Primordial Nucleosynthesis

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Abstract

The current status of big bang nucleosynthesis is reviewed and the concordance between theory and observation is examined in detail. It is argued that when using the observational data on $^4$He and $^7$Li, the two isotopes whose abundances are least affected by chemical and stellar evolution, both are completely consistent with BBN theory. In addition, these isotopes determine the value of the baryon-to-photon ratio, $\eta$, to be relatively low, $\eta \approx 1.8 \times 10^{-10}$, which happens to agree with some recent measurements of D/H in quasar absorption systems. These results have far reaching consequences for galactic chemical evolution, the amount of baryonic dark matter in the Universe and on the allowed number of degrees of freedom in the early Universe.

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The concordance between big bang nucleosynthesis (BBN) theory and observation has been the subject of considerable recent debate. It is clear however, that the real questions lie not with the concordance between BBN and the observational data, but rather between the theories of chemical and stellar evolution and the data. BBN theory (see for example [1]) is quite stable in the sense that over time very little in the fundamental theory has changed. Cross-sections are now somewhat more accurately measured, the neutron mean life is known with a much higher degree of precision, and if we restrict our attention to the standard model, the number of neutrinos has also been determined. In contrast, the status of the observational data has changed significantly in the last several years. There is better data on $^4$He, more data on $^7$Li, and data on D and $^3$He that was simply non-existent several years ago. For the most part, the inferred abundances of $^4$He and $^7$Li have remained relatively fixed, giving us a higher degree of confidence in the assumed primordial abundances of these isotopes as is reflected in their observational uncertainties. Indeed, the abundances of $^4$He and $^7$Li alone are sufficient in order to probe and test the theory and determine the single remaining parameter in the standard model, namely, the baryon-to-photon ratio, $\eta$ [2]. In contrast, D and $^3$He are highly dependent on models of chemical evolution ($^3$He is in addition dependent on the uncertain stellar yields of this isotope). New data from quasar absorption systems, on what may be primordial D/H is at this time disconcordant, different measurements give different abundances. As a consequence of the uncertainties in D and $^3$He, one can use the predictions based on $^4$He and $^7$Li in order to construct models of galactic chemical evolution. These results also have important implications for the amount of (non)-baryonic dark matter in the galaxy and on the number of allowed relativistic degrees of freedom at the time of BBN, commonly parameterized as $N_\nu$.

Before commencing with the direct comparison between theory and observations, it will be useful to briefly review the main events leading to the synthesis of the light elements. Conditions for the synthesis of the light elements were attained in the early Universe at temperatures $T \lesssim 1$ MeV. 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, $(n/p) \simeq 1$. As the temperature fell and approached the point where the weak interaction rates were no longer fast enough to maintain equilibrium, the neutron to proton ratio was given approximately by the Boltzmann factor, $(n/p) \approx e^{-\Delta m/T}$, 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 \( \bar{E}_\gamma \approx 2.7T \)). 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 \( \eta \). 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. 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. Uncertainties in the produced \(^7\)Li abundances have been adopted from the results in Hata et al. [4]. Uncertainties in \( D \) and \(^3\)He production are negligible on the scale of this figure. The boxes correspond to the observed abundances and will be discussed below.

There is now a good collection of abundance information on the \(^4\)He mass fraction, \( Y \), \( O/H \), and \( N/H \) in over 70 extragalactic HII (ionized hydrogen) regions [5, 6, 7]. The observation of the heavy elements is important as the helium mass fraction observed in these HII regions has been augmented by some stellar processing, the degree to which is given by the oxygen and nitrogen abundances. In an extensive study based on the data in [5, 6], it was found [8] that the data is well represented by a linear correlation for \( Y \) vs. \( O/H \) and \( Y \) vs. \( N/H \). It is then expected that the primordial abundance of \(^4\)He can be determined from the intercept of that relation. The overall result of that analysis indicated a primordial mass fraction, \( Y_p = 0.232 \pm 0.003 \). In [5],
Figure 1: The light element abundances from big bang nucleosynthesis.
the stability of this fit was verified by a statistical bootstrap analysis showing that
the fits were not overly sensitive to any particular HII region. In addition, the data
from [4] was also included, yielding a $^4\text{He}$ mass fraction $Y_p = 0.234 \pm 0.003 \pm 0.005$ (2)

The second uncertainty is an estimate of the systematic uncertainty in the abundance
determination. The solid box for $^4\text{He}$ in figure 1 represents the range (at $2\sigma_{\text{stat}} + \sigma_{\text{sys}}$)
from (2). The dashed box extends this by $\sigma_{\text{sys}}$. With the addition of the newer data in
[7], the resulting $^4\text{He}$ abundance is also given by (2) with a smaller statistical error of
0.002, although a case can also be made for a somewhat lower primordial abundance
of $Y_p = 0.230 \pm .003$ by restricting to the most metal poor regions [11].

The $^7\text{Li}$ abundance is also reasonably well known. In old, hot, population-II
stars, $^7\text{Li}$ 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 (so that effects
such as stellar convection may not be important), the abundances show little or no
dispersion beyond that which is consistent with the errors of individual measurements.
Indeed, as detailed in [11], much of the work concerning $^7\text{Li}$ has to do with the presence
or absence of dispersion and whether or not there is in fact some tiny slope to a [Li] = log $^7\text{Li}/\text{H} + 12$ vs. $T$ or [Li] vs. [Fe/H] relationship. There is $^7\text{Li}$ data from nearly
100 halo stars, from a variety of sources. I will use the value given in [12] as the best
estimate for the mean $^7\text{Li}$ abundance and its statistical uncertainty in halo stars

$$\frac{\text{Li}}{\text{H}} = (1.6 \pm 0.1^{+0.4+1.6}_{-0.3-0.5}) \times 10^{-10}$$ (3)

The first error is statistical, and the second is a systematic uncertainty that covers
the range of abundances derived by various methods. The solid box for $^7\text{Li}$ in figure 1
represents the $2\sigma_{\text{stat}} + \sigma_{\text{sys}}$ range from (3). The third set of errors in Eq. (3) accounts
for the possibility that as much as half of the primordial $^7\text{Li}$ has been destroyed in
stars, and that as much as 30% of the observed $^7\text{Li}$ may have been produced in cosmic
ray collisions rather than in the Big Bang. The dashed box in figure 1, accounts for
this additional uncertainty. Observations of $^6\text{Li}$, Be, and B help constrain the degree
to which these effects play a role [13]. For $^7\text{Li}$, the uncertainties are clearly dominated
by systematic effects.

Turning to D/H, we have three basic types of abundance information: 1) ISM
data, 2) solar system information, and perhaps 3) a primordial abundance from quasar
absorption systems. The best measurement for ISM D/H is [14]

$$(\text{D/H})_{\text{ISM}} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5}$$ (4)

The lower bound from deuterium establishes an upper bound on $\eta$ which is robust and
is shown by the lower right of the solid box in figure 1. The solar abundance of D/H
is inferred from two distinct measurements of $^3$He. The solar wind measurements of $^3$He as well as the low temperature components of step-wise heating measurements of $^3$He in meteorites yield the presolar $(D + ^3$He)/H ratio, as D was efficiently burned to $^3$He in the Sun’s pre-main-sequence phase. These measurements indicate that $^{[15, 16]}$

$$
\left( \frac{D + ^3\text{He}}{\text{H}} \right)_\odot = (4.1 \pm 0.6 \pm 1.4) \times 10^{-5}
$$

(5)

The high temperature components in meteorites are believed to yield the true solar $^3$He/H ratio of $^{[15, 16]}$

$$
\left( \frac{^3\text{He}}{\text{H}} \right)_\odot = (1.5 \pm 0.2 \pm 0.3) \times 10^{-5}
$$

(6)

The difference between these two abundances reveals the presolar D/H ratio, giving,

$$
(D/H)_\odot \approx (2.6 \pm 0.6 \pm 1.4) \times 10^{-5}
$$

(7)

It should be noted that recent measurements of surface abundances of HD on Jupiter show a somewhat higher value for D/H, $D/H = 5 \pm 2 \times 10^{-5}$ $^{[17]}$. If this value is confirmed and if fractionation does not significantly alter the D/H ratio (as it was suspected to for previous measurements involving CH$_3$D), it may have an important impact on galactic chemical evolution models. This value is marginally consistent with the inferred meteoritic values.

Finally, there have been several recent reported measurements of D/H is high redshift quasar absorption systems. Such measurements are in principle capable of determining the primordial value for D/H and hence $\eta$, because of the strong and monotonic dependence of D/H on $\eta$. However, at present, detections of D/H using quasar absorption systems indicate both a high and low value of D/H. As such, it should be cautioned that these values may not turn out to represent the true primordial value and it is very unlikely that both are primordial and indicate an inhomogeneity $^{[18]}$. The first of these measurements $^{[19]}$ indicated a rather high D/H ratio, $D/H \approx 1.9 - 2.5 \times 10^{-4}$. A re-observation of the high D/H absorption system has been resolved into two components, both yielding high values with an average value of $D/H = 1.9^{+0.4}_{-0.3} \times 10^{-4}$ $^{[20]}$. Other high D/H ratios were reported in $^{[21]}$. However, there are reported low values of D/H in other such systems $^{[22]}$ with values $D/H \approx 2.5 \times 10^{-5}$, significantly lower than the ones quoted above. Though this primordial D/H value is consistent with the solar and present values of D/H, it is not consistent (at the 2 $\sigma$ level) with the determinations of D/H in Jupiter, if they are correct. The range of quasar absorber D/H is shown by the dashed box in figure 1. It is probably premature to use either of these values as the primordial D/H abundance in an analysis of big bang nucleosynthesis, but it is certainly encouraging that future
observations may soon yield a firm value for D/H. It is however important to note that there does seem to be a trend that over the history of the Galaxy, the D/H ratio is decreasing, something we expect from galactic chemical evolution. Of course the total amount of deuterium astration that has occurred is still uncertain, and model dependent.

There are also several types of $^3$He measurements. As noted above, meteoritic extractions yield a presolar value for $^3$He/H as given in Eq. (6). In addition, there are several ISM measurements of $^3$He in galactic HII regions [23] which show a wide dispersion which may be indicative of pollution or a bias [24]

$$\left( \frac{^3\text{He}}{\text{H}} \right)_{\text{HII}} \simeq 1 - 5 \times 10^{-5}$$

(8)

There is also a recent ISM measurement of $^3$He [25] with

$$\left( \frac{^3\text{He}}{\text{H}} \right)_{\text{ISM}} = 2.1^{+9}_{-8} \times 10^{-5}$$

(9)

Finally there are observations of $^3$He in planetary nebulae [26] which show a very high $^3$He abundance of $^3$He/H $\sim 10^{-3}$.

Each of the light element isotopes can be made consistent with theory for a specific range in $\eta$. Overall consistency of course requires that the range in $\eta$ agree among all four light elements. However, as will be argued below D and $^3$He are far more sensitive to chemical evolution than $^4$He or $^7$Li and as such a the direct comparison between the theoretical predictions of the primordial abundances of D and $^3$He with the observational determination of their abundances is far more difficult. Therefore in what follows I will restrict the comparison between theory and observation to the two isotopes who suffer the least from the effects of chemical evolution.

Monte Carlo techniques are proving to be a useful form of analysis for big bang nucleosynthesis [27, 28, 4]. In [2], we performed just such an analysis using only $^4$He and $^7$Li. It should be noted that in principle, two elements should be sufficient for not only constraining the one parameter ($\eta$) theory of BBN, but also for testing for consistency. We begin by establishing likelihood functions for the theory and observations. For example, for $^4$He, the theoretical likelihood function takes the form

$$L_{\text{BBN}}(Y, Y_{\text{BBN}}) = e^{-(Y-Y_{\text{BBN}}(\eta))^2/2\sigma_1^2}$$

(10)

where $Y_{\text{BBN}}(\eta)$ is the central value for the $^4$He mass fraction produced in the big bang as predicted by the theory at a given value of $\eta$, and $\sigma_1$ is the uncertainty in that value derived from the Monte Carlo calculations [4] and is a measure of the theoretical uncertainty in the big bang calculation. Similarly one can write down an
expression for the observational likelihood function. Assuming a Gaussian to describe
the systematic uncertainty, the likelihood function for the observations would have
take a form similar to that in (10).

A total likelihood function for each value of $\eta_{10}$ is derived by convolving the
theoretical and observational distributions, which for $^4$He is given by

$$ L^{^4\text{He}}_{\text{total}}(\eta) = \int dY L_{\text{BBN}}(Y, Y_{\text{BBN}}(\eta)) L_{\text{O}}(Y, Y_{\text{O}}) \quad (11) $$

An analogous calculation is performed for $^7$Li. The resulting likelihood functions
from the observed abundances given in Eqs. (2) and (3) is shown in Figure 2. As one
can see there is very good agreement between $^4$He and $^7$Li in the vicinity of $\eta_{10} \approx 1.8$.

The combined likelihood, for fitting both elements simultaneously, is given by the
product of the two functions in Figure 2 and is shown in Figure 3. From Figure 2 it
is clear that $^4$He overlaps the lower (in $\eta$) $^7$Li peak, and so one expects that there will
be concordance in an allowed range of $\eta$ given by the overlap region. This is what
one finds in Figure 3, which does show concordance and gives a preferred value for $\eta$,
$\eta_{10} = 1.8^{+1}_{-2}$ corresponding to

$$ \Omega_B h^2 = 0.006^{+0.004}_{-0.001} \quad (12) $$

Thus, we can conclude that the abundances of $^4$He and $^7$Li are consistent, and

Figure 2: Likelihood distribution for each of $^4$He and $^7$Li, shown as a function of $\eta$. The one-peak structure of the $^4$He curve corresponds to its monotonic increase with $\eta$, while the two-peaks for $^7$Li arise from its passing through a minimum.
Figure 3: Combined likelihood for simultaneously fitting $^4\text{He}$ and $^7\text{Li}$, as a function of $\eta$.

select an $\eta_{10}$ range which overlaps with (at the 95% CL) the longstanding favorite range around $\eta_{10} = 3$. Furthermore, by finding concordance using only $^4\text{He}$ and $^7\text{Li}$, we deduce that if there is problem with BBN, it must arise from D and $^3\text{He}$ and is thus tied to chemical evolution or the stellar evolution of $^3\text{He}$. The most model-independent conclusion is that standard BBN with $N_\nu = 3$ is not in jeopardy, but there may be problems with our detailed understanding of D and particularly $^3\text{He}$ chemical evolution. It is interesting to note that the central (and strongly) peaked value of $\eta_{10}$ determined from the combined $^4\text{He}$ and $^7\text{Li}$ likelihoods is at $\eta_{10} = 1.8$. The corresponding value of D/H is $1.8 \times 10^{-4}$, very close [29] to the high value of D/H in quasar absorbers [19, 20, 21]. Since D and $^3\text{He}$ are monotonic functions of $\eta$, a prediction for $\eta$, based on $^4\text{He}$ and $^7\text{Li}$, can be turned into a prediction for D and $^3\text{He}$. The corresponding 95% CL ranges are D/H = $(5.5 - 27) \times 10^{-5}$ and and $^3\text{He}/\text{H}$ = $(1.4 - 2.7) \times 10^{-5}$.

If we did have full confidence in the measured value of D/H in quasar absorption systems, then we could perform the same statistical analysis using $^4\text{He}$, $^7\text{Li}$, and D. To include D/H, one would proceed in much the same way as with the other two light elements. We compute likelihood functions for the BBN predictions as in Eq. (10) and the likelihood function for the observations using D/H = $(1.9 \pm 0.4) \times 10^{-4}$. We are using only the high value of D/H here. These are then convolved as in Eq.
In figure 4, the resulting normalized distribution, $L_{\text{total}}^D(\eta)$ is super-imposed on distributions appearing in figure 2. It is indeed startling how the three peaks, for D, $^4\text{He}$ and $^7\text{Li}$ are literally on top of each other. In figure 5, the combined distribution is shown. We now have a very clean distribution and prediction for $\eta$, $\eta_{10} = 1.75^{+0.3}_{-0.1}$ corresponding to $\Omega_B h^2 = 0.006^{+0.001}_{-0.004}$, with the peak of the distribution at $\eta_{10} = 1.75$. The absence of any overlap with the high-$\eta$ peak of the $^7\text{Li}$ distribution has considerably lowered the upper limit to $\eta$. Overall, the concordance limits in this case are dominated by the deuterium likelihood function.

This type of analysis also has the potential for placing constraints on the degree of $^7\text{Li}$ depletion in stars which is one of the major uncertainties associating the primordial abundance with the observations. If depletion say by a factor of two were assumed rather than treated as an uncertainty which has the effect of widening the distribution functions in figures 2 and 4, the two lithium peaks would appear thinner and split further apart [2]. As a result, there would be far less overlap between the likelihood distributions of $^4\text{He}$ and $^7\text{Li}$. The combined distribution would show two distinct peaks centered on $\eta_{10} = 1.3$ and 5.0 with heights of 0.15 and 0.1 respectively with the same scaling as shown in figures 3 and 5. If in addition, we had confidence in the high redshift D/H measurements, the high value of D/H would eliminate the high $\eta$ peak and leave a single blip at $\eta_{10} = 1.5$ with a relative height of 0.03 and essentially exclude any depletion of $^7\text{Li}$ in these stars.
Figure 5: Combined likelihood for simultaneously fitting $^4$He and $^7$Li, and D as a function of $\eta$.

For the most part I have concentrated on the high D/H measurements in the likelihood analysis. If instead, we assume that the low value $^{[22]}$ of $D/H = (2.5 \pm 0.5) \times 10^{-5}$ is the primordial abundance, then we can again compare the likelihood distributions as in figure 4, now substituting the low D/H value. As one can see from figure 6, there is now hardly any overlap between the D and the $^7$Li distributions and essentially no overlap with the $^4$He distribution. The combined distribution shown in figure 7 is compared with that in figure 5. Though one can not use this likelihood analysis to prove the correctness of the high D/H measurements or the incorrectness of the low D/H measurements, the analysis clearly shows the difference in compatibility between the two values of D/H and the observational determinations of $^4$He and $^7$Li. To make the low D/H measurement compatible, one would have to argue for a shift upwards in $^4$He to a primordial value of 0.249 (a shift by 0.015) which is certainly not warranted by the data, and a $^7$Li depletion factor of about 3, which exceeds recent upper limits to the amount of depletion $^{[30]}$.

The predictions by the above analysis for D and $^3$He have important implications for models of chemical evolution. $^3$He (together with D) has stood out in its importance for BBN, because it provided a (relatively large) lower limit for the baryon-to-photon ratio $^{[31]}$, $\eta_{10} > 2.8$. This limit for a long time was seen to be
Figure 6: As in Figure 4, with the likelihood distribution for low D/H.

Figure 7: Combined likelihood for simultaneously fitting $^4\text{He}$ and $^7\text{Li}$, and low D/H as a function of $\eta$. The dashed curve represents the combined distribution shown in figure 5.
essential because it provided the only means for bounding $\eta$ from below and in effect allows one to set an upper limit on the number of neutrino flavors $N_\nu$, as well as other constraints on particle physics properties. That is, the upper bound to $N_\nu$ is strongly dependent on the lower bound to $\eta$. This is easy to see: for lower $\eta$, the $^4$He abundance drops, allowing for a larger $N_\nu$, which would raise the $^4$He abundance. However, for $\eta < 4 \times 10^{-11}$, corresponding to $\Omega h^2 \sim 0.001 - 0.002$, which is not too different from galactic mass densities, there is no bound whatsoever on $N_\nu$. Of course, with the improved data on $^7$Li, we do have lower bounds on $\eta$ which exceed $10^{-10}$.

In [31], it was argued that since stars (even massive stars) do not destroy $^3$He in its entirety, we can obtain a bound on $\eta$ from an upper bound to the solar $D$ and $^3$He abundances. One can in fact limit [31, 34] the sum of primordial $D$ and $^3$He by applying the expression below at $t = \odot$

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

(13)

In (13), $g_3$ is the fraction of a star’s initial $D$ and $^3$He which survives as $^3$He. For $g_3 > 0.25$ as suggested by stellar models, and using the solar data on $D/H$ and $^3$He/H, one finds $\eta_{10} > 2.8$. This limit on $\eta$ is shown by the upper left of the solid box in figure 1. This argument has been improved recently [35] ultimately leading to a stronger limit [36] $\eta_{10} > 3.8$ and a best estimate $\eta_{10} = 6.6 \pm 1.4$. The stochastic approach used in Copi et al. [37] could only lower the bound from 3.8 to about 3.5 when assuming as always that $g_3 > 0.25$.

The limit $\eta_{10} > 2.8$ derived using (13) is really a one shot approximation. Namely, it is assumed that material passes through a star no more than once. To determine whether or not the solar (and present) values of $D/H$ and $^3$He/H can be matched it is necessary to consider models of galactic chemical evolution [8]. In the absence of stellar $^3$He production, particularly by low mass stars, it was shown [39] that there are indeed suitable choices for a star formation rate and an initial mass function to: 1) match the $D/H$ evolution from a primordial value $(D/H)_p = 7.5 \times 10^{-5}$, corresponding to $\eta_{10} = 3$, through the solar and ISM abundances, while 2) at the same time keeping the $^3$He/H evolution relatively flat so as not to overproduce $^3$He at the solar and present epochs. This was achieved for $g_3 > 0.3$. Even for $g_3 \sim 0.7$, the present $^3$He/H could be matched, though the solar value was found to be a factor of 2 too high. For $(D/H)_p \simeq 2 \times 10^{-4}$, corresponding to $\eta_{10} \simeq 1.7$, models could be found which destroy $D$ sufficiently; however, overproduction of $^3$He occurred unless $g_3$ was tuned down to about 0.1 [24].

In the context of models of galactic chemical evolution, there is, however, little justification a priori for neglecting the production of $^3$He in low mass stars. Indeed,
stellar models predict that considerable amounts of $^3\text{He}$ are produced in stars between 1 and $3\,M_\odot$. For $M < 8M_\odot$, Iben and Truran [40] calculate

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

so that at $\eta_{10} = 3$, and $((\text{D} + ^3\text{He})/\text{H})_i = 9 \times 10^{-5}$, $g_3(1M_\odot) = 2.7$! It should be emphasized that this prediction is in fact consistent with the observation of high $^3\text{He}/\text{H}$ in planetary nebulae [26].

Generally, implementation of the $^3\text{He}$ yield in Eq. (14) in chemical evolution models leads to an overproduction of $^3\text{He}/\text{H}$ particularly at the solar epoch [24, 41]. In Figure 8, the evolution of D/H and $^3\text{He}/\text{H}$ is shown as a function of time from [15, 24]. The solid curves show the evolution in a simple model of galactic chemical evolution with a star formation rate proportional to the gas density and a power law IMF (see [24] for details). The model was chosen to fit the observed deuterium abundances. However, as one can plainly see, $^3\text{He}$ is grossly overproduced (the deuterium data is represented by squares and $^3\text{He}$ by circles). Depending on the particular model chosen, it may be possible to come close to at least the upper end of the range of the $^3\text{He}/\text{H}$ observed in galactic HII regions [23], although the solar value is missed by many standard deviations.

The overproduction of $^3\text{He}$ relative to the solar meteoritic value seems to be a generic feature of chemical evolution models when $^3\text{He}$ production in low mass stars is included. In [13], a more extreme model of galactic chemical evolution was tested. There, it was assumed that the initial mass function was time dependent in such a way so as to favor massive stars early on (during the first two Gyr of the galaxy). Massive stars are preferential from the point of view of destroying $^3\text{He}$. However, massive stars are also proficient producers of heavy elements and in order to keep the metallicity of the disk down to acceptable levels, supernovae driven outflow was also included. The degree of outflow was limited roughly by the observed metallicity in the intergalactic gas in clusters of galaxies. One further assumption was necessary; we allowed the massive stars to lose their $^3\text{He}$ depleted hydrogen envelopes prior to explosion. Thus only the heavier elements were expelled from the galaxy. With all of these (semi-defensible) assumptions, $^3\text{He}$ was still overproduced at the solar epoch, as shown by the dashed curve in Figure 8. Though there certainly is an improvement in the evolution of $^3\text{He}$ without reducing the yields of low mass stars, it is hard to envision much further reduction in the solar $^3\text{He}$ predicted by these models.

The model which results in an evolution given by figure 8, has a modest amount of deuterium destruction. If $\eta_{10}$ is close to 1.8 as predicted by $^4\text{He}$ and $^7\text{Li}$ or as may be inferred from the high D/H QSO absorber measurements, the primordial value of D/H is higher than that depicted in figure 8, and requires substantially more destruction of D. In Scully et al. [12], a dynamically generated supernovae wind model was coupled
to models of galactic chemical evolution with the aim of reducing a primordial D/H abundance of $2 \times 10^{-4}$ to the present ISM value without overproducing heavy elements and remaining within the other observational constraints typically imposed on such models. $^3\text{He}$ remains a challenge to models of chemical and stellar evolution.

As indicated earlier, the presence of a lower bound on $\eta$ allows us to place an upper bound to the number of neutrino flavors. From (13), the limit $\eta_{10} > 2.8$ corresponds to the limit $N_\nu < 3.3 \ [1]$. However, it should be noted that for values of $\eta$ larger than 2.8, the central or best-fit value for $N_\nu$ is closer to 2 [3, 28, 36] and the upper bound is actually found to be much smaller with a careful treatment of the uncertainties, $N_\nu \lesssim 3.1 \ [3, 28]$, though this limit is relaxed somewhat when the distribution for $N_\nu$ is renormalized [13]. The range in $\eta$ of $6.6 \pm 1.4$, corresponds to an even tighter limit on $N_\nu = 2.0 \pm 0.3 \ [36]$ and indicates a problem when trying to make use of D and $^3\text{He}$ in conjunction with $^4\text{He}$.

Given the magnitude of the problems concerning $^3\text{He}$, it would seem unwise to make any strong conclusion regarding big bang nucleosynthesis which is based on $^3\text{He}$. Perhaps as well some caution is deserved with regard to the recent D/H measurements, although if the present trend continues and is verified in several different quasar absorption systems, then D/H will certainly become our best measure for the baryon-
to-photon ratio. Just as $^4$He and $^7$Li were sufficient to determine a value for $\eta$, in so doing, a limit on $N_\nu$ can be obtained as well \[2 \text{,} 44\]. The resulting best-fit to $N_\nu$ based on $^4$He and $^7$Li was found to be \[2\]

$$N_\nu = 3.0 \pm 0.2 \pm 0.4^{+0.1}_{-0.6}$$

(15)

thus preferring the standard model result of $N_\nu = 3$ and leading to $N_\nu < 3.90$ at the 95\% CL level when adding the errors in quadrature. In (14), the first set of errors are the statistical uncertainties primarily from the observational determination of $Y$ and the measured error in the neutrino half life $\tau_\nu$. The second set of errors is the systematic uncertainty arising solely from $^4$He, and the last set of errors from the uncertainty in the value of $\eta$ and is determined by the combined likelihood functions of $^4$He and $^7$Li, ie taken from Eq. (12). A similar result is obtained when D/H is included in the analysis.

The implications of the resulting predictions from big bang nucleosynthesis on dark matter are clear. First, if $\Omega = 1$ (as predicted by inflation), and $\Omega_B \lesssim 0.1$ which is certainly a robust conclusion based on D/H, then non-baryonic dark matter is a necessity. Second, on the scale of small groups of galaxies, $\Omega \gtrsim 0.05$, and is expected to sample the dark matter in galactic halos. This value is probably larger than the best estimate for $\Omega_B$ from equation (12). $\Omega_B h^2 = 0.0065$ corresponds to $\Omega_B = 0.025$ for $h = 1/2$. In this event, some non-baryonic dark matter in galactic halos is required. This conclusion is unchanged by the inclusion of the high D/H measurements in QSO absorbers. In contrast \[45\], the low D/H measurements would imply that $\Omega_B h^2 = 0.023$ allowing for the possibility that $\Omega_B \simeq 0.1$. In this case, no non-baryonic dark matter is required in galactic halos. However, I remind the reader that the low D/H is at present not consistent with either the observations of $^4$He nor $^7$Li and their interpretations as being primordial abundances.

To summarize on the subject of big bang nucleosynthesis, I would assert that one can conclude that the present data on the abundances of the light element isotopes are consistent with the standard model of big bang nucleosynthesis. Using the the isotopes with the best data, $^4$He and $^7$Li, it is possible to constrain the theory and obtain a best value for the baryon-to-photon ratio of $\eta_{10} = 1.8$, a corresponding value $\Omega_B h^2 = 0.0065$ and

$$0.005 < \Omega_B h^2 < 0.014$$

95\%CL

(16)

For $0.4 < h < 1$, we have a range $0.005 < \Omega_B < 0.09$. This is a rather low value for the baryon density and would suggest that much of the galactic dark matter is non-baryonic \[46\]. These predictions are in addition consistent with recent observations of D/H in quasar absorption systems which show a high value. Difficulty remains however, in matching the solar $^3$He abundance, suggesting a problem with our current
understanding of galactic chemical evolution or the stellar evolution of low mass stars as they pertain to $^3\text{He}$.

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References

[1] T.P. Walker, G. Steigman, D.N. Schramm, K.A. Olive and K. Kang, Ap.J. 376 (1991) 51.

[2] B.D. Fields and K.A. Olive, Phys. Lett. B368 (1996) 103; B.D. Fields, K. Kainulainen, D. Thomas, and K.A. Olive, astro-ph/9603009, New Astronomy 1 (1996) 77.

[3] Review of Particle Properties, Phys. Rev. 54 (1996) 1.

[4] N. Hata, R.J. Scherrer, G. Steigman, D. Thomas, and T.P. Walker, Ap.J. 458 (1996) 637.

[5] B.E.J. Pagel, E.A. Simonson, R.J. Terlevich and M. Edmunds, MNRAS 255 (1992) 325.

[6] E. Skillman et al., Ap.J. Lett. (in preparation) 1996.

[7] Y.I. Izatov, T.X. Thuan, and V.A. Lipovetsky, Ap.J. 435 (1994) 647; preprint 1996.

[8] K.A. Olive and G. Steigman, Ap.J. Supp. 97 (1995) 49.

[9] K.A. Olive and S.T. Scully, IJMPA 11 (1995) 409.

[10] K.A. Olive and G. Steigman, in preparation.

[11] M. Spite, P. Francois, P.E. Nissen, and F. Spite, A.A. 307 (1996) 172; F. Spite, to be published in the Proceedings of the IIInd Rencontres du Vietnam: The Sun and Beyond, ed. J. Tran Thanh Van, 1996.

[12] P. Molaro, F. Primas, and P. Bonifacio, A.A. 295 (1995) L47.
[13] T.P. Walker, G. Steigman, D.N. Schramm, K.A. Olive and B. Fields, Ap.J. 413 (1993) 562; K.A. Olive, and D.N. Schramm, Nature 360 (1993) 439; G. Steigman, B. Fields, K.A. Olive, D.N. Schramm, and T.P. Walker, Ap.J. 415 (1993) L35.

[14] J.L. Linsky, et al., Ap.J. 402 (1993) 694; J.L. Linsky, et al., Ap.J. 451 (1995) 335.

[15] S.T. Scully, M. Cassé, K.A. Olive, D.N. Schramm, J.W. Truran, and E. Vangioni-Flam, astro-ph/0508086, Ap.J. 462 (1996) 960.

[16] J. Geiss, in Origin and Evolution of the Elements, eds. N. Prantzos, E. Vangioni-Flam, and M. Cassé (Cambridge: Cambridge University Press, 1993), p. 89.

[17] H.B. Niemann, et al. Science 272 (1996) 846.

[18] C. Copi, K.A. Olive, and D.N. Schramm, astro-ph/9606156 (1996).

[19] R.F. Carswell, M. Ranch, R.J. Weymann, A.J. Cooke, and J.K. Webb, MNRAS 268 (1994) L1; A. Songaila, L.L. Cowie, C. Hogan, and M. Rugers, Nature 368 (1994) 599.

[20] M. Rugers and C.J. Hogan, Ap.J. 459 (1996) L1.

[21] M. Rugers and C.J. Hogan, A.J. 111 (1996) 2135; R.F. Carswell, et al. MNRAS 278 (1996) 518; E.J. Wampler, et al. astro-ph/9512084, A.A. (1996) in press.

[22] D. Tytler, X.-M. Fan, and S. Burles, Nature 381 (1996) 207; S. Burles and D. Tytler, Ap.J. 460 (1996) 584.

[23] D.S. Balser, T.M. Bania, C.J. Brockway, R.T. Rood, and T.L. Wilson, Ap.J. 430 (1994) 667.

[24] K.A. Olive, R.T. Rood, D.N. Schramm, J.W. Truran, and E. Vangioni-Flam, Ap.J. 444 (1995) 680.

[25] G. Gloeckler, and J. Geiss, Nature 381 (1996) 210.

[26] R.T. Rood, T.M. Bania, and T.L. Wilson, Nature 355 (1992) 618; R.T. Rood, T.M. Bania, T.L. Wilson, and D.S. Balser, 1995, in the Light Element Abundances, Proceedings of the ESO/EIPC Workshop, ed. P. Crane, (Berlin:Springer), p. 201.

[27] L.M. Krauss and P. Romanelli, Ap.J. 358 (1990) 47; L.M. Krauss and P.J. Kernan, Phys. Lett. B347 (1995) 347; M. Smith, L. Kawano, and R.A. Malaney, Ap.J. Supp. 85 (1993) 219.

[28] P.J. Kernan and L.M. Krauss, Phys. Rev. Lett. 72 (1994) 3309.

[29] A. Dar, Ap.J. 449 (1995) 550.

[30] S. Vauclair and C. Charbonnel, A.A. 295 (1995) 715.
[31] J. Yang, M.S. Turner, G. Steigman, D.N. Schramm, and K.A. Olive, *Ap.J.* **281** (1984) 493.

[32] G. Steigman, D.N. Schramm, and J. Gunn, *Phys. Lett.* **B66** (1977) 202.

[33] K.A. Olive, D.N. Schramm, G. Steigman, M.S. Turner, and J. Yang, *Ap.J.* **246** (1981) 557.

[34] D. Black, *Nature Physical Sci.*, **24** (1971) 148.

[35] G. Steigman and M. Tosi, *Ap.J.* **401** (1992) 15; G. Steigman and M. Tosi, *Ap.J.* **453** (1995) 173.

[36] N. Hata, R. J. Scherrer, G. Steigman, D. Thomas, T. P. Walker, S. Bludman and P. Langacker, *Phys. Rev. Lett.* **75** (1995) 3977.

[37] C.J. Copi, D.N. Schramm, and M.S. Turner, *Ap.J.* **455** (1995) L95.

[38] B.M. Tinsley, *Fund Cosm Phys* **5** (1980) 287.

[39] E. Vangioni-Flam, K.A. Olive, and N. Prantzos, *Ap.J.* **427** (1994) 618.

[40] I. Iben, and J.W. Truran, *Ap.J.* **220** (1978) 980.

[41] D. Galli, F. Palla, F. Ferrini, and U. Penco, *Ap.J.* **443** (1995) 536; D. Dearborn, G. Steigman, and M. Tosi, *Ap.J.* **465** (1996) in press.

[42] S. Scully, M. Cassé, K.A. Olive, and E. Vagioni-Flam, [astro-ph/9607106](http://arxiv.org/abs/astro-ph/9607106), *Ap.J.* (1996) in press.

[43] K.A. Olive and G. Steigman, *Phys. Lett.* **B354** (1995) 357.

[44] K.A. Olive and D. Thomas, in preparation.

[45] C.Y. Cardall and G.M. Fuller, [astro-ph/9603071](http://arxiv.org/abs/astro-ph/9603071) (1996); N. Hata, G. Stiegman, S. Bludman, and P. Langacker, [astro-ph/9603084](http://arxiv.org/abs/astro-ph/9603084) (1996).

[46] E. Vangioni-Flam and M. Cassé, *Ap.J.* **441** (1995) 471.