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BIG-BANG NUCLEOSYNTHESIS PREDICTIONS FOR PRECISION COSMOLOGY

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ABSTRACT

The determination of the primeval deuterium abundance has opened a precision era in big-bang nucleosynthesis (BBN), making accurate predictions more important than ever before. We present in analytic form new, more precise predictions for the light-element abundances and their error matrix. Using our predictions and the primeval deuterium abundance we infer a baryon density of $\Omega_B h^2 = 0.020 \pm 0.002$ (95% cl) and find no evidence for stellar production (or destruction) of ^{3}He beyond burning D to ^{3}He. Conclusions about ^{4}He and ^{7}Li currently hinge upon possible systematic error in their measurements.

Subject headings: nuclear reactions, nucleosynthesis, abundances – cosmology : theory

1. INTRODUCTION

The BBN prediction of a large primeval abundance of ^{4}He ($Y_P \approx 0.25$) was the first success of the hot big-bang model. For two decades the consistency of the BBN predictions for the abundances of D, ^{3}He, ^{4}He and ^{7}Li with their inferred primeval abundances has been an important test of the standard cosmology at early times ($t \sim 1\,$sec). BBN has also been used to "inventory" ordinary matter at a simpler time and to probe fundamental physics (see e.g., Schramm & Turner 1998 or Olive et al. 2000).

With the detection of the deuterium Ly-α feature in the absorption spectra of 3 high-redshift ($z > 2$) quasars and the accurate determination of the primeval abundance of deuterium, $(\mathrm{D/H})_P = (3.0 \pm 0.2) \times 10^{-5}$ (Burles et al. 2000; Tytler et al. 2000; O'Meara et al. 2001) BBN has entered a new precision era (Schramm & Turner 1998). Because its abundance depends strongly upon the baryon density, and its subsequent chemical evolution is so simple (astrophysical processes only destroy D), deuterium can accurately peg the baryon density. Once determined, the baryon density allows the abundances of ^{3}He, ^{4}He and ^{7}Li to be predicted. These predictions can be used to test the consistency of the big-bang framework and to probe astrophysics.

The chemical evolution of ^{4}He is simple (stars produce it) and so its predicted abundance, $Y_P = 0.246 \pm 0.001$ (Lopez & Turner 1999), can be used as a consistency test of BBN and the standard cosmology. Because the ^{7}Li abundance in old pop II stars may be depleted, lithium probes both stellar models and the consistency of the standard cosmology.

While the post-big-bang evolution of ^{3}He is complex, the sum D+^{3}He can be used to study the chemical evolution of the Galaxy. All stars burn D to ^{3}He as they evolve onto the main sequence (MS). Later stages of stellar evolution may produce or destroy ^{3}He, depending on stellar mass and subject to uncertainty in modeling. Thus, the evolution of D+^{3}He measures the net stellar production of ^{3}He beyond pre-MS burning (Yang et al. 1984), providing an important probe of stellar models.

A key to realizing BBN's full potential in the precision era is accurate and reliable predictions. With this in mind, we have recently used Monte-Carlo techniques (Burles et al. 1999; Nollett & Burles 2000) to link the calculated abundances directly to the nuclear data, making the predictions more reliable.

Previous work (Smith et al. 1993, Fiorentini et al. 1998) was based on fitting cross-section data to standard forms, estimating conservative uncertainties to accommodate most or all of the data for each reaction. Very recent work (Esposito et al. 2000; Vangioni-Flam et al. 2000) computes only "maximum" uncertainties, using upper and lower limits quoted in a compilation of charged-particle reaction rates (Angulo et al. 1999). In contrast, our procedure ties the abundance errors directly to the experimental measurements by weighting the data by their quoted errors, and furthermore, leads to smaller estimated abundance errors (by factors of 2-3).

In this *Letter* we present our results in the form of analytic fits for the abundances and their error matrix. We then use these predictions to make inferences about the baryon density, the consistency of BBN, ^{7}Li depletion and stellar ^{3}He production.

2. ANALYTIC RESULTS

Our BBN code draws reaction rates from a statistical distribution and computes the corresponding distribution of BBN yields. It varies all of the laboratory data (over 1200 individual data points) simultaneously, drawing random realizations of each data point and normalizations for each data set from Gaussian distributions representing reported values and uncertainties. For each realization, the BBN yields are computed using thermally-averaged smooth representations of the realized data. The results presented here are based on 25 000 such realizations of the data (see Fig. 1). More details are given in Burles et al (1999), and Nollett & Burles (2000).

Here we present fits of the means, variances, and correlation matrix of the predicted abundances to fifth-order polynomials in $x \equiv \log_{10}\eta + 10$, where η is the baryon-to-photon ratio; see Tables 1–3. Applicable over the range $0 \leq x \leq 1$, our fits are accurate to better than 0.2% for the abundances and 10% for the variances. For the mean ^{4}He yields, we adopt the fitting formula of Lopez & Turner (1999) which is accurate to

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0.05%[6]. Some of the abundances follow approximate power laws, and so we have obtained accurate fits by fitting the means and variances of their base-ten logarithms in all cases except the mean Y_P. Because our estimates for the uncertainties are small, $\mathrm{Var}(Y_i) = (\bar{Y}_i/0.4343)^2\,\mathrm{Var}(\log_{10} Y_i)$. The covariance matrix is written in terms of the variances and a correlation matrix r_{ij}:

$$\rho_{ij} = r_{ij}\sqrt{\mathrm{Var}(Y_i)\mathrm{Var}(Y_j)}. \qquad (1)$$

where Y_i is baryon fraction for ^{4}He and number relative to Hydrogen for the other nuclides, and $\bar{Y}_i$ is its mean over the output yields.

Finally, because BBN produces ^{7}Li by two distinct processes, direct production and indirect production through ^{7}Be with subsequent electron capture to ^{7}Li, we have split the ^{7}Li yield into these two pieces to obtain more accurate fits. The mean prediction for ^{7}Li is just the sum of the two contributions; the variance $\mathrm{Var}(Y_7) = \mathrm{Var}(Y_{\mathrm{Li}}) + \mathrm{Var}(Y_{\mathrm{Be}}) + 2\rho_{\mathrm{Li,Be}}$. The covariance between the total BBN ^{7}Li and another nuclide $\rho_{i,7} = \rho_{i,\mathrm{Li}} + \rho_{i,\mathrm{Be}}$.

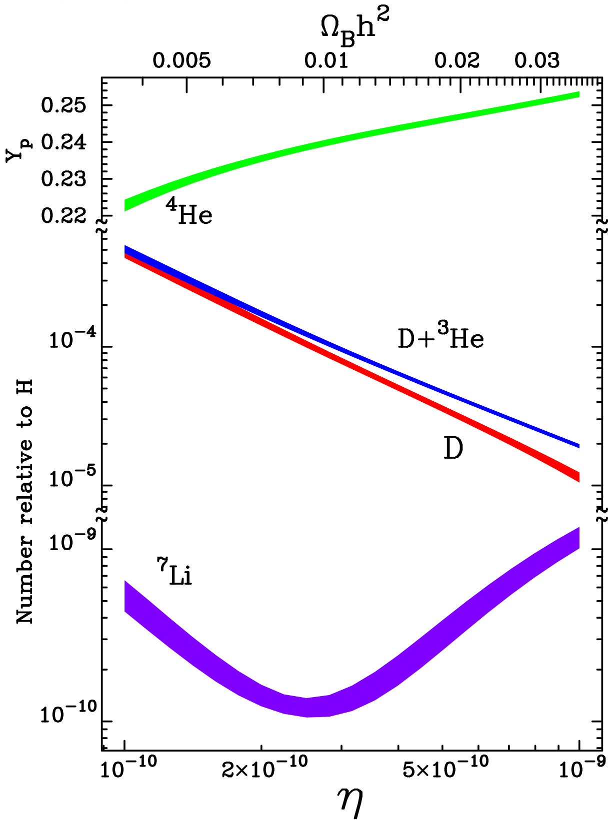

FIG. 1. Predicted big-bang abundances of the light elements shown as bands of 95% confidence.

3. IMPLICATIONS

To use our predictions we need observed abundances of the light elements. This is a lively area of research, with some controversy. Here, based upon our evaluation of the data, we state our choices with brief justification and point the reader interested in more detail to the relevant literature.

For the primordial deuterium abundance we use the weighted average of the 3 detections in high-redshift Ly-α, $(\mathrm{D/H})_P = (3.0 \pm 0.2) \times 10^{-5}$ (for further discussion see Burles et al. 2000; Tytler et al. 2000; O'Meara et al. 2001).

For the present abundance of D+^{3}He, we use measurements of both elements made in the local interstellar medium (ISM). The deuterium abundance, D/H= $(1.5 \pm 0.2 \pm 0.5) \times 10^{-5}$, comes from HST, IUE and Copernicus measurements along 12 lines of sight to nearby stars (Linsky 1998; Lemoine et al. 1999; McCullough 1992). The first error is statistical, and the second error represents the possibility of scatter due to spatial variations (Vidal-Madjar & Gry 1984; Linsky 1998; Vidal-Madjar et al. 1999; Sonneborn et al. 2000); as it turns out, the uncertainty in ^{3}He dominates both. Gloeckler & Geiss (1998) have determined the ratio of ^{3}He to ^{4}He in the local ISM using the pick-up ion technique. Allowing for a local ^{4}He mass fraction between 25% and 30%, their measurement translates to ^{3}He/H= $(2.2 \pm 0.8) \times 10^{-5}$ and (D+^{3}He)/H= $(3.7 \pm 1) \times 10^{-5}$.

For the primordial ^{7}Li abundance we use the value advocated by Ryan (2000), based upon the extant measurements of ^{7}Li in the atmospheres of old halo stars. His value, ^{7}Li/H= $1.2^{+0.35}_{-0.2} \times 10^{-10}$, includes empirical corrections for cosmic-ray production, stellar depletion, and improved atmospheric models, and the uncertainty arises mainly from these corrections. This is consistent with other estimates (see e.g., Bonifacio & Molaro 1997; Ryan et al. 1999; Thorburn 1994).

The primordial abundance of ^{4}He is best inferred from HII regions in metal-poor, dwarf emission-line galaxies. While such measurements are some of the most precise in astrophysics, the values for Y_P obtained from the two largest samples of such objects are not consistent and concerns remain about systematic error.

Olive et al (1997) have compiled a large sample of objects and find $Y_P = 0.234 \pm 0.002$. On the other hand, Izotov & Thuan (1998) have assembled a large sample from a single observational program, extracting Y_P from the spectra by a different method. They find $Y_P = 0.244 \pm 0.002$ (consistent with the earlier sample of Kunth & Sargent 1983, which found $Y_P = 0.245 \pm 0.003$). Further, they have shown that at least one of the most metal-poor objects (IZw18) used in the earlier sample suffered from stellar absorption, and argue that it and possibly other metal-poor objects in this sample explain the discrepancy. Viegas et al. (2000) argue that the Izotov and Thuan sample should be corrected downward by a small amount ($\Delta Y_P \approx 0.003$) to account for neutral and doubly ionized ^{4}He; Ballantyne et al. (2000) agree on the magnitude of the effect, but not the direction. Finally, a recent study of different parts of a single HII region in the SMC finds $Y = 0.241 \pm 0.002$ (Peimbert et al. 2000), at face value implying $Y_P \leq 0.241 \pm 0.002$.

Clearly, the final word on Y_P is not in. For now, because of the homogeneity and size of the Izotov and Thuan sample and the possible corruption of the other sample by stellar absorption, with caution we adopt $Y_P = 0.244 \pm 0.002$. (Had we adopted an intermediate value, with a systematic error reflecting the discrepancy between the two data sets, our conclusions would be largely the same.)

Using these choices, we have constructed separate likelihood functions for the baryon-to-photon ratio η from the abundances of D, D+^{3}He, ^{4}He and ^{7}Li, assuming Gaussian distributions for the uncertainties; see Fig. 2. While the D, D+^{3}He and ^{4}He

[6] Our fit coefficients are the a_i from Eq. 44. We note that their fitting formula for the dependence of Y_P on neutron lifetime (δY_P in Equation 43 of that paper) has a misprint in the signs but not the magnitudes of the coefficients b_i. The correct sequence of signs for the b_i is $++-+-$. They also provide a fit for the N_ν dependence of Y_P.

TABLE 1
FITS TO THE ABUNDANCES, $\log_{10}\bar{Y}_i = \sum_i a_i x^i$, EXCEPT, $\bar{Y}_P = \sum_i a_i x^i$.

Nuclide	a_0	a_1	a_2	a_3	a_4	a_5
Y_P	0.22292	0.05547	-0.05639	0.04587	-0.01501	–
D/H	-3.3287	-1.6277	-0.2286	0.7794	-0.6207	0.0846
^{3}He/H	-4.4411	-0.7955	0.4153	-0.9909	1.0925	-0.3924
(D+^{3}He)/H	-3.2964	-1.5675	-0.1355	0.8018	-0.7421	0.2225
^{7}Li/H	-9.2729	-2.1707	-0.6159	4.1289	-3.6407	0.7504
^{7}Be/H	-12.0558	3.6027	2.7657	-6.5512	4.4725	-1.1700

TABLE 2
FITS TO THE VARIANCES, $\mathrm{Var}(\log_{10} Y_i) = \sum_i a_i x^i$.

Nuclide	a_0	a_1	a_2	a_3	a_4	a_5
$10^5\, Y_P$	0.2544	-1.3463	4.0384	-6.3448	4.9910	-1.5446
10^3 (D/H)	0.2560	0.1379	-2.3363	5.0495	-4.6972	1.9351
10^3 (^{3}He/H)	0.0776	0.1826	-0.7725	1.5357	-0.9106	0.1522
10^3 (D+^{3}He)/H	0.2181	-0.0287	-1.6284	3.5182	-2.8499	0.8323
10^2 (^{7}Li/H)	0.2154	-0.0049	-1.7200	4.0635	-3.8618	1.3946
10^2 (^{7}Be/H)	0.7970	1.2036	-6.5462	6.0483	-0.2788	-1.1190

TABLE 3
FITS TO THE CORRELATION COEFFICIENTS, $r_{j,k} = \sum_i a_i x^i$.

Coefficient j	k	a_0	a_1	a_2	a_3	a_4	a_5
Y_P	D	-0.8121	0.6430	3.3284	-7.2925	5.6748	-1.5914
Y_P	^{3}He	0.2129	1.3468	-8.3646	15.8093	-12.8939	3.9055
Y_P	D + ^{3}He	-0.8091	0.6468	3.3848	-7.4565	5.7605	-1.5838
Y_P	^{7}Li	-0.3630	-0.1017	5.1531	-10.3563	7.5445	-1.8680
Y_P	^{7}Be	0.7744	-0.3414	-4.0492	8.4836	-6.7167	1.9345
D	^{3}He	-0.1924	-1.9722	8.2683	-13.6301	8.1108	-1.2999
D	D + ^{3}He	0.9995	-0.0238	0.1229	-0.2574	-0.1625	0.1352
D	^{7}Li	0.4219	0.2824	-0.9063	-6.9928	14.5503	-6.8278
D	^{7}Be	-0.8820	-0.0647	-0.4330	3.9867	-4.9394	1.6666
^{3}He	D + ^{3}He	-0.1526	-1.7701	7.2981	-9.4669	3.7557	0.1560
^{3}He	^{7}Li	-0.1321	-0.8465	3.1187	0.7518	-6.1419	2.9935
^{3}He	^{7}Be	0.3293	1.6390	-6.3839	8.9361	-4.2279	0.3574
D + ^{3}He	^{7}Li	0.4186	0.3165	-1.2759	-6.0646	14.4155	-7.2783
D + ^{3}He	^{7}Be	-0.8744	-0.0455	-0.3596	3.9249	-4.6197	1.5773
^{7}Li	^{7}Be	-0.4091	-0.1971	-0.5008	11.8943	-19.0115	8.0258

abundances are all consistent with $\eta \approx 5\times10^{-10}$, most precisely pegged by D, the ^{7}Li abundance favors a significantly lower value. Combining these, we find $\chi^2 = 23.2$ for 3 degrees of freedom (4 abundances minus 1 parameter). This is the well-known lithium problem: the deuterium-inferred value for the baryon density predicts a ^{7}Li abundance that is about 3σ larger than that measured in old pop II halo stars (see e.g., Burles et al. 1999; or Olive et al. 2000)

Since it is possible, and some stellar models suggest, that there has been more depletion of ^{7}Li in old halo stars than the 5% inferred by Ryan (2000), we introduce a model parameter, f_7, the ratio of the inferred ^{7}Li/H in old pop II stars to its predicted primordial value. It quantifies how much the primordial ^{7}Li/H has been affected by additional stellar depletion, cosmic-ray production, or theoretical difficulties (e.g., systematic errors in the nuclear cross sections or in the modeling of stellar atmospheres). An $f_7 \neq 1$ might also reflect fundamental problems, such as systematic problems with the deuterium abundance or inconsistencies in BBN.

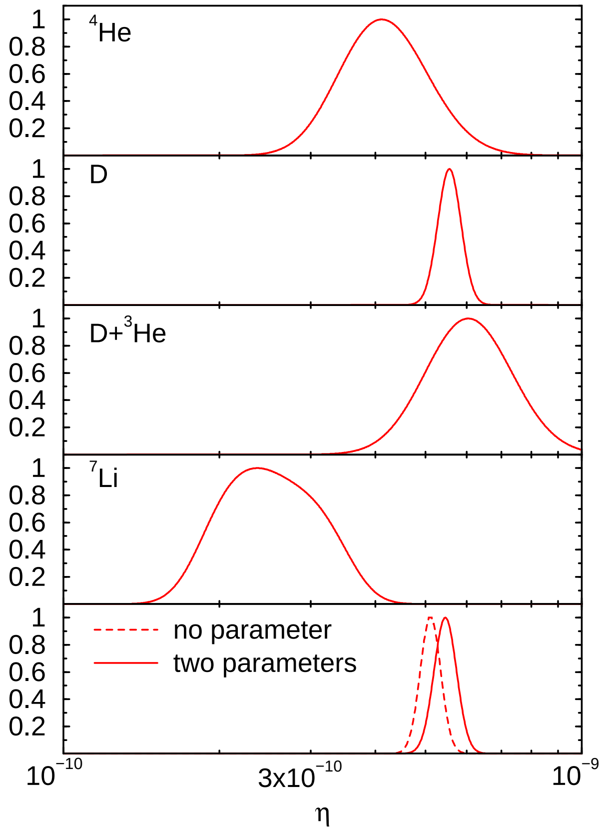

FIG. 2. Likelihood functions, normalized to unit maximum, for η derived from single-abundance analyses (top four panels) and from simultaneous analysis of all four abundances and their covariances (bottom panel). In the "two-parameter" analysis the likelihood is marginalized over f_7 and f_{23} (see text).

Since there is no reason to believe that the present value of (D+^{3}He)/H in the local ISM is the primordial value, we introduce an analogous factor, f_{23}, which is the ratio of the present (D+^{3}He)/H to its primordial value. If $f_{23} = 1$, then the light-element abundances are consistent with the simple hypothesis that stars only convert D into ^{3}He during pre-MS burning, conserving D+^{3}He by number; $f_{23} > 1$ indicates additional net stellar production of ^{3}He, and $f_{23} < 1$ indicates net stellar destruction of ^{3}He after the pre-MS.

Fig. 3 shows the distributions for f_7 and f_{23}, each marginalized over our other two parameters (e.g., the f_{23} curve results from marginalizing over η and f_7). The most likely value for f_7 is 0.32, with 95% confidence interval 0.20 − 0.55. That is, consistency between the deuterium-predicted ^{7}Li abundance and the pop II abundance requires a depletion of greater than a factor of two or some as-yet unidentified source of systematic error in the BBN prediction or measurement. Such depletion can be achieved in stellar models and still be consistent with other observational constraints, including the plateau in ^{7}Li abundance in old pop II stars and the detection of ^{6}Li in several stars (see e.g., Vauclair & Charbonnel 1995; Pinsonneault et al. 1999; Salaris & Weiss 2001).

The most likely value for f_{23} is 0.88, with 95% confidence interval 0.55 − 1.54. Unlike f_7, this new parameter has essentially no effect on the question of concordance, and its value supports the simple hypothesis of only pre-MS ^{3}He production. It also disfavors stellar models that predict significant net ^{3}He production (or destruction) and is consistent with an earlier comparison of pre-solar and ISM measurements of D+^{3}He which showed no evidence for an increase over the last 4.5 Gyr (Turner et al. 1996). This is somewhat surprising, since the conventional models for the galactic chemical evolution of ^{3}He predict a significant increase in D+^{3}He due to net ^{3}He production by low mass stars (Iben & Truran 1978; Dearborn, Schramm, & Steigman 1986). However, Wasserburg, Boothroyd, & Sackmann (1995) argue that ^{3}He destruction by some low-mass stars is possible.

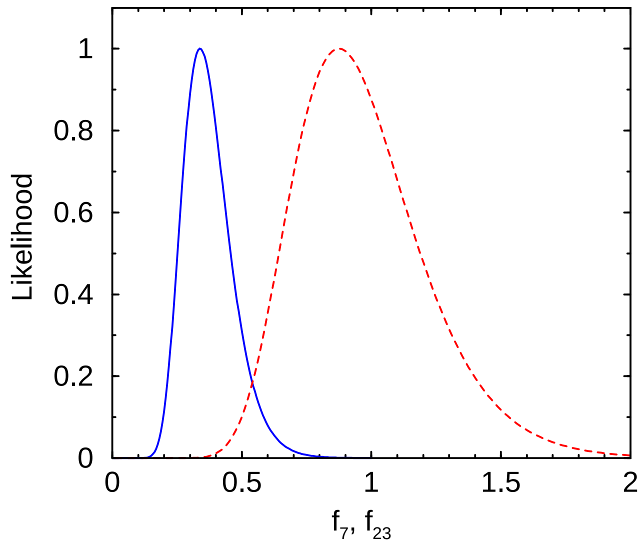

FIG. 3. Marginalized likelihoods for f_7 (solid curve) and f_{23} (broken curve).

BBN and the light-element abundances can be used to fix the baryon-to-photon ratio at the end of BBN ($t \sim 200$ sec). We have computed the likelihood function for the baryon density using the abundances of all four light elements and marginalizing over f_7 and f_{23}, giving all the weight to D and ^{4}He. We find: $\eta = (5.5\pm0.5)\times10^{-10}$, shown as the "two-parameter" curve in Fig. 2. The value is driven almost entirely by deuterium: using the deuterium alone we find $\eta = (5.6\pm0.5)\times10^{-10}$.

To relate η to the present baryon density ($\Omega_B h^2$) one needs to know the present photon temperature ($T = 2.725\,\mathrm{K}\pm 0.001\,\mathrm{K}$) and the average mass per baryon number, $\bar{m} = 1.6700$ (1.6701) $\times10^{-24}$ g for the post-BBN mix (solar abundance), and make the assumption that the expansion has been adiabatic since BBN. Then, η and the baryon density are related by $\Omega_B h^2 = (3.650 \pm 0.004) \times 10^7 \eta_{\rm BBN}$. Within the standard cosmology, $\eta = (5.5 \pm 0.5) \times 10^{-10}$ translates to a baryon density,

$$\Omega_B h^2 = 0.020 \pm 0.002 \qquad \text{(95\% confidence)}. \qquad (2)$$

Finally, we mention other recent likelihood analyses of BBN. Hata et al. (1995) addressed the consistency of BBN, focusing especially on ^{4}He and ^{7}Li (also see Copi et al. 1995). Olive & Thomas (1997) and Fiorentini et al. (1998) carried out assessments of BBN using older estimates of the theoretical errors and a broader range for primordial D/H. The present analysis is the first using the new Nollett & Burles (2000) error estimates as well as the recently clarified primeval D/H.

4. CONCLUDING REMARKS

We have presented analytical fits for our new, more accurate predictions of the light-element abundances and their error matrix. These results have already renewed interest in more accurately determining key nuclear rates, and further improvements are likely (see e.g., Schreiber et al. 2000; Rupak 2000).

Using our results and the primeval deuterium abundance from three high-redshift Ly-α systems we infer $\Omega_B h^2 = 0.020 \pm 0.002$ (95% cl). For $h = 0.7 \pm 0.07$, this implies a baryon fraction $\Omega_B = 0.041 \pm 0.009$, with the error dominated by that in H_0. Measurements of cosmic microwave background (CMB) anisotropy have recently also determined the baryon density. The physics underlying this method is very different – gravity-driven acoustic oscillations in the Universe at 500 000 yrs – but the result is similar: $\Omega_B h^2 = 0.032^{+0.009}_{-0.008}$ at 95% cl (Jaffe et al. 2000). While there is about a 2σ difference, this first result from CMB anisotropy confirms the long-standing BBN prediction of a low baryon density, and with it, the need for nonbaryonic dark matter.

The sum of D+^{3}He predicted for the deuterium baryon density is consistent with that in the ISM today, implying no significant production (or destruction) of ^{3}He beyond pre-MS burning. The deuterium-predicted ^{4}He abundance is an important consistency test of BBN; however, systematic measurement error (the Y_P values from the two key data sets differ by 5 times the statistical error) precludes firm conclusions at this time. Likewise, the discrepancy between the predicted ^{7}Li abundance and the abundance measured in pop II stars has no simple explanation: The discrepancy could indicate that ^{7}Li has been depleted in pop II stars by about a factor of two, that uncertainties (in observations or predictions) have been grossly underestimated, or that there is an inconsistency in BBN.

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