No Crisis for Big Bang Nucleosynthesis

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Abstract

Contrary to a recent claim, the inferred primordial abundances of the light elements are quite consistent with the expectations from standard big bang nucleosynthesis when attention is restricted to direct observations rather than results from chemical evolution models. The number of light neutrino (or equivalent particle) species ($N_\nu$) can be as high as 4.53 if the nucleon-to-photon ratio ($\eta$) is at its lower limit of $1.65 \times 10^{-10}$, as constrained by the upper bound on the deuterium abundance in high redshift quasar absorption systems. Alternatively, with $N_\nu = 3$, $\eta$ can be as high as $8.90 \times 10^{-10}$ if the deuterium abundance is bounded from below by its interstellar value.
In a recent Letter, Hata et al. [1] have made the startling claim that the number of light neutrino species deduced from considerations of big bang nucleosynthesis (BBN) is $N_{\nu} = 2.1 \pm 0.3$ (1$\sigma$), i.e. inconsistent with the standard model ($N_{\nu} = 3$) at the 98.6% C.L. Their analysis is based on 3 key inputs. First, they adopt a primordial $^4$He mass fraction, $Y_p = 0.232 \pm 0.003$ (stat) $\pm 0.005$ (syst), estimated [2] from selected observations [3] of low metallicity HII regions in blue compact galaxies (BCG). Second, they adopt for the primordial abundances of D and $^3$He, $y_{2p} \equiv D/H = 3.5^{+2.7}_{-1.8} \times 10^{-5}$ (95% C.L.) and $y_{3p} \equiv ^3\text{He}/H = 1.2 \pm 0.3 \times 10^{-5}$ (95% C.L.), using a “generic” chemical evolution model [4] normalized to solar system abundances [5], and convolved with BBN predictions. Finally, they estimate the primordial abundance of $^7$Li to be $y_7p \equiv ^7\text{Li}/H = 1.2^{+0.8}_{-0.5} \times 10^{-10}$ (95% C.L.), and state that this is consistent with observational data on Pop II stars, taking into account possible post big bang production and stellar depletion. They now compare all four elements simultaneously against the theoretical predictions, with the theoretical uncertainties determined by Monte Carlo methods [6], and obtain the likelihood function for $N_{\nu}$. This yields the best fit quoted earlier, corresponding to an upper bound of $N_{\nu} < 2.6$ (95% C.L.).

Hata et al. suggest that this “crisis” can be resolved if the $^4$He mass fraction has been underestimated by $0.014 \pm 0.004$ (1$\sigma$), or if the constraint on the D abundance is relaxed by assuming that the $^3$He survival factor $g_3$ is $\leq 0.10$ at 95% C.L. rather than its adopted value of 0.25 in their chemical evolution model.

In an accompanying Letter, Copi et al. [7] perform a Bayesian analysis, adopting the same $^4$He abundance [2] but allowing for a larger statistical error $\sigma_Y$, and a possible offset in the central value, $Y_p = 0.232 + \Delta Y$. Departing from previous assumptions [8], they consider three different models of galactic chemical evolution which have varying degrees of $^3$He destruction [9] (with the average survival fraction being about 15% in Model 1, the extreme case), and two possible values for the primordial $^7$Li abundance estimated from data on Pop II stars, $^7\text{Li}/H = 1.5 \pm 0.3 \times 10^{-10}$ (no depletion), and $^7\text{Li}/H = 3.0 \pm 0.6 \times 10^{-10}$ (depletion by a factor of 2). They too conclude that $Y_p$ has been systematically underestimated by about 0.01. Adopting $\Delta Y = 0.01$, allowing for maximal $^3$He destruction (Model 1), and assuming zero prior for $N_{\nu} < 3$, then yields the 95% C.L. bound $N_{\nu} < 3.5$ for the lower $^7$Li abundance; the bound decreases to 3.4 for the higher $^7$Li abundance. Copi et al. [8] suggest that the situation can be clarified by measuring D in quasar absorption systems (QAS) and testing whether $^7$Li has indeed been depleted in Pop II stars.

In fact it has been recognized for some time [10] that the systematic error in $Y_p$ may be larger than in the above estimate [6]. Recently it has been emphasized [11] that previous analyses [3] have adopted an old set of helium emissivities [12] while the recalculated new set [13] allow much better fits to detailed line ratios. This question has been examined in a study [14] of 27 HII regions in 23 BCG identified in the Byurakan surveys, where, as before, the regression of the helium abundance against ‘metals’ ($Z$) such as oxygen and nitrogen is extrapolated down to zero metallicity to extract its primordial value. Whereas use of the old emissivities yields $Y_p = 0.229 \pm 0.004$ in agreement with previous results, use of the new emissivities (together with new correction factors [13] for the collisional enhancement of He I emission lines) raises the value to [14]

$$Y_p = 0.243 \pm 0.003.$$  

Both the dispersion of the data points in the regression plots and their slope $(dY/dZ \approx 1.7 \pm$
Further observations have resolved D lines at \( z = 3.320482 \) and \( z = 3.320790 \), thus eliminating the possibility of confusion with an `interloper' hydrogen cloud \([17]\). The measured abundances in the two clouds are, respectively, \( \frac{D}{H} \approx 10^{-3.73 \pm 0.12} \) and \( 10^{-3.72 \pm 0.09} \) (where the errors are not gaussian); an independent lower limit of \( \frac{D}{H} \geq 1.3 \times 10^{-4} \) is set on their sum from the Lyman limit opacity. Recently, there has been a detection of \( \frac{D}{H} = 1.9^{+0.6}_{-0.9} \times 10^{-4} \) in another QAS at \( z = 2.797957 \) towards the same quasar \([18]\). The errors are higher because the D feature is saturated; nevertheless a 95\% C.L. lower limit of \( \frac{D}{H} > 0.7 \times 10^{-4} \) is set. There have been other, less definitive, observations of QAS consistent with this abundance, e.g. \( \frac{D}{H} \approx 10^{-3.95 \pm 0.54} \) at \( z = 2.89040 \) towards GC0636+68 \([19]\), \( \frac{D}{H} \lesssim 1.5 \times 10^{-4} \) at \( z = 4.672 \) towards BR 1202-0725 \([20]\) and \( \frac{D}{H} \lesssim 10^{-3.9 \pm 0.4} \) at \( z = 3.08 \) towards Q0420-388 \([21]\). However, very recently, other observers have found much lower values in QAS at \( z = 3.572 \) towards Q1937-1009 \([22]\) and at \( z = 2.504 \) towards Q1009+2956 \([23]\); their average abundance is

\[
\frac{D}{H} \mid_{QAS(2)} = 2.4 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (syst)} \times 10^{-5}.
\]

Unlike the cloud in which the abundance \([2]\) was measured, these QAS also exhibit absorption due to carbon and silicon, whose synthesis in stars would have been accompanied by destruction of D. It is argued \([22]\) that this must have been negligible since the metallicity is very low. Although this is true averaged over the cloud, large fluctuations in the observed D abundance are possible since the mass of absorbing gas covering the QSO image is only \( \sim 10^{-6} M_\odot \); thus D may well have been significantly depleted in it by a star which was not massive enough to eject `metals' \([18]\). Keeping in mind that D is always destroyed by stellar processing, the high D measurement \([2]\) in the chemically unevolved cloud should be taken as a conservative upper limit on its primordial abundance. (The consequences of assuming that this measurement provides the true primordial value have been investigated elsewhere \([24]\).)

More data is clearly needed to establish that there is indeed a “ceiling” to the D abundance. Nevertheless, these observations already call into question the chemical evolution model \([4]\) employed by Hata \textit{et al.} This model assumes that primordial D is burnt in stars to \(^3\text{He}\), a fraction \( g_3 \geq 0.25 \) of which survives stellar processing when averaged over all stars \([25]\). However, the recent measurement of \( \frac{^3\text{He}}{^4\text{He}} = 2.2^{+0.7}_{-0.2} \text{(stat)} \pm 0.2 \text{(syst)} \times 10^{-4} \) in the local interstellar gas \([26]\) is close to its value of \( 1.5 \pm 0.3 \times 10^{-4} \) in the pre-solar nebula \([4]\), demonstrating that the \(^3\text{He}\) abundance has not increased significantly in the \( 4.6 \times 10^9 \) yr since the formation of the solar system. Indeed, \( g_3 \) must be less than 0.1 if an initial D abundance as high as in Eq. \((2)\) is to be reduced to its present value in the interstellar medium (ISM) \([27]\).
D/H |_{ISM} \approx 1.5 \pm 0.2 \times 10^{-5}, \quad (4)

without producing $^3$He in excess of its observed value, $^3$He/H $\approx (1 - 4) \times 10^{-5}$, in galactic HII regions [28]. This would be so if there is net destruction of $^3$He in $(1 - 2) \ M_\odot$ stars through the same mixing process which appears to be needed to explain other observations, e.g. the $^{12}$C/$^{13}$C ratio [29]; a plausible mechanism for this has been suggested recently [30]. Note that the ISM abundance of D sets a lower limit to its primordial value $y_{2p}$, since there is no known astrophysical source of D [31].

Finally, accurate $^7$Li abundances have been determined for 80 hot, metal-poor Pop II stars, of which 3 have no detectable lithium [32]. Ignoring these reveals a trend of increasing $^7$Li abundance with both increasing temperature and increasing metallicity implying that about 35% of the $^7$Li was produced by galactic cosmic ray spallation processes. The average value in the hottest, most metal-poor stars is [32]

$$^7\text{Li}/H |_{\text{Pop II}} = (0.05 - 2.63) \times 10^{-10} \ (95\% \ C.L.). \quad (5)$$

However it may be premature to identify this with the primordial abundance until the absence of $^7$Li in some of these stars is understood. The primordial abundance may instead correspond to the much higher value observed in Pop I stars which has been depleted down to (and in some cases, below) the Pop II 'plateau'. Stellar evolution modelling [33] then indicates that the initial abundance could have been as high as

$$^7\text{Li}/H |_{\text{Pop I}} = (9.54 - 15.1) \times 10^{-10} \ (95\% \ C.L.). \quad (6)$$

A recent study [34], which includes new data on 7 halo dwarfs, fails to find evidence of significant depletion through diffusion, although other mechanisms are not excluded. For example, stellar winds can deplete a primordial abundance of $^7$Li/H $= 10^{-9.5 \pm 0.1}$ down to the Pop II value (5) in a manner consistent with observations [35].

In Fig. 1 we show that the standard model ($N_\nu = 3$) can be consistent with these observations over a wide range of the nucleon-to-photon ratio, $\eta \equiv n_N/n_{\gamma}$. It will be close to its minimum allowed value if $y_{2p}$ is actually given by Eq. (2) and $y_{7p}$ by Eq. (5), while it will be close to its maximum allowed value if $y_{2p}$ is given by Eq. (4) and $y_{7p}$ by Eq. (6). Of course a value in between is also possible, depending on the true primordial abundances of D and $^7$Li. Since only the $^4$He abundance (Eq. 1) can be reasonably taken to be primordial, we do not attempt a likelihood analysis. Instead we determine the upper bounds on the parameters $N_\nu$ and $\eta$ corresponding to the two extreme possibilities above, taking into account uncertainties in the nuclear cross-sections and the neutron lifetime by Monte Carlo methods [3,30].

First we evaluate how many species of light neutrinos are allowed subject to the upper limits $Y_p < 0.25$ (Eq. 1), $y_{2p} < 2.5 \times 10^{-4}$ (Eq. 2) and $y_{7p} < 2.6 \times 10^{-10}$ (Eq. 5). Fig. 2 plots the number ($N$) of computation runs (out of 1000) which satisfy the joint observational constraints, for different values of $N_\nu$. It is seen that (up to $\sqrt{N}$ statistical fluctuations) the “95% C.L.” bound is $N_\nu < 4.53$. This bound varies with the adopted upper limit to the helium abundance as

$$N_\nu^{\text{max}} = 3.75 + 78 \ (Y_p^{\text{max}} - 0.240). \quad (7)$$
For $N_{\nu} = 3$, $Y_p$ should exceed 0.230; to have $Y_p$ exceed 0.236 (Eq. 4), we require $\eta > 2.02 \times 10^{-10}$.

Secondly, we calculate the maximum value of $\eta$ permitted by the data by requiring that 50 runs out of 1000 (up to $\sqrt{N}$ statistical fluctuations) satisfy the constraints $y_{2p} > 1.1 \times 10^{-5}$ (Eq. 4) and $y_{7p} < 2.6 \times 10^{-10}$ (Eq. 5). A good fit for $Y_p < 0.247$ is

$$\eta^\text{max} = [3.19 + 375.7 (Y_p^\text{max} - 0.240)] \times 10^{-10};$$

for higher $Y_p$, the $y_{7p}$ constraint does not permit $\eta$ to exceed $5.7 \times 10^{-10}$, similar to the result found earlier [36]. If we choose instead to use the more conservative limit $y_{7p} < 1.5 \times 10^{-9}$ (Eq. 6), the bound is further relaxed to

$$\eta^\text{max} = [3.28 + 216.4 (Y_p^\text{max} - 0.240) + 34521 (Y_p^\text{max} - 0.240)^2] \times 10^{-10},$$

for $Y_p < 0.252$ and saturates at $1.06 \times 10^{-9}$ for higher values, essentially due to the $y_{2p}$ constraint (see Fig. 3). Thus for $Y_p^\text{max} = 0.25$, we find $\eta^\text{max} = 8.9 \times 10^{-10}$, which corresponds to a nucleon density in ratio to the critical density of $\Omega_N = 0.033h^{-2}$, where $h$ is the Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. For comparison, Hata et al. [1] find $\eta = 4.4^{+0.8}_{-0.6} \times 10^{-10} (1\sigma)$ and Copi et al. [7] quote the concordance range $\eta \simeq (2 - 6.5) \times 10^{-10}$.

In conclusion, the “crisis” is not with big bang nucleosynthesis but with the naïve model of galactic chemical evolution and restricted set of observational data considered by Hata et al. [1]. Their claim that the standard model is excluded follows from the unreliable “95% C.L.” limits they adopt on the input elemental abundances. Copi et al. [7] find, using statistical arguments, that assumptions concerning primordial abundances in previous work, including their own [8], must be relaxed for consistency with the standard model. In fact a variety of observational data had already pointed to the need for this, as reviewed elsewhere [37].

Our results have important implications for physics beyond the standard model [37]. For example, the relaxation of the bound on the number of neutrino species due to the new D and $^4\text{He}$ observations now permits the existence of a gauge singlet neutrino even if it has large mixing with doublet neutrinos, as in suggested solutions to the solar and atmospheric neutrino problems [38]. On the other hand, if the primordial D abundance is actually close to its present interstellar value and the primordial $^7\text{Li}$ abundance is that inferred from Pop I stars, then the nucleon density may be consistent with the observed large nucleon fractions in clusters of galaxies, even for a critical density universe [39].

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FIG. 1. Predicted light element abundances versus $\eta$, with 95% C.L. limits determined by Monte Carlo. The rectangles indicate the various observational determinations. Only the $^4$He abundance is established to be primordial in origin.
FIG. 2. Number of Monte Carlo runs (out of 1000) which simultaneously satisfy the constraints \( Y_p \leq 0.25 \), \( y_{2p} \leq 2.5 \times 10^{-4} \) and \( y_{7p} \leq 2.6 \times 10^{-10} \), as a function of \( \eta \) (in units of \( 10^{-10} \)), for various values of \( N_\nu \).
FIG. 3. The upper limit to $\eta$ (in units of $10^{-10}$) implied by the constraints $y_{2p} > 1.1 \times 10^{-5}$ and $y_{7p} < 1.5 \times 10^{-9}$, as a function of the maximum value of $Y_p$. 