BIG BANG NUCLEOSYNTHESIS: AN UPDATE

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The current status of big bang nucleosynthesis is reviewed with an emphasis on the comparison between the observational determination of the light element abundances of $D, ^3He, ^4He$ and $^7Li$ and the predictions from theory. In particular, we present new analyses for $^4He$ and $^7Li$. Implications for physics beyond the standard model are also discussed. Limits on the effective number of neutrino flavors are also updated.

1. Introduction

The overall status of big bang nucleosynthesis is determined by the comparison of the rather slowly changing theoretical predictions of the light element abundances and the sometimes quickly changing observationally determined abundances. The observed elements, $D, ^3He, ^4He, ^7Li$, have abundances relative to hydrogen which span nearly nine orders of magnitude. By and large, these observations are consistent with the theoretical predictions and play a key role in determining the consistency of what we refer to as the standard big bang model and its extrapolation to time scales on the order of one second. Here, we will review the status of this consistency. We begin by briefly outlining the key sequence of events in the early Universe which leads to the formation of the light elements and then discuss the current status of the observations in relation to theory of each of the light elements. Finally, we will discuss the current limits on physics beyond the standard model.
2. A Brief Primer on the Theoretical Predictions

Conditions for the synthesis of the light elements were attained in the early Universe at temperatures $T \lesssim 1$ MeV, corresponding to an age of about 1 second. At somewhat higher temperatures, weak interaction rates were in equilibrium, thus fixing the ratio of number densities of neutrons to protons. At $T \gg 1$ MeV, $(n/p) \simeq e^{-\Delta m/T}$, where $\Delta m$ is the neutron-proton mass difference. The final abundance of $^4$He is very sensitive to the $(n/p)$ ratio.

The nucleosynthesis chain begins with the formation of deuterium through the process, $p + n \rightarrow D + \gamma$. However, because the large number of photons relative to nucleons, $\eta^{-1} = n_\gamma/n_B \sim 10^{10}$, deuterium production is delayed past the point where the temperature has fallen below the deuterium binding energy, $E_B = 2.2$ MeV (the average photon energy in a blackbody is $\bar{E}_\gamma \simeq 2.7T$). When the quantity $\eta^{-1} \exp(-E_B/T) \sim 1$ the rate for deuterium destruction ($D + \gamma \rightarrow p + n$) finally falls below the deuterium production rate and the nuclear chain begins at a temperature $T \sim 0.1 MeV$.

The dominant product of big bang nucleosynthesis is $^4$He resulting in an abundance of close to 25% by mass. This quantity is easily estimated by counting the number of neutrons present when nucleosynthesis begins. When the weak interaction rates freeze-out, at $T \approx 0.8$ MeV, the neutron to proton ratio is about 1/6. When free neutron decays are taken into account prior deuterium formation, the ratio drops to $(n/p) \approx 1/7$. Then simple counting yields a $^4$He mass fraction

$$Y_p = \frac{2(n/p)}{1 + (n/p)} \approx 0.25$$

In the standard model, the $^4$He mass fraction depends primarily on the baryon to photon ratio, $\eta$ as it is this quantity which determines the onset of nucleosynthesis via deuterium production. But because the $(n/p)$ ratio is only weakly dependent on $\eta$, the $^4$He mass fraction is relatively flat as a function of $\eta$. The change due to the uncertainty in the neutron half-life is small (this effect is shown in Fig. 1). When we go beyond the standard model, the $^4$He abundance is very sensitive to changes in the expansion rate which can be related to the effective number of neutrino flavors as will be discussed below. Lesser amounts of the other light elements are produced: D and $^3$He at the level of about $10^{-5}$ by number, and $^7$Li at the level of $10^{-10}$ by number.

The resulting abundances of the light elements are shown in Figure 1 from the calculations in ref. 2. The curves for the $^4$He mass fraction, $Y$, bracket the computed range based on the uncertainty of the neutron mean-life which has been taken as $\tau_n = 887 \pm 2$ s. The $^4$He curves have been adjusted according to the corrections in ref. 4. Uncertainties in the produced $^7$Li abundances have been adopted from the results in ref. 5. Uncertainties in D and $^3$He production are negligible on the
Fig. 1. The light element abundances from big bang nucleosynthesis.
scale of this figure. The boxes correspond to the observed abundances and will be discussed below. It is clear that as the observational boxes line up on top of each other, there is an overall agreement between theory and observations in the range $\eta_{10} = 10^{10}\eta = 2.8 - 4.5$.

3. The Observations

3.1. $^4\text{He}$

Because helium is produced in stars along with heavier elements, it is necessary to look for primordial helium in regions where the stellar processing is minimal, i.e., in regions where the abundances of elements such as carbon, nitrogen and oxygen are very low. The $^4\text{He}$ abundance in very low metallicity regions is best determined from observations in extragalactic HII regions of HeII $\rightarrow$ HeI recombination lines. There are extensive compilations of observed abundances of $^4\text{He}$, N, and O, in many different galaxies. In Figure 2, the $^4\text{He}$ vs. O/H data is shown along with its associated linear fit. This is an updated version of the plot from ref. 9, including data from ref. 8 (details of this fit are given in the last line of Table 1).

Fig. 2. The observed abundances of $^4\text{He}$ vs. O/H in extragalactic HII regions along with a linear fit to the data.

In Table 1, various fits to the data and subsets of the data are given. Details
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Table 1. Linear Fits for $Y$ vs. $O/H$.

| Set         | # Regions | $r$  | $\chi^2$/dof | $Y_p$   | $10^{-2} \times$ slope | $Y^{2\sigma}_p$ |
|-------------|-----------|------|--------------|---------|------------------------|-----------------|
| “All”       | 49        | 0.56 | 0.78         | 0.234 ± 0.003 | 1.14 ± 0.24 | 0.239                |
| 1st cut     | 41        | 0.51 | 0.61         | 0.232 ± 0.003 | 1.38 ± 0.36 | 0.238                |
| -outliers   | 34        | 0.45 | 0.70         | 0.232 ± 0.003 | 1.39 ± 0.38 | 0.238                |
| 2nd cut     | 21        | 0.41 | 0.64         | 0.229 ± 0.005 | 2.37 ± 1.13 | 0.238                |
| -outliers   | 19        | 0.40 | 0.70         | 0.229 ± 0.005 | 2.42 ± 1.15 | 0.238                |
| C           | 22        | 0.35 | 0.71         | 0.232 ± 0.003 | 1.58 ± 0.54 | 0.238                |
| IZ + “All”  | 55        | 0.53 | 0.82         | 0.236 ± 0.002 | 1.02 ± 0.23 | 0.240                |
| IZ + 1st cut| 47        | 0.49 | 0.69         | 0.234 ± 0.003 | 1.24 ± 0.33 | 0.239                |

Concerning the subsets of the data shown (as well as a more complete discussion on primordial $^4$He) can be found in ref. 9. As one can see there is a considerable degree of stability in these fits, leading to a 2σ upper limit of 0.238–0.240 for the primordial abundance of $^4$He. There is in addition an overall systematic uncertainty of about 0.005 in $Y_p$.

The size of the assumed systematic errors has recently been questioned. Several sources for the systematic errors have been discussed and it has been argued that the systematic error is in fact significantly larger than 0.005. Though the cumulative effect from several systematic uncertainties is unclear, linearly adding the various systematic errors assumes that they are correlated and will surely result in an over-estimate of the true error. On the other hand, the effects of detailed radiative transfer may be more important than previously thought in determining the $^4$He abundance, and pending new results concerning these calculations it is premature to estimate the size of the correction to $Y$, if any. For now, we will continue to assume that $\sigma_{\text{systematic}} = 0.005$ though we must bear in mind that the true error may be somewhat larger.

As was noted, from Table 1 it appears that the results for $Y_p$, the intercept of the linear fit to the $Y$ vs. $O/H$ data, are quite stable. In order to test the stability of the fit, we have randomly sampled 49 points from the 49 observed points from refs. 6 and 7 and included in fig. 2. 10,000 separate sets of 49 points were obtained. We then performed a least squares linear fit to each set of points. The helium fraction for the zero metallicity point for each of the fits is illustrated in fig. 3. The fits are strongly peaked around the mean value of $0.232 \pm 0.003$ (0.005 at 95% CL) in remarkable agreement with the simple linear fit in the first line of Table 1. We can conclude that there are apparently no observed points that are strongly influencing the fit. We have similarly run tests on the first cut data set of 41 points, with the resulting mean value for the intercepts of $0.232 \pm 0.003$ (0.007 at 95% CL).

Subsequent to the analysis in ref. 9, concerning primordial $^4$He, there has been some newer data on $^4$He in low metallicity extragalactic HII regions. Here we show how these results modify the above fits of $^4$He vs O/H. The data in Izatov et al. consists of $^4$He, O/H, and N/H measurements in 10 extragalactic HII regions. Four

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[Work done in collaboration with G. Steigman]
of these regions had been observed in Skillman et al. 7 and these have been averaged together with the new data. Thus there are a total of 6 new points in the data set. We will not enter into the discussion regarding the methods of data reductions used by Izatov. Here we have used their data based on having taken electron densities from the ratio of collisionally excited SII lines (see ref. 8, for details). Though there is a slight shift upwards, the shift is entirely consistent within the statistical uncertainties. One could however make a case that based on this set of data (the combined set) that the $2 \sigma$ upper limit to $Y_p$ is 0.239 which moves up to 0.244 when a systematic uncertainty of 0.005 is added.

It is also of interest to compare the correlation of $^4\text{He}$ with N/H. Indeed, a comparison of N/H vs O/H is also of interest. Since the stars which produce oxygen do not coincide exactly with those which produce nitrogen, the linear regression of $Y$ vs N/H is another consistency check. For the same data as discussed above, the
corresponding results to $Y$ vs N/H are given in Table 2. Again, we see that there is a considerable degree of consistency within the data. The 2 $\sigma$ upper limit is slightly higher. The stability of the $Y$ vs N/H fits was also checked (by the same method used to generate Fig.3). For the full data set of 49 points from ref. 9 (line 1 of Table 2), the mean value of intercepts found was $0.234 \pm 0.002$ (0.005 at 95% CL). For the first cut set of points (line 2 of Table 2), the resulting mean value was also $0.234$ with a slightly larger uncertainty $\pm 0.003$ (0.006 at 95%CL).

Looking at Tables 1 and 2, it is not unreasonable to take as the best estimate to the primordial mass fraction of $^4$He

$$Y_p = 0.234 \pm 0.003 \pm 0.005$$

with a $2 \sigma$ upper limit of 0.240 and 0.245 when systematic uncertainties are included. Thus we will assume a range ($2 \sigma$ plus systematic) of $0.223 - 0.245$ for $Y_p$ which is shown in Fig. 1 as the large box bracketing the $^4$He curves.

Before concluding the discussion on $^4$He, we would like to update an older analysis concerning the correlation of $^4$He with C/H. It was suggested that because carbon (and nitrogen) are produced in intermediate mass stars, that the correlation between these elements and $^4$He might be more significant than that of $^4$He and O/H. The correlation between $^4$He and C/H was tested in Walker et al.
where the fit to $Y$ vs. C/H gave similar results as for $Y$ vs O/H and N/H albeit with larger uncertainties due to the poor statistics (there were only 6 extragalactic HII regions with measured C/H). Recently there have been new measurements of C/O ratios in seven regions. The data are somewhat better than previous data (at least for small C/H) and are shown in Fig. 5. Once again, $Y$ vs C/H is of limited value because of the paucity of data, yet yields a consistent (with O/H and N/H) fit with an intercept $Y_p = 0.231 \pm 0.004$ with a 2 $\sigma$ upper limit of 0.240; the same as we have concluded above from O/H and N/H.

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Table 2. Linear Fits for $Y$ vs. N/H.

| Set               | # Regions | $r$  | $\chi^2$/dof | $Y_p$       | $10^{-2} \times$ slope | $Y_p^{2\sigma}$ |
|-------------------|-----------|------|--------------|-------------|-------------------------|-----------------|
| All               | 49        | 0.66 | 0.66         | 0.236 ± 0.002 | 1.72 ± 0.33             | 0.240           |
| 1st cut           | 41        | 0.57 | 0.58         | 0.234 ± 0.002 | 2.71 ± 0.68             | 0.239           |
| -outliers         | 34        | 0.48 | 0.69         | 0.234 ± 0.003 | 2.77 ± 0.76             | 0.239           |
| 2nd cut           | 21        | 0.47 | 0.63         | 0.231 ± 0.004 | 4.85 ± 2.27             | 0.239           |
| -outliers         | 19        | 0.44 | 0.70         | 0.232 ± 0.004 | 4.79 ± 2.29             | 0.239           |
| C                 | 22        | 0.46 | 0.60         | 0.233 ± 0.003 | 3.62 ± 1.17             | 0.238           |
| IZ + “All”        | 55        | 0.61 | 0.74         | 0.239 ± 0.002 | 1.51 ± 0.31             | 0.242           |
| IZ + 1st cut      | 47        | 0.52 | 0.70         | 0.237 ± 0.002 | 2.35 ± 0.64             | 0.241           |

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Fig. 5. The observed abundances of $^4$He vs. C/H in extragalactic HII regions along with a linear fit to the data.
3.2. D and $^3$He

It is more difficult to compare the primordial deuterium and $^3$He abundances with the observations. Despite the fact that all observed deuterium is primordial, deuterium is destroyed in stars. A comparison between the predictions of the standard model and observed solar and interstellar values of deuterium must be made in conjunction with models of galactic chemical evolution. The problem concerning $^3$He is even more difficult. Not only is primordial $^3$He destroyed in stars but it is very likely that low mass stars are net producers of $^3$He. Thus the comparison between theory and observations is complicated not only by our lack of understanding regarding chemical evolution but also by the uncertainties of the production of $^3$He in stars. Furthermore, due to the large uncertainty in the age of the galaxy, it is difficult to directly compare the observed and modeled values of deuterium and $^3$He since the exact galactic age at which the pre-solar epoch occurs is unknown. We will return to this problem below.

It appears that D/H has decreased over the age of the galaxy. The (pre)-solar system abundance of deuterium is inferred from a variety of $^3$He measurements in the solar wind, lunar soil samples and meteoritic samples. There are two components of $^3$He: one associated with the pre-solar abundance of deuterium and $^3$He (the deuterium was converted in the early pre-main-sequence stage of the sun); while the second is $^3$He trapped in meteorites which represents the true solar value of $^3$He

$$\frac{D + ^3\text{He}}{H} \odot = (4.1 \pm 1.0) \times 10^{-5}$$ (3)

$$\frac{^3\text{He}}{H} \odot = (1.5 \pm 0.3) \times 10^{-5}$$ (4)

The difference between the two $^3$He measurements represents the presolar D abundance and is $D/H \approx (2.6 \pm 1.0) \times 10^{-5}$. On the other hand, the present ISM abundance of D/H is

$$D/H = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5}$$ (5)

It is this lower limit on D/H (since D is only destroyed) that provides us with the the upper bound on $\eta$. It is shown as the lower side of the D and $^3$He box in Fig. 1. Thus, if $\eta_{10}$ is in the range 2.8 – 3.9 then the primordial abundance of D/H is between $4.5 - 8 \times 10^{-5}$, and it would appear that significant destruction of deuterium is necessary.

Note that there are reported detections of D in high redshift, low metallicity quasar absorption systems. In principle, these measured abundances should represent the primordial one. Unfortunately, at this time, the two observations do not yield a single value for D$_p$. In one, D/H $\approx 1.9 - 2.5 \times 10^{-4}$ while the second gives, D/H $\approx 1 - 2 \times 10^{-5}$. (One should note that it has been argued that these types of measurements are subject to large systematic corrections, thus it may not be all that surprising that the two measurements differ.) The former observation
is shown in Fig. 1 by the small box on the D/H curve at a value of $\eta_{10} \approx 1.5$. As one can see the corresponding value of $Y_p$ (at the same value of $\eta$) is in excellent agreement with the data. $^7$Li is also acceptable at this value as well. Due to the still some what preliminary status of this observation it is premature to fix the primordial abundance with this value. A high value for the D abundance would require an even greater degree of D destruction over the age of the galaxy. The lower measurement for D/H is problematic for both $^4$He and $^7$Li.

To trace the evolution of D and $^3$He, we can make use of some simple models of galactic chemical evolution. For a general review on chemical evolution see ref. 20. We shall adapt her same basic notation in the following discussion. One can relate the deuterium abundance at any time to the gas mass fraction noting that deuterium is only destroyed in stars. The equation for the gas mass in the galactic disk is

$$\frac{dM_G}{dt} = e(t) - \psi(t) + f(t).$$

(6)

In this equation, $e(t)$ is the gas ejected from stars at the end of their lifetimes either in planetary nebulae or supernova events,

$$e(t) = \int_{m(t)}^{m_{upp}} (m - m_R)\psi(t - \tau(m))\phi(m) \, dm.$$  

(7)

In these equations, $f(t)$ is the infall rate onto the disk of gas whose origins is external to the galaxy. $\phi(m)$ is the initial mass function (IMF), and $\psi(t)$ is the star formation rate (SFR). $m_{upp}$ is the upper mass limit on $\phi(m)$. $\tau(m)$ is the lifetime of a star of mass $m$, and $m_R$ is the remnant mass left over by a star of mass $m$. $m(t)$ is is the mass of a star which at time $t$ is returning gas back into the ISM.

In order to model the deuterium evolution, we consider D to be totally astrated within stars. We may extend equation (6),

$$\frac{dD}{dt} = -e(t)D + f(t)(D_f - D).$$

(8)

where $D_f$ is the mass fraction of D in the infall gas. Using the instantaneous recycling approximation (an assumption which ignores delays due to finite stellar lifetimes, and is an acceptable approximation at early times and for elements which are produced in massive stars whose lifetimes are short) we can combine Eqs. (6) and (8) to give the total amount of deuterium destruction relative to its initial primordial value $D_p$,

$$\frac{D}{D_p} = \sigma R/(1-R)$$

(9)

where $\sigma$ is the gas mass fraction and the return fraction $R$ is given by

$$R = \int_{m(t)}^{m_{upp}} (m - m_R)\phi(m) \, dm$$

(10)
By a suitable choice for the IMF (and SFR) a considerable amount of deuterium may have been destroyed.

As we noted above, to match the abundances in a model of galactic evolution to the observations requires knowledge of the time at which the solar system was formed. In order to solve this problem, we have incorporated the production of the long-lived r-process nuclear chronometers $^{232}\text{Th}$, $^{235}\text{U}$, and $^{238}\text{U}$ into chemical evolution models. Previously, these chronometers have been used in simple chemical evolution models in an attempt to constrain the overall galactic age. This is accomplished by finding a time at which the modeled ratios $^{232}\text{Th}/^{238}\text{U}$ and $^{235}\text{U}/^{238}\text{U}$ match (if ever) the values of these ratios determined from meteorite data ($^{232}\text{Th}/^{238}\text{U} = 2.32$ and $^{235}\text{U}/^{238}\text{U} = .317$). This time is taken to be the pre-solar epoch, and 4.6 Gyrs. later, today.

A full description of how nuclear chronometers may be incorporated in general into galactic chemical evolution models can be found in ref. 25. We summarize the main points below. Nuclear chronometers are incorporated into the calculation by an extension of the basic equation of the gas mass in the galactic disk discussed above. We may extend equation (6) to determine the rate of change in the number of nuclear species $A$,

$$\frac{dN_A}{dt} = P_A\psi(t) - \frac{\psi(t)N_A}{M_G} + \frac{e(t)N_A}{M_G} + \frac{f}{M_G} Z_f \frac{Z}{Z_f} N_A - \lambda_A N_A. \quad (11)$$

In this equation, $P_A$ is the number of newly synthesized nuclei of species $A$ per unit mass going into star formation. The relative production ratios, $P_{232}/P_{238}$, and $P_{235}/P_{238}$, have been determined by supernova models: $P_{232}/P_{238} = 1.60$, and $P_{235}/P_{238} = 1.16$. Since we have assumed the infall gas to be primordial, $Z_f$, the metallicity of the infall gas, has been taken to be zero. And finally, $\lambda_A$ is the rate of decay of nuclear species $A$. As a simplification, the amount of nuclear species “$A$” which decays while locked up in stars was not taken into account equation (3). Only large stars will contribute to the production of these nuclear species and they have lifetimes which are very short when compared with the decay times.

Equations (6) and (11) can then be solved numerically. In order to satisfy observational constraints, the value of $N_A(0)$ is allowed to be non-zero. This corresponds to an initial enrichment ($S_0$) in the galactic disk of metals. This solves the so-called G-dwarf problem; where observationally, there appear to be very few metal poor dwarf stars in the disk.

We have found a wide range of chemical evolution models capable of destroying $D$ by a factor of 5, which also satisfy our nuclear chronometer constraint. These models result in a range of galactic ages ($11.1 - 15.0$ Gyrs). The result of one of these models is shown in Fig. 6.

There are however potential problems for $^3\text{He}$. A lower limit on $\eta$ was derived by noting that although stars can destroy $^3\text{He}$, even very massive stars, still preserve at least 25 % of the initial D + $^3\text{He}$. (It is the sum of D and $^3\text{He}$ that is important as D is burned to $^3\text{He}$ in the premain-sequence phase of stars.) A value of $\eta_0$ lower than 2.8 would yield $(\text{D+}^3\text{He})/\text{H} > 10^{-4}$ so that even if the maximal amount of $^3\text{He}$ is
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Fig. 6. The evolution of D/H in several models of galactic chemical evolution.

destroyed, it would still exceed the presolar value of \((D+^3\text{He})/H \approx 4.1 \pm 1.0 \times 10^{-5}\). But, in low mass stars, \(^3\text{He}\) is produced rather than destroyed. A calculation of the final \(^3\text{He}\) abundance relative to the initial abundance of \((D+^3\text{He})\) gives,

\[
\left(\frac{^3\text{He}}{H}\right)_f = 1.8 \times 10^{-4} \left(\frac{M_\odot}{M}\right)^2 + 0.7 \left(\frac{(D+^3\text{He})}{H}\right)_i \tag{12}
\]

so that a 1 \(M_\odot\) star produces 2.7 times as much \(^3\text{He}\) as the initial \((D+^3\text{He})\) (for \((D+^3\text{He})_{\text{initial}} = 9 \times 10^{-5}\)). This would lead to an evolutionary behavior of the type shown in Fig. 7. The chemical evolution model has been chosen so that D/H agrees with the data and assumes that \(\eta_{10} = 3\). The problem being emphasized concerns \(^3\text{He}\) and can be seen by comparing the solid curve with the filled diamonds.

A number of questions regarding the \(^3\text{He}\) discrepancy can be raised. First, one can ask whether or not the formula for \(^3\text{He}\) production is valid. There is indeed evidence that \(^3\text{He}\) is produced in planetary nebulae where abundances are found as high as \(^3\text{He}/H \sim 10^{-3}\). Secondly, one may ask how uniform are the \(^3\text{He}\) measurements. As it turns out, they are in fact not very uniform and show variations as large as a factor of 5 between different HII regions. Indeed, there may even be a correlation between the size (mass) of the region and the amount of \(^3\text{He}\) observed. Thus it may be possible that the solar values are depleted in \(^3\text{He}\). It is hoped that future \(^3\text{He}\) observations will help to resolve this puzzle.
Before we conclude with D and $^3$He, we address the overall issue regarding consistency of the data and the big bang nucleosynthesis calculations. Recently, it has been suggested [33] that there is a crisis in big bang nucleosynthesis because of an underlying inconsistency between the “predicted” value of $\eta$ (from deuterium) and the $^4$He observations. The conclusion was that to a high degree of confidence, the standard model with three light neutrino flavors is excluded. Though we will return to neutrino limits in the next section, we can here dispel the notion of a major inconsistency. The crisis in ref. 33, arises from using a pedagogical expression [28] relating deuterium and $^3$He at a given time assuming that a fraction $f$ of the total gas mass passed through stars at time $t$, and that a fraction $g_3$ of the initial $D + ^3$He survives as $^3$He when $^3$He production is neglected:

$$\left(\frac{D + ^3\text{He}}{H}\right)_p \leq \left(\frac{D}{H}\right)_t + \frac{1}{g_3} \left(\frac{^3\text{He}}{H}\right)_t - \left(\frac{1 - g_3}{g_3}\right) f \left(\frac{^3\text{He}}{H}\right)_t$$

This expression has been used extensively to place a lower bound on $\eta$ by inserting the observed values for D/H and $^3$He/H at the solar epoch. This is what leads to $\eta_{10} > 2.8$ when $g_3 > 0.25$ and corresponds to the upper limit on the D + $^3$He box in Fig. 1. To be sure, this expression indicates that the best fit to deuterium is a low value for D/H ($\approx 2.3 \times 10^{-5}$). Clearly for the corresponding value of $\eta$, there is
a significant discrepancy with $^4$He. However, rather than to conclude on this basis that there is a problem with the standard model, or that we have learned something about neutrino physics, it is evident to us that what we have learned is that there is something wrong with the expression (13). Indeed it is known that even simple models of galactic evolution with $g_3 \sim 0.3$ (i.e. neglecting $^3$He production) can give a good match to the D and $^3$He solar data. In this case, the discrepancy between the prediction and observations of $^4$He is at most at the 2σ level. Of course when $^3$He production is included, the problem is more acute, requiring, perhaps, more dramatic changes in the chemical evolution models of the galaxy.

3.3. $^7$Li

Finally we turn to $^7$Li. Over the last several years, there has been a considerable increase in the number of $^7$Li observations. $^7$Li in old, hot, population II stars, is found to have a very nearly uniform abundance. For stars with a surface temperature $T > 5500$ K and a metallicity less than about 1/20th solar, the $^7$Li abundance shows little or no dispersion beyond what is consistent with errors of individual measurements. A large quantity of data has been obtained from a variety of sources and consists of observations of 55 different halo stars. The corresponding mean $^7$Li abundance is $[\text{Li}] = 12 + \log \text{Li/H} = 2.08 \pm 0.02$ or the abundance by number is Li/H = $(1.22 \pm 0.04) \times 10^{-10}$. Systematic errors however dominate the uncertainty in the $^7$Li abundance.

Furthermore there has been considerable attention to trends in the data. Namely, it appears that there may be real correlations in the $^7$Li abundances with respect to temperature and metallicity. It has been argued that to avoid any temperature dependence which may mask a real metallicity dependence, one should renormalize the derived $^7$Li abundances to a single temperature, say 6200K. For the data discussed above, there is only a weak dependence on temperature, $[\text{Li}] = 1.20 \pm 0.44 + (14 \pm 7) \times 10^{-5}T$. This fit is a modest improvement (at the 87 % CL) over the straight average. “Correcting” the data by sliding each point up to 6200K, along the line given by the fit above, one finds on the average a slightly higher $^7$Li abundance, $[\text{Li}] = 2.13 \pm 0.02$. If one were to take the raw data, (ie. $^7$Li abundances uncorrected for differing temperatures) then only a questionable correlation with metallicity would result $[\text{Li}] = 2.14 \pm 0.05 + (0.025 \pm 0.023)[\text{Fe/H}]$, where [Fe/H] is the log of the iron abundance relative to the solar iron abundance. In contrast, when the corrected lithium abundances are used a more significant correlation appears, $[\text{Li}] = 2.24 \pm 0.05 + (0.051 \pm 0.022)[\text{Fe/H}]$. This fit represents an improvement at the 98% CL over the straight average. The derived $^7$Li abundance is quite sensitive to the assumed temperatures of the stars. Most authors have obtained abundances through color-based temperatures from photometry. In addition, the results depend on the particular stellar model used. In Thorburn’s analysis of over 70 halo stars, she finds a systematically higher temperature and hence $^7$Li abundance. In this sample $[\text{Li}] = 2.26 \pm 0.01$ or Li/H = $(1.82 \pm 0.04) \times 10^{-10}$. 

The same correlation (and to higher degree) between Li and temperature and metallicity is present in the Thorburn data. The correlation with temperature in that data appears to be very strong $[\text{Li}] = 0.06 \pm 0.37 + (36 \pm 6) \times 10^{-5}T$ which leads to a higher mean $^7\text{Li}$ abundance $[\text{Li}] = 2.33 \pm 0.01$. There is also marked effect on the fit with respect to $[\text{Fe/H}]$. Using the raw $^7\text{Li}$ abundances, $[\text{Li}] = 2.49 \pm 0.09 + (0.087 \pm 0.036)[\text{Fe/H}]$ and using the corrected $^7\text{Li}$ abundances gives $[\text{Li}] = 2.73 \pm 0.08 + (0.16 \pm 0.03)[\text{Fe/H}]$. These fits all have significantly lower $\chi^2$ than does the straight average. Of course these trends make it more difficult to determine with any certainty the true primordial abundance.

Recently however, the method of obtaining temperatures by means of broadband photometry has been criticized and a strong case has been made to use a spectroscopic method based on Balmer line profiles. This method was employed in reanalyzing a relatively large set of halo stars (24 with $T > 5700K$ with $[\text{Fe/H}] < -1.4$). In this data set the mean value for $^7\text{Li}$ is $[\text{Li}] = 2.21 \pm 0.02$ or $\text{Li/H} = (1.62 \pm 0.07) \times 10^{-10}$. However in this case, there is absolutely no evidence for a trend with respect to temperature, $[\text{Li}] = 1.90 \pm 0.57 + (5 \pm 9) \times 10^{-5}T$ which corrects the mean value to $[\text{Li}] = 2.22 \pm 0.02$. More importantly there is no correlation with metallicity either. The uncorrected data gives $[\text{Li}] = 2.20 \pm 0.10 + (0.00 \pm 0.04)[\text{Fe/H}]$ while the “corrected” data gives $[\text{Li}] = 2.23 \pm 0.10 + (0.01
± 0.04)[Fe/H].

Though it is difficult to place a specific value on the total systematic error in any of the $^7\text{Li}$ abundances, from the spread in the obtained values it would appear that a fair estimate of the systematic uncertainty is about 0.1 dex. It may indeed be smaller in the last analyses.\textsuperscript{41} Taken together with what should be considered the best estimate for the $^7\text{Li}$ abundance in halo dwarfs, we arrive at a final $^7\text{Li}$ abundance of

$$[\text{Li}] = 2.21 \pm 0.02 \pm 0.1$$

(14)
corresponding to a range for Li/H between $\sim 1.2$ and $2.2 \times 10^{-10}$ which is shown in Fig. 1 as the observed range for $^7\text{Li}$. These values (and their uniformity) should be compared with observations of Li in younger stars where the abundance can be much larger (by an order of magnitude) and shows considerable dispersion. Two key questions remain however: how much of the observed Li is primordial (since Li is known to be produced); and how much of the primordial Li remains in the stars where Li is observed?

Aside from the big bang, Li is produced together with Be and B in cosmic ray spallation of C,N,O by protons and $\alpha$-particles. Li is also produced by $\alpha-\alpha$ fusion. Be and B have recently been observed in these same pop II stars and in particular there are a dozen or so, stars in which both Be and $^7\text{Li}$ have been observed. Thus Be (and B though there is still a paucity of data) can be used as a consistency check on primordial Li.\textsuperscript{41} Based on the Be abundance found in these stars, one can conclude that no more than 10-20% of the $^7\text{Li}$ is due to cosmic ray nucleosynthesis leaving the remainder (an abundance near $10^{-10}$) as primordial. It is also possible however, that some of the initial Li in these stars has been depleted. Standard stellar models\textsuperscript{41} predict that any depletion of $^7\text{Li}$ would be accompanied by a very severe depletion of $^6\text{Li}$. Until recently, $^6\text{Li}$ had never been observed in hot pop II stars. The observation\textsuperscript{42} of $^6\text{Li}$ (which turns out to be consistent with its origin in cosmic-ray nucleosynthesis and with a small amount of depletion as expected from standard stellar models) is a good indication that $^7\text{Li}$ has not been destroyed in these stars.\textsuperscript{44}

3.4. Summary

Consistency of the standard model of big bang nucleosynthesis relies on the concordance between theory and observation of the light element abundances for a single value of $\eta$. We now summarize the constraints on $\eta$ from each of the light elements. From the $^4\text{He}$ mass fraction, $Y < 0.240(0.245)$, we have that $\eta_{10} < 2.9(4.5)$ as a 2$\sigma$ upper limit (the higher value takes into account possible systematic errors). It is appropriate to note here the sensitivity of the bound on $\eta$ to the assumed $^4\text{He}$ upper limit. When the data of Izatov et al.\textsuperscript{8} are not included, our upper limit to $Y$ was $Y < 0.238(0.243)$. In this case the corresponding upper limit to $\eta$ is $\eta_{10} < 2.5(3.9)$. Because of the sensitivity to the assumed upper limit on $Y$, the upper limit on $\eta$ from D/H, though weaker is still of value. From D/H $> 1.5 \times 10^{-5}$ we have $\eta_{10} < 7$. The lower limit on $\eta$, comes from the upper limit on D
+$^3\text{He}$ and is $\eta_{10} \gtrsim 2.8$ if one ignores $^3\text{He}$ production. We stress that this limit is only exemplary as the upper limit on D + $^3\text{He}$ depends critically on models of galactic chemical evolution, which are far from being understood. Finally, $^7\text{Li}$ allows a broad range for $\eta$ consistent with other light elements. When both uncertainties in the reaction rates and systematic uncertainties in the observed abundances are taken into account, $^7\text{Li}$ allows values of $\eta_{10}$ between 1.3 – 4.9. The resulting consistent range for $\eta_{10}$ becomes 2.8 – 4.5. These bounds on $\eta$ constrain the fraction of critical density in baryons, $\Omega_B$ to be

$$0.01 < \Omega_B < 0.1$$

(15)

for a hubble parameter, $h_o$, between 0.4 – 1.0. The corresponding range for $\Omega_B h_o^2$ is 0.010 – 0.016.

4. Constraints on Physics beyond the Standard Model

Limits on particle physics beyond the standard model are mostly sensitive to the bounds imposed on the $^4\text{He}$ abundance. As is well known, the $^4\text{He}$ abundance is predominantly determined by the neutron-to-proton ratio just prior to nucleosynthesis and is easily estimated assuming that all neutrons are incorporated into $^4\text{He}$ (see Eq. (1)). As discussed earlier, the neutron-to-proton ratio is fixed by its equilibrium value at the freeze-out of the weak interaction rates at a temperature $T_f \sim 1 \text{ MeV}$ modulo the occasional free neutron decay. Furthermore, freeze-out is determined by the competition between the weak interaction rates and the expansion rate of the Universe

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

(16)

where $N$ counts the total (equivalent) number of relativistic particle species. The presence of additional neutrino flavors (or any other relativistic species) at the time of nucleosynthesis increases the overall energy density of the Universe and hence the expansion rate leading to a larger value of $T_f$, ($n/p$), and ultimately $Y_p$. Because of the form of Eq. (16) it is clear that just as one can place limits on $N$, any changes in the weak or gravitational coupling constants can be similarly constrained (for a recent discussion see ref. 46).

In the standard model, the number of particle species entering into Eq. (16) can be written as $N = 5.5 + \frac{3}{2} N_\nu$ (5.5 accounts for photons and $e^\pm$). The observationally derived primordial $^4\text{He}$ abundance from Eq. (3) of $Y_p = 0.234 \pm 0.003 \pm .005$ translates into a best value for $N_\nu = 2.2 \pm 0.27 \pm .42$ (assuming a central value for $\eta_{10}$ of 3.6, with $\eta_{10} = 3$, the best value for $N_\nu$ increase to 2.4) which implies a $2\sigma$ upper limit of 2.74 which is extended to $N_\nu < 3.16$ when systematics are included. At face value, such a limit would exclude even a single additional scalar degree of freedom (which counts as $\frac{1}{2}$) such as a majoron unless it decoupled early enough so that its temperature, $T_B$ at the time of nucleosynthesis was suppressed so that $(T_B/T_f)^4 < \frac{2}{7}(1.6) = .28$. In models with right-handed interactions, and three right-handed neutrinos, the constraint is more severe. The right-handed states must have decoupled early enough to ensure $(T_{\nu R}/T_{\nu L})^4 < (1.6)/3 \simeq .05$. The temperature
of a decoupled state is easily determined from entropy conservation, \((T_x/T_ν) = ((43/4)/N(T_d))^{1/3}\). One additional scalar requires \(N(T_d) > 28\) or decoupling must have occurred above the QCD phase transition at a temperature \(T_d > T_{\text{QCD}} \sim 200\) MeV. Three right-handed neutrinos would require \(N(T_d) \gtrsim 100\), so that \(T_d > M_W\). If right-handed interactions are mediated by additional gauge interactions, the associated mass scale becomes \(M_{Z'} > O(100)\) TeV!

The limits on \(N_ν\), however, are sensitive to the upper limit on \(^4\)He which is in turn sensitive to assumed systematic errors and to the lower bound on \(η\). In addition, the limits described above may be overly restrictive. The best value for \(N_ν\) is 2.2 and may in fact be unphysical if \(ν_τ\) is lighter than \(\sim 1\) MeV, as is quite likely. In this case the limits on \(N_ν\) must be accordingly renormalized as has been discussed extensively in ref. 48. In Fig. 9, the effect of renormalizing the limit on \(N_ν\) is shown. In Fig. 9, the central value of \(Y_p = 0.232\) was assumed. For the higher value of 0.234, an additional \(\approx 0.2\) should be added to the limits on \(N_ν\).

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5. Summary

In summary, we have argued for the overall agreement between theory and ob-
servations as they pertain to the light element abundances as well as concordance between big bang nucleosynthesis and galactic cosmic-ray nucleosynthesis. There is now quite a bit of data on $^4\text{He}$ which appears to be coherent. Because the inferred primordial $^4\text{He}$ abundance found from extrapolating the data to zero metallicity gives a somewhat low value, smaller values for the baryon to photon ratio are preferred. In contrast, there may be a problem with $^3\text{He}$. The data in the ISM shows a large dispersion, which may be an indication of possible local pollution, and spans a factor of $\sim 5$ in abundance. Additional data is clearly needed here before strong conclusions can be made regarding potential problems. The solar value of $^3\text{He}$ seems to indicate that little $^3\text{He}$ is produced over the early history of the galaxy. While higher values of the baryon to photon ratio certainly help in this direction, we believe that this is ultimately a problem to be resolved by chemical evolution models. $^7\text{Li}$, because of relatively large allowed range (dominated by systematic uncertainties) allows a wide range for the baryon to photon ratio.

There are however, open issues: Are the quasar line-of-sight measurements of $\text{D}/\text{H}$ real; Why isn’t there more $^3\text{He}$, particularly in the solar system; Can the statistical and systematic errors in $^4\text{He}$ measurements be reduced; Can the large systematic errors in the $^7\text{Li}$ abundance be reduced? Clearly new data will be necessary to resolve these problems. Nevertheless, in spite of these uncertainties, nucleosynthesis is still able to set strong constraints on physics beyond the standard model.

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