Light–Element Nucleosynthesis: Big Bang and Later on

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Production of the light nuclides \(D\), \(^3\)He, \(^4\)He, and \(^7\)Li in their currently inferred primordial abundances by standard, homogeneous big bang nucleosynthesis (SHBBN) would imply a baryon fraction of the cosmic closure density \(\Omega_b\) in the range:

\[
0.04 \leq \Omega_b h_{50}^2 \leq 0.08 \quad (1)
\]

where \(h_{50}\) is the Hubble constant in units of 50 km s\(^{-1}\) Mpc\(^{-1}\) \([1], [2]\). Therefore, for the long–time most generally favored cosmological model with critical matter density and zero cosmological constant \((\Omega_M = 1, \Omega_{\Lambda} = 0)\), more than 90% of the matter in the universe should be nonbaryonic. That has led to explore different alternatives to SHBBN (see [3] for a review).

Baryon inhomogeneities generated in a first–order quark–hadron phase transition \([4]\) and resulting in regions with different \(n/p\) ratios has been the most thoroughly explored alternative. Agreement with the inferred primordial abundances could only be obtained for \(\Omega_b\) within the range (1) again, for spherically condensed fluctuations at least \([5]\). Recently, however, it has been shown that \(\Omega_b h_{50}^2\) might be as high as \(\simeq 0.2\) in inhomogeneous models if one assumes cylindrical shape for the inhomogeneities together with a very high density contrast \([6]\).

Another approach has been to assume that there are unstable particles \(X\), with masses \(m_X\) higher than a few GeV and lifetimes \(\tau_X\) longer than the standard thermonuclear nucleosynthesis epoch \([7]\). Gravitinos produced during reheating at the end of inflation might be an example of such particles. Their decay would give rise to both electromagnetic and hadron cascades, and the resulting high–energy photons would mainly photodisintegrate a fraction of the preexisting He whilst the high–energy hadrons would produce light nuclides via spallation–like reactions. A caveat of this model is that it predicts \(^6Li/\(^7Li \gg 1\) whereas observations show that \(^6Li/\(^7Li \leq 0.1\).

Concerning SHBBN, recent determinations of D abundances in high–redshift QSO absorbers, when confronted with the currently inferred pri-
mordial $^4$He abundance, might be in conflict with the predictions for $N_\nu = 3$ \[^8\]. That suggests a temporary abandon at least of SHBBN as a criterion to set bounds to $\Omega_b$. On the other hand, values of $\Omega_M$ much lower than the closure density are now being derived from a variety of sources, including high–$z$ supernova searches \[^9\], \[^10\]. The questions of which fraction of $\Omega_M$ could be baryonic and of the primordial nucleosynthesis bounds are thus posed in new terms.

Here we explore a composite model: baryon inhomogeneities are first produced at some phase transition prior to thermonuclear nucleosynthesis. The latter, therefore, takes place in two different types of regions: neutron–rich and neutron–poor ones. Then, when the universe has cooled down further and thermonuclear reactions do no longer take place, X–particle decay starts and the resulting electromagnetic and hadronic showers modify the light–nuclide abundances in both regions.

We model the inhomogeneities in a very simple way: there are two types of regions characterized by their density contrast $R$ and by their respective volume fractions $f_v$ and $1 - f_v$. Their comoving length scale $(d/a)$ enters in the neutron diffusion rate and is a third parameter of the model. The treatment is the same as in \[^{11}\]. The X–particles, in turn, are characterized by their half–life $\tau_x$, their mass $m_x$, the ratio of their number density to that of photons $r \equiv n_x/n_\gamma$, plus their mode of decay. The product $rm_x$ enters in the model as one of the parameters, together with $\tau_x$. The last parameter is the effective baryon ratio $r^*_B$, which takes into account the dependence of the number of baryons produced in the decays on $m_x$ together with the dependence of the light–element yields on the kinetic energies of the primary shower baryons. A more detailed account of the model can be found in \[^{12}\] and \[^{13}\].

We have explored the parameter space of our model and found good agreement with currently inferred primordial abundances for:

a) Density contrasts $500 \leq R \leq 5000$.
b) Volume fractions $0.144 \leq f_v \leq 0.192$.
c) Comoving length scales $(d/a) \simeq 10^{7.5}$ cm Mev (little neutron diffusion).
d) Small abundances of the X–particles: $1.5 \times 10^{-12} GeV \leq rm_x \leq 1.5 \times 10^{-11} GeV$.
e) Half–lives of the X–particles: $6.19 \times 10^5 s \leq \tau_x \leq 7.43 \times 10^5 s$.
f) Moderate numbers and energies of the shower baryons: $1.5 \times 10^{-12} \leq r^*_B \leq 1.5 \times 10^{-11}$.
g) Baryon density parameter: $18 \leq \eta_{10} \leq 22$. 
Those results are illustrated in Figure 1, where we show the predicted primordial abundances of the light nuclides as a function of $\tau_x$, for $\eta_{10} = 18$, and fixed values of the other parameters taken within the intervals a)–d) and f). The $\eta_{10}$ range translates into:

$$0.25 \leq \Omega_b h^2_{50} \leq 0.35$$

in sharp contrast with (1).

As we also see in the Figure, a testable prediction of the model is the production of a Be abundance $(^{9}Be/H)_p \sim 10^{-13}$. The predicted B abundance is much smaller. Production of Be and B is a typical feature of inhomogeneous models. Data on Be and B abundances in halo stars now extend down to metallicites $[Fe/H] \sim -3.0$ and they show a nearly constant B/Be ratio $\sim 10$ [14] while the smallest Be abundances measured are already of the order of our model prediction. Agreement with the observations would thus require a reversal in the B/Be ratio at still lower metallicities. On the other hand, the apparently primary behaviour of the Be and B abundances in the Galactic halo, together with the Li abundances there, is a still unsolved puzzle [15].

Figure 1: Primordial abundances of the light nuclides as a function of $\tau_x$, the half–life of the X–particles, for fixed values of the other parameters.
The model presented here is an example of how comparatively minor deviations from SHBBN might very significantly broaden the range of $\Omega_b$ compatible with the primordial abundances inferred from observations. Planned improvements of the model are a more realistic treatment of the inhomogeneities, and also consideration of shorter $\tau_x$ for which X–particle decays would occur simultaneously with the thermonuclear reactions.

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