).

The dominant contribution to changes in the helium abundance, Y, come from changes in the neutron-proton mass difference, Δm_N and changes in the fine structure constant affect Δm_N directly,

$$\Delta m_N \sim a\alpha\Lambda_{QCD} + bv, \qquad (3)$$

where $\Lambda_{QCD} \sim O(100)$ MeV is the mass scale associated with strong interactions, $v \sim O(100)$ GeV is the Higgs vacuum expectation value which determines the weak scale. The constants a and b are numbers which fix the final contribution to Δm_N to be −0.8 MeV and 2.1 MeV, respectively. Because of the relatively good agreement between theory and observation for ^{4}He, one can obtain a reasonable limit on $\Delta\alpha/\alpha$ from BBN (Kolb, Perry, & Walker 1986; Bergstrom, Iguri, & Rubenstein 1999; Campbell & Olive 1995; Nollett & Lopez 2002; Ichikawa & Kawasaki 2004). If the dominant contribution to $\Delta\alpha$ comes from changes in Δm_N, and we use the current uncertainty in the observationally determined value of Y_p (Aver et al. 2012), we obtain a bound of $|\Delta\alpha/\alpha| < 0.03$. If the variations in α are related to other gauge and Yukawa couplings, this limit improves by about two orders of magnitude (Campbell & Olive 1995; Ichikawa

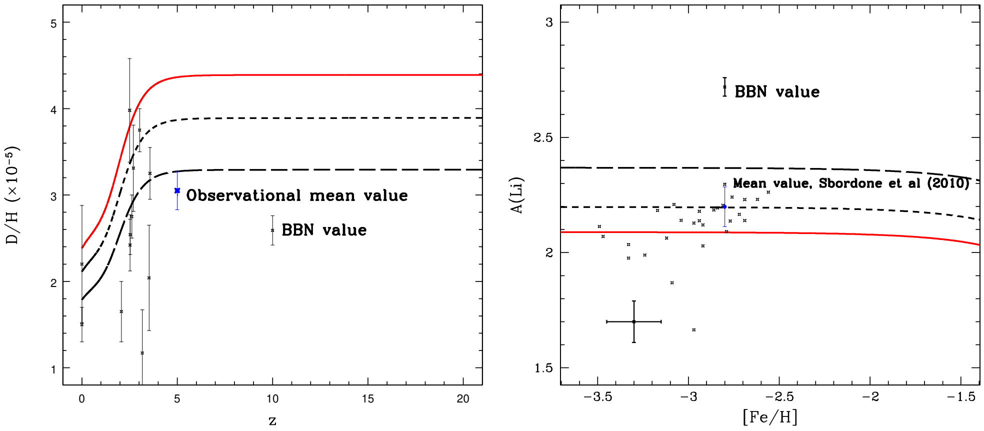

Fig. 4. D/H abundance as a function of redshift (left) and A(Li) = $\log(Li/H) + 12$ as a function of [Fe/H] (right). The red solid (black short dashed and large dashed) lines correspond to initial post-BBN Li/H, D/H values: 1.23×10^{-10}, 4.4×10^{-5}, (1.58×10^{-10} , 3.9×10^{-5}, and 2.34×10^{-10}, 3.3×10^{-5}) respectively.

& Kawasaki 2002; Müller et al. 2004; Coc et al. 2007).

In unified theories of particle interactions, one often imposes gauge coupling unification at some high energy scale. At that scale (typically of order 2×10^{16} GeV), all gauge couplings are equal and run to their respective values at low energies (though in order to obtain the correct values at low energies one requires supersymmetry). In this case, a change in the fine structure constant would directly imply a change in other gauge couplings (Campbell & Olive 1995). More importantly, variations in the strong gauge coupling, α_s, will induce variations in the QCD scale, Λ_{QCD}, as is evident from the low energy expression for Λ when mass thresholds are included

$$\Lambda = \mu \left(\frac{m_c\, m_b\, m_t}{\mu^3} \right)^{2/27} \exp\left(-\frac{2\pi}{9\alpha_s(\mu)} \right) . \tag{4}$$

for a renormalization scale $\mu > m_t$ up to the unification scale (Campbell & Olive 1995; Langanker, Segre, & Strassler 2002), where $m_{c,b,t}$ are the masses of the charm, bottom, and top quarks.

In addition, it may happen that variations in gauge couplings also induce variations in the Yukawa couplings. This is expected in many string theories where all such couplings are determined by the expectational value of a dilaton and we might expect (Campbell & Olive 1995)

$$\frac{\Delta h}{h} = \frac{1}{2} \frac{\Delta \alpha}{\alpha}, \tag{5}$$

where h is a Yukawa coupling and fermion masses are simply proportional to hv. Variations in Yukawa couplings will also affect variations in Λ_{QCD} so that

$$\begin{aligned} \frac{\Delta \Lambda}{\Lambda} &= R \frac{\Delta \alpha}{\alpha} \\ &+ \frac{2}{27} \left(3 \frac{\Delta v}{v} + \frac{\Delta h_c}{h_c} + \frac{\Delta h_b}{h_b} + \frac{\Delta h_t}{h_t} \right) . \end{aligned} \tag{6}$$

Typical values for R are of order 30 in many grand unified theories, but there is considerable model dependence in this coefficient (Dine et al. 2003).

Furthermore, in theories in which the electroweak scale is derived by dimensional transmutation, changes in the Yukawa couplings (particularly the top Yukawa) lead to exponentially large changes in the Higgs vev (Campbell & Olive 1995)

$$v \sim M_P \exp(-2\pi c/\alpha_t), \tag{7}$$

where c is a constant of order 1, and $\alpha_t = h_t^2/4\pi$. Thus small changes in h_t will induce large changes in v. For $c \sim h_t \sim 1$,

$$\frac{\Delta v}{v} \sim S\frac{\Delta h}{h}, \tag{8}$$

with $S \sim 240$, though there is considerable model dependence in this value as well. For example, in supersymmetric models, S can be related to the sensitivity of the Z gauge boson mass (also proportional to the Higgs vev) to the top Yukawa, and may take values anywhere from about 80 to 500 (Ellis et al. 2002). This dependence gets translated into a variation in all low energy particle masses (Dixit & Sher 1988; Scherrer & Spergel 1993; Yoo & Scherrer 2003). In short, once we allow α to vary, virtually all masses and couplings are expected to vary as well, typically much more strongly than the variation induced by the Coulomb interaction alone.

The quantities of interest in this calculation are (Coc et al. 2007), the neutron-proton mass difference, $Q = \Delta m_N$, the neutron mean life, τ_n, and the deuterium binding energy, B_D. These can be expressed in terms of R and S assuming Eq. (5), as (Coc et al. 2007)

$$\frac{\Delta B_D}{B_D} = -[6.5(1+S) - 18R]\frac{\Delta\alpha}{\alpha} \tag{9}$$

$$\frac{\Delta Q}{Q} = (0.1 + 0.7S - 0.6R)\frac{\Delta\alpha}{\alpha} \tag{10}$$

$$\frac{\Delta\tau_n}{\tau_n} = -[0.2 + 2S - 3.8R]\frac{\Delta\alpha}{\alpha}\,. \tag{11}$$

These relations can then be implemented in a BBN calculation. Some results (Coc et al. 2007) are shown in Fig. 5 where the parameter $S = 240$ is held fixed and results are shown for three values of R. For $R = 36$, the deuterium abundance can be used to set a limit

$$-1.6\times10^{-5} < \frac{\Delta h}{h} < 2.1\times10^{-5}\,. \tag{12}$$

As one can see, from Fig. 5, as one moves towards the upper end of the constraint on Δh given in Eq. (12), we see that the ^{7}Li abundance is lower than the standard BBN result and moves within the range of abundances determined from field stars. The limit (12) is in fact established from upper limit on the mean D/H abundance determined from quasar absorption systems. As argued earlier, resolving the ^{7}Li problem at the expense of higher D/H implies the in situ destruction of deuterium in those systems.

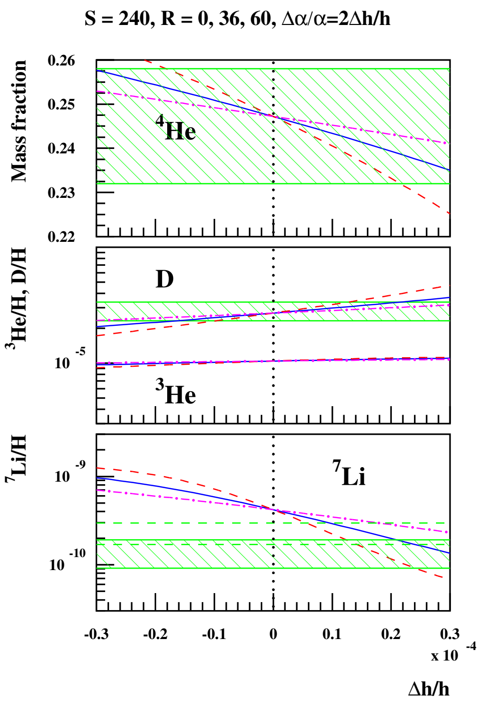

Fig. 5. Primordial abundances of ^{4}He, D, ^{3}He and ^{7}Li as a function of $\Delta h/h = (1/2)\Delta\alpha/\alpha$ when allowing a variation of the fine structure constant for three values of the R parameter: $R = 0$ (red lines), $R = 36$ (blue lines) and $R = 60$ (magenta lines).

4. Conclusions

While there is overall concordance between BBN calculations of D/H and Y and their observational determination, there is at present a problem with ^{7}Li. Despite many efforts, there is still no acceptable solution within the context of the standard model. When one goes beyond the standard model, there are several possibilities. Here, two of these have been discussed. Supersymmetric theories naturally contain a long lived particle, the gravitino, which if massive enough may decay during or shortly after BBN and could lower the ^{7}Li abundance to acceptable values. It is also possible that the fundamental constants of nature have varied across cosmological timescales, though there are many constraints on such variations. It is possible that a variation of order 10^{-5} would decrease the primordial abundance of ^{7}Li while slightly increasing D/H. Indeed both exotic solutions discussed here, lead to enhanced D/H. These solutions to the Li problem may require a change in our interpretation of D/H in quasar absorption systems. Perhaps only those systems showing the highest D/H actually correspond to primordial D/H.

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