The Nuclear Reactions in Standard BBN

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Nowadays, the Cosmic Microwave Background (CMB) anisotropy studies accurately determine the baryon fraction $\omega_b$, showing an overall and striking agreement with previous determinations of $\omega_b$ obtained from Big Bang Nucleosynthesis (BBN). However, a deeper comparison of BBN predictions with the determinations of the primordial light nuclide abundances shows some tension, motivating an effort to further improve the accuracy of theoretical predictions, as well as to better evaluate systematics in both observations and nuclear reactions measurements. We present some results of an important step towards an increasing precision of BBN predictions, namely an updated and critical review of the nuclear network, and a new protocol to perform the nuclear data regression.

1. Introduction

In the framework of the “Cosmological Concordance Model”, BBN probes the earliest times, but once $\omega_b$ is fixed, as now allowed by accurate CMB anisotropies analysis [1], it is completely ruled by Standard Physics, at least in its minimal formulation, thus providing useful insights on a wide range of astrophysical and cosmological issues.

As well known, the nuclide abundance predictions are mainly affected by the nuclear reaction uncertainties. The suggested range of $\omega_b$ and the low-energy nuclear data taken in the last decade justify a revision of the BBN network reliability, with respect to the one performed in the seminal paper by Smith et al. [2]: here we summarize our techniques and some results. For a detailed discussion of the issues presented here and of other refinements (like a better treatment of the neutrino sector and of plasma and QED effects) see [3].

2. From the data to the rates

The reaction rates are obtained as thermal averages of the relevant astrophysical factors $S(E)$ [1], so the first and most critical step is how to combine the data $\{i_k\}$ of several experiments $\{k\}$, each one affected in general by statistical, $\sigma_{i_k}$, and normalization errors, $\epsilon_k$, in a meta-analysis where both the magnitude and the energy behavior of the $S(E)$ have to be deduced. Usually, different experiments disagree within the quoted errors, suggesting some systematic discrepancy, the bulk of which can be attributed to different

1In what follows for simplicity we will refer to the S-factor, clearly defined only for reactions induced by charged particles. Similar relations also hold for neutron induced reactions.
normalizations. There is obviously no unique and unambiguous way to deal with such discrepancies and several methods appeared in the literature. In a recent one described in [4], both the errors are included in the covariance matrix entering the expression of the $\chi^2$ function to be minimized. This approach clearly takes into account the correlations between data of the same experiment, but as addressed in [5], a bias is thus introduced, leading to a systematic underestimate of the fitted functions, that typically pass below the majority of the data, and possibly affecting the nuclide predictions and errors estimates.

In our method, that generalizes the approach suggested in [5], the $\chi^2$ is calculated as

$$\chi^2(a_l, \omega_k) = \chi^2_{\text{stat}} + \chi^2_{\text{norm}} \equiv \sum_{i_k} \frac{(S_{th}(E_{i_k}, a_l) - S_{i_k}\omega_k)^2}{\omega_k^2\sigma_{i_k}^2} + \sum_{i_k} \frac{(\omega_k - 1)^2}{\epsilon_k^2},$$

where $S_{i_k}$ is the data point at the energy $E_{i_k}$ and $S_{th}(E)$ is the theoretical value of the astrophysical factor, depending on some parameters $a_l$ to be determined together with the renormalizing factors $\omega_k$ by standard minimization procedures. The covariance matrix was built by considering the statistical errors only, while different renormalization factors were allowed for each data set; the introduction of $\chi^2_{\text{norm}}$ disfavors renormalizations greater than the estimated $\epsilon_k$. The best-fit curves thus produced pass through the data, closer to the best determinations, as one would expect from an unbiased estimator (see Figs. 1, 2). In such an approach, the bulk of the systematic uncertainty has been taken into account and the residual discrepancies can be considered as due to some unidentified/underestimated source of error in one or several experiments. Then, we simply inflated the calculated error by a scale factor $\sqrt{\chi^2_{\nu}}$, as prescribed by the Particle Data Book [6]. Using this prescription, the overall normalization uncertainty cannot be clearly worse than the one determined by the most accurate experiment: this error was quadratically added to the previous one. Finally, a typical renormalization factor $\epsilon$ was calculated, to give an idea of the current disagreement on the scale of $S(E)$ among several experiments

$$\epsilon^2 \equiv \frac{\sum_k w_k (\omega_k - 1)^2}{\sum_k w_k}$$

where $w_k = (\chi_k^2/N_k)^{-1}$, $N_k$ is the number of data and $\chi_k^2$ the contribution to the $\chi^2$ of the $k$-th data set, thus assigning a larger weight to the experiments closer to the fitted $S$.

The rate $R$ was obtained by numerical integration of $S(E)$ convolved with the Boltzmann/Gamow Kernel $K(E, T) \sim e^{-E/T} e^{-\sqrt{E_G/E}}$

$$R = \int_0^\infty dE K(E, T) S(E, \hat{a})$$

and its error $\delta R$ through the standard error propagation as

$$\delta R^2 = \int_0^\infty dE' K(E', T) \int_0^\infty dE K(E, T) \sum_{l,m} \left. \frac{\partial S(E', a)}{\partial a_l} \right|_{\hat{a}} \left. \frac{\partial S(E, a)}{\partial a_m} \right|_{\hat{a}} \text{cov}(a_l, a_m),$$

thus fully including the correlations among the fitted parameters. The uncertainties on the nuclides yields were finally obtained with a generalization of the linear propagation method described in [3, 7, 8].

\(^{2}\)Or conservatively the total ones, if $\epsilon_k$ and $\sigma_{i_k}$ were unavailable in a separate form.
3. From the rates to the predictions

In Fig. 3 we plot the net contribution to the right-hand side of the leading and main sub-leading reactions to the synthesis and destruction of \(^7\text{Li}\) \((^7\text{Be})\), obtained for the typical value \(\omega_b = 0.023\). It is easily seen that the first stage of \(^7\text{Li}\) production around \(T \simeq 70\) keV mainly proceeds through the \(^4\text{He}(t,\gamma)^7\text{Li}\) reaction, but \(^7\text{Li}\) is soon burned via \(^7\text{Li}(p,\alpha)^4\text{He}\) reaching a low plateau value. The final \(^7\text{Li}\) content is thus mainly given by the late \(^7\text{Be}\) EC decay: this isotope, synthesized via the key route \(^4\text{He}(^3\text{He},\gamma)^7\text{Be}\), is less easily destroyed through the (experimentally poorly known) channels \(^7\text{Be}(n,\alpha)^4\text{He}\) and \(^7\text{Be}(d,p)^4\text{He}\) \(^3\), or the two steps process \(^7\text{Be}(n,p)^7\text{Li} + ^7\text{Li}(p,\alpha)^4\text{He}\), now determined with good accuracy. The former two reactions are indeed responsible for the bulk of the \(^7\text{Li}\) error budget, at least if a conservative uncertainty of one order of magnitude is assumed.

We also found that sub-leading processes as \(^7\text{Li}+p\rightarrow ^8\text{Be}^*\rightarrow \gamma+2^4\text{He}\), often neglected in BBN studies, for which new measurements exists, are truly marginal, even if their little contribution to the final error is similar to the much widely treated \(^4\text{He}(t,\gamma)^7\text{Li}\). The same is true e.g. for the other overlooked reactions \(^6\text{Li}(d,p)^7\text{Li}\) and \(^6\text{Li}(d,n)^7\text{Be}\).

We checked that only a handful of reactions dominate the error budget, and, apart for useful measurements of poorly known cross sections, a determination of both the magnitude and the shape of the \(^2\text{H}(d,n)^3\text{He}, ^2\text{H}(d,p)^3\text{H}, ^4\text{He}(^3\text{He},\gamma)^7\text{Be}\) reactions at the 1% accuracy level over all the interval of interest for the BBN (say, up to \(\sim 2\) MeV) could significantly

\(^3\)The latter has been measured at Louvain la Neuve, see the contribution of C. Angulo to these proceedings.
improve the reliability of the predictions of both $^2\text{H}$ and $^7\text{Li}$. In these cases, indeed, the systematics coming from several experiments dominate the uncertainty, and more reliable data are needed, since even very detailed regression methods may fail in these cases. On the other hand, the BBN theory would surely benefit of refined studies of the $^4\text{He}$ and $^7\text{Li}$ observational systematics, as well as from an increase in the statistics of the $^2\text{H}/\text{H}$ determinations in the high-$z$ damped Ly-$\alpha$ absorption systems.

We also confirm that the $^4\text{He}$ error is dominated by that on the neutron lifetime, while the new value of $G_N$ quoted in [6] makes its uncertainty of no relevance for the BBN.

In summary, we presented some highlights on a new method of data regression and a reanalysis and update of the BBN nuclear network. Some differences with the results currently quoted in the literature were discussed, but typically a reassuring agreement with the usual results has been found, confirming the robustness of the BBN predictions.

Obviously, the new compilation produced will also turn to be useful to deepen our insights on several non standard BBN scenarios.

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