Big bang nucleosynthesis: Present status

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(published 23 February 2016)

Big bang nucleosynthesis (BBN) describes the production of the lightest nuclides via a dynamic interplay among the four fundamental forces during the first seconds of cosmic time. A brief overview of the essentials of this physics is given, and new calculations presented of light-element abundances through ^{6}Li and ^{7}Li, with updated nuclear reactions and uncertainties including those in the neutron lifetime. Fits are provided for these results as a function of baryon density and of the number of neutrino flavors N_ν. Recent developments are reviewed in BBN, particularly new, precision *Planck* cosmic microwave background (CMB) measurements that now probe the baryon density, helium content, and the effective number of degrees of freedom $N_{\rm eff}$. These measurements allow for a tight test of BBN and cosmology using CMB data alone. Our likelihood analysis convolves the 2015 *Planck* data chains with our BBN output and observational data. Adding astronomical measurements of light elements strengthens the power of BBN. A new determination of the primordial helium abundance is included in our likelihood analysis. New D/H observations are now more precise than the corresponding theoretical predictions and are consistent with the standard model and the *Planck* baryon density. Moreover, D/H now provides a tight measurement of N_ν when combined with the CMB baryon density and provides a 2σ upper limit $N_\nu < 3.2$. The new precision of the CMB and D/H observations together leaves D/H predictions as the largest source of uncertainties. Future improvement in BBN calculations will therefore rely on improved nuclear cross-section data. In contrast with D/H and ^{4}He, ^{7}Li predictions continue to disagree with observations, perhaps pointing to new physics. This paper concludes with a look at future directions including key nuclear reactions, astronomical observations, and theoretical issues.

DOI: 10.1103/RevModPhys.88.015004

CONTENTS

I. INTRODUCTION

Big bang nucleosynthesis (BBN) is one of the few probes of the very early Universe with direct experimental or observational consequences (Walker *et al.*, 1991; Olive, Steigman, and Walker, 2000; Fields and Olive, 2006; Steigman, 2007; Iocco *et al.*, 2009; Fields, Molaro, and Sarkar, 2014). In the context of the standard models of cosmology and of nuclear and particle physics, BBN is an effectively parameter-free

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$\pm 1\sigma$ spread in the predicted abundances. These results assume $N_\nu = 3$ and the current measurement of the neutron lifetime $\tau_n = 880.3 \pm 1.1$ s.

Using a Monte Carlo approach also allows us to extract sensitivities of the light-element predictions to reaction rates and other parameters. The sensitivities are defined as the logarithmic derivatives of the light-element abundances with respect to each variation about our fiducial model parameters (Fiorentini *et al.*, 1998), yielding a simple relation for extrapolating about the fiducial model:

$$X_i = X_{i,0} \prod_n \left(\frac{p_n}{p_{n,0}}\right)^{\alpha_n}, \quad (12)$$

where X_i represents either the helium mass fraction or the abundances of the other light elements by number. The p_n represent input quantities to the BBN calculations (η, N_ν, τ_n) and the gravitational constant[5] G_N as well as key nuclear rates which affect the abundance X_i. $p_{n,0}$ refers to our standard input value. The information contained in Eqs. (13)–(17) is summarized in Table III:

$$Y_p = 0.24703 \left(\frac{10^{10}\eta}{6.10}\right)^{0.039} \left(\frac{N_\nu}{3.0}\right)^{0.163} \left(\frac{G_N}{G_{N,0}}\right)^{0.35} \left(\frac{\tau_n}{880.3s}\right)^{0.73} [p(n,\gamma)d]^{0.005} [d(d,n)^3\mathrm{He}]^{0.006} [d(d,p)t]^{0.005}, \quad (13)$$

$$\frac{\mathrm{D}}{\mathrm{H}} = 2.579 \times 10^{-5} \left(\frac{10^{10}\eta}{6.10}\right)^{-1.60} \left(\frac{N_\nu}{3.0}\right)^{0.395} \left(\frac{G_N}{G_{N,0}}\right)^{0.95} \left(\frac{\tau_n}{880.3s}\right)^{0.41} [p(n,\gamma)d]^{-0.19} [d(d,n)^3\mathrm{He}]^{-0.53} [d(d,p)t]^{-0.47}$$
$$\times [d(p,\gamma)^3\mathrm{He}]^{-0.31} [^3\mathrm{He}(n,p)t]^{0.023} [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.012}, \quad (14)$$

$$\frac{^3\mathrm{He}}{\mathrm{H}} = 9.996 \times 10^{-6} \left(\frac{10^{10}\eta}{6.10}\right)^{-0.59} \left(\frac{N_\nu}{3.0}\right)^{0.14} \left(\frac{G_N}{G_{N,0}}\right)^{0.34} \left(\frac{\tau_n}{880.3s}\right)^{0.15} [p(n,\gamma)d]^{0.088} [d(d,n)^3\mathrm{He}]^{0.21} [d(d,p)t]^{-0.27}$$
$$\times [d(p,\gamma)^3\mathrm{He}]^{0.38} [^3\mathrm{He}(n,p)t]^{-0.17} [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.76} [t(d,n)^4\mathrm{He}]^{-0.009}, \quad (15)$$

$$\frac{^7\mathrm{Li}}{\mathrm{H}} = 4.648 \times 10^{-10} \left(\frac{10^{10}\eta}{6.10}\right)^{2.11} \left(\frac{N_\nu}{3.0}\right)^{-0.284} \left(\frac{G_N}{G_{N,0}}\right)^{-0.73} \left(\frac{\tau_n}{880.3s}\right)^{0.43} [p(n,\gamma)d]^{1.34} [d(d,n)^3\mathrm{He}]^{0.70} [d(d,p)t]^{0.065}$$
$$\times [d(p,\gamma)^3\mathrm{He}]^{0.59} [^3\mathrm{He}(n,p)t]^{-0.27} [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.75} [t(d,n)^4\mathrm{He}]^{-0.023}$$
$$\times [^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}]^{0.96} [^7\mathrm{Be}(n,p)^7\mathrm{Li}]^{-0.71} [^7\mathrm{Li}(p,\alpha)^4\mathrm{He}]^{-0.056} [t(\alpha,\gamma)^7\mathrm{Li}]^{0.030}, \quad (16)$$

$$\frac{^6\mathrm{Li}}{\mathrm{H}} = 1.288 \times 10^{-13} \left(\frac{10^{10}\eta}{6.10}\right)^{-1.51} \left(\frac{N_\nu}{3.0}\right)^{0.60} \left(\frac{G_N}{G_{N,0}}\right)^{1.40} \left(\frac{\tau_n}{880.3s}\right)^{1.37} [p(n,\gamma)d]^{-0.19} [d(d,n)^3\mathrm{He}]^{-0.52} [d(d,p)t]^{-0.46}$$
$$\times [d(p,\gamma)^3\mathrm{He}]^{-0.31} [^3\mathrm{He}(n,p)t]^{0.023} [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.012} [d(\alpha,\gamma)^6\mathrm{Li}]^{1.00}. \quad (17)$$

B. The neutron mean lifetime

As noted in the Introduction, the value of the neutron mean lifetime has had a turbulent history. Unfortunately, the predictions of SBBN remain sensitive to this quantity. This sensitivity is displayed in the scatter plot of our Monte Carlo error propagation with fixed $\eta = 6.10 \times 10^{-10}$ in Fig. 2. The correlation between the neutron mean lifetime and ^{4}He abundance prediction is clear. The correlation is not infinitesimally narrow because other reaction rate uncertainties significantly contribute to the total uncertainty in ^{4}He.

C. *Planck* likelihood functions

For this paper, we consider two sets of *Planck* Markov chain data, one for standard BBN (SBBN) and one for

TABLE III. The sensitivities α_n's defined in Eq. (12) for each of the light-element abundance predictions, varied with respect to key parameters and reaction rates.

Variant	Y_p	D/H	^{3}He/H	^{7}Li/H	^{6}Li/H
η (6.1×10^{-10})	0.039	−1.598	−0.585	2.113	−1.512
N_ν (3.0)	0.163	0.395	0.140	−0.284	0.603
G_N	0.354	0.948	0.335	−0.727	1.400
n decay	0.729	0.409	0.145	0.429	1.372
$p(n,\gamma)d$	0.005	−0.194	0.088	1.339	−0.189
$^3\mathrm{He}(n,p)t$	0.000	0.023	−0.170	−0.267	0.023
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$	0.000	0.000	0.000	−0.705	0.000
$d(p,\gamma)^3\mathrm{He}$	0.000	−0.312	0.375	0.589	−0.311
$d(d,\gamma)^4\mathrm{He}$	0.000	0.000	0.000	0.000	0.000
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	0.000	0.000	0.000	−0.056	0.000
$d(\alpha,\gamma)^6\mathrm{Li}$	0.000	0.000	0.000	0.000	1.000
$t(\alpha,\gamma)^7\mathrm{Li}$	0.000	0.000	0.000	0.030	0.000
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	0.000	0.000	0.000	0.963	0.000
$d(d,n)^3\mathrm{He}$	0.006	−0.529	0.213	0.698	−0.522
$d(d,p)t$	0.005	−0.470	−0.265	0.065	−0.462
$t(d,n)^4\mathrm{He}$	0.000	0.000	−0.009	−0.023	0.000
$^3\mathrm{He}(d,p)^4\mathrm{He}$	0.000	−0.012	−0.762	−0.752	−0.012

[5]In models beyond the standard model, one may also consider variations of the gravitational constant (for fixed nucleon masses). See Yang *et al.* (1979), Accetta, Krauss, and Romanelli (1990), Sarkar (1996), Copi, Davis, and Krauss (2004), and Cyburt *et al.* (2005) for BBN limits on variations of G_N.