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BBN Predictions for ^{4}He

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Abstract

The range of primordial ^{4}He abundances predicted by the standard model of big bang nucleosynthesis is discussed. In order to be consistent with an inferred primordial abundance of D + ^{3}He $\leq 10^{-4}$ the mass fraction of primordial ^{4}He must satisfy $Y_p \geq 0.235$ (at $2-\sigma$). A comparison of these predictions is made with observations and the BBN constraints on $\Omega_B h^2$ and ΔN_ν are updated.

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The standard model of the hot big bang assumes a homogeneous and isotropic Universe with gravity described by General Relativity and strong and electroweak interactions described by the Standard Model of particle physics. The hot big bang model makes the unavoidable prediction the production of primordial elements about one minute after the big bang (referred to as big bang or primordial nucleosynthesis). This review concerns the range of the primordial abundance of ^{4}He as predicted by standard BBN (*i.e.*, primordial nucleosynthesis assuming a homogeneous distribution of baryons). In it I discuss:

1. Uncertainties in the calculation of Y_p (the mass fraction of primordial ^{4}He)
2. The expected range of Y_p
3. How the predictions stack up agaisnt the latest observations
4. The latest BBN bounds on $\Omega_B h^2$ and N_ν

UNCERTAINTIES IN THE CALCULATION

There are three significant sources of uncertainty in the calculation of Y_p :

- Reaction Network
- Numerical
- Higher Order Weak Sector Effects

The only of these uncertainties we can't in principle control are the uncertainties in Y_p due to the variations in the nuclear reactions responsible for ^{4}He production. By that I mean that we can make the code as numerically accurate as we want, we can in principle include all of the higher order corrections to the tree level weak rates, and all the non-thermal effects, etc. that we want, so that the accuracy of the BBN prediction for Y_p is limited by our ability to measure the relevant nuclear cross sections. Because of the relatively large binding energy of the ^{4}He nucleus, we really only need to know the uncertainty in the neutron lifetime. When enough deuterium is around in the early Universe, all the available neutrons are converted into ^{4}He with an efficiency of about 1 part in 10^{-3}. So we expect uncertainties in the weak interactions which interconvert neutrons and protons, and thus govern the neutron-to-proton ratio, to dominate the uncertainties in Y_p . And indeed this is the case. In Figure 1, I show a calculation by Kernan and myself of Y_p vs. η[1].

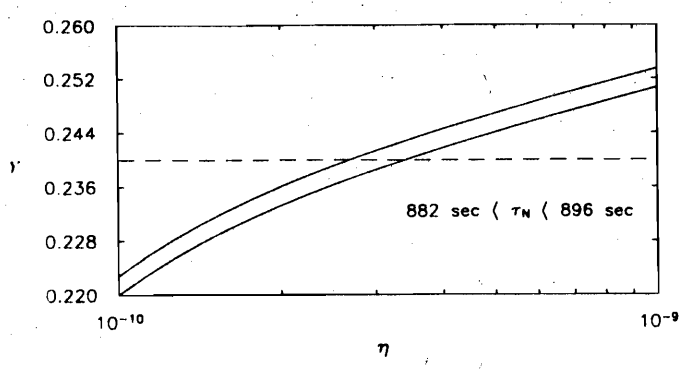

Figure 1. The BBN predictions for the mass fraction of primordial ^{4}He as a function of the baryon-to-photon ratio for neutron lifetimes in the range 882 - 896 seconds (lower and upper solid lines, respectively). The dotted line corresponds to the $2-\sigma$ upper limit to Y_p as inferred from observation[7].

This is the most accurate calculation of Y_p done to date. The numerical uncertainties are at least a factor of 30 smaller than the uncertainties shown for $2-\sigma$ variations in τ_n, the neutron lifetime (we have altered the Wagoner code to take smaller time steps than the smallest allowed by the Kawano

version of the code[2] and improved the accuracy of the code's integrator). We have included Coulomb, radiative, and finite-temperature corrections to the tree-level weak rates. This plot is for a fixed reaction network (except for variations in τ_n). I have used other work[3,4] to estimate the statistical uncertainties due to variations in the network. A good fit for Y_p over the range $2 \leq \eta_{10} \leq 5$ (where η_{10} is the baryon-to-photon ratio in units of 10^{-10}) is

$$Y_p = 0.2269 + 0.0117 \ln \eta_{10} \pm 0.0017 \pm 0.0002.$$

The errors quoted above represent the $2-\sigma$ statistical errors found by Monte Carlo of the nuclear reaction network[3,4] and our estimate of the systematic error introduced by the choice of treatment of "higher order weak effects", respectively. Roughly 80-90% of the $2-\sigma$ statistical variation quoted comes from the $2-\sigma$ variation of the neutron lifetime (which we take to be $\tau_n = 889 \pm 7$ sec). The systematic error is associated with the choice of scheme for treating finite temperature effects on the weak interaction rates[5] and on which of the non-equilibrium effects one chooses to include (*e.g.*, heating of neutrinos during e^+e^- annihilations leads to $\Delta Y \simeq 1 \times 10^{-4}$ [6]). So, given a $2-\sigma$ lower bound to the neutron lifetime, I think its safe to say that we can calculate Y_p to 3 significant figures.

THE PREDICTED RANGE OF Y_p

Once we have Y_p as a function of η, we use an upper bound on the primordial abundance of D + ^{3}He to obtain a lower bound to η and thus a lower bound on Y_p (for further discussion see Yang *et al.* [7] or Walker *et al.* [8]). If we allow for $2-\sigma$ variations in the primordial D + ^{3}He prediction[3,4] then a bound of D + ^{3}He $\leq 10^{-4}$ implies $\eta_{10} \geq 2.4$. The lowest value of Y_p possible for this choice of η is

$$Y_p \geq 0.235.$$

I would like to point out here that there is more information available than this in the Monte Carlo analysis. This is because the predicted abundance of D +^{3}He is *correlated* with Y_p [4]. As you can see from Figure 2, for fixed η the fact that you throw a low D +^{3}He abundance enhances your chances for throwing a high Y_p (not surprising since the overproduction of ^{4}He is the cause for the D +^{3}He deficit). So you cannot just take the $2-\sigma$ lower limit

to D+^{3}He and "read off" the $2-\sigma$ lower limit to Y_p . The true bound on Y_p will be more stringent than what I have listed here.

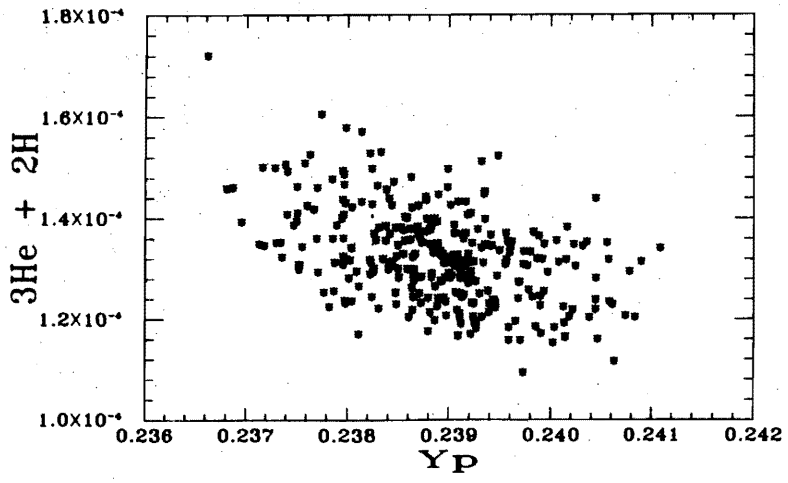

Figure 2. Monte Carlo scatter plot of primordial D +^{3}He vs. Y_p yields (from [4]).

In addition, the extraction of the primordial abundance of D +^{3}He from observations relies on models of chemical evolution since it involves an estimate of the fraction of ^{3}He which survives stellar processing (see Dearborn's contribution to these proceedings). Detailed models of the Galaxy[9] suggest smaller values of the primordial abundance of D +^{3}He than estimated above and thus a more stringent lower bound on Y_p .

Y_p OBSERVATIONS VS. PREDICTIONS

Using the fact that a by-product of stellar evolution is the production of ^{4}He by stars, one might hope to extract Y_p from observations of low-metallicity regions by looking for a correlation of the observed ^{4}He with C, N, or O and then extrapolating to zero metallicity[10]. Statistically, a 2-parameter fit is the best fit of the available data [8,11,12] and such analysis of metal-poor HII regions are all consistent with

$$Y_p = 0.23 \pm 0.01,$$

where the $2-\sigma$ errors quoted are pseudo-statistical due to systematic effects. Most chemical evolution models would predict a change in the slope of Y vs. Z at some low metallicity. If indeed Y vs. Z turns over at small Z, then the value of Y_p inferred from the data would be smaller than that determined by a linear extrapolation[13]. Until the new observations by Skillman (see Skillman's contributions to these proceedings), there was not enough data at low metallicity to statistically distinguish between 2 and 3 parameter fits. Skillman's preliminary data seem to show no evidence for a departure from linearity in Y vs. Z at low metallicity. If anything, the $2-\sigma$ upper limit to Y_p might be more like 0.245. Comparison with the lower bound of 0.235 coming from BBN shows that all is well on the primordial helium front.

BBN BOUNDS ON BARYONS AND PARTICLE PHYSICS

Since we know the number density of MWB photons today, the range of η consistent with BBN abundances gives a range of acceptable baryon densities ($\Omega_B h_{50}^2 = 0.015 T_{2.75}^3 \eta_{10}$). An upper bound to Y_p can be used to constrain η from above, albeit in a very uncertain way since Y_p depends on $\ln \eta$. Usually we use the ^{7}Li abundance from metal-poor halo stars as a more reliable constraint (although this involves some assumptions about the amount of ^{7}Li depletion)[8]. Here I give the bounds obtained by both methods:

$$\Omega_B h_{50}^2 \leq 0.05\ (8) \quad (Y_p \leq 0.240\ (5))$$

$$\Omega_B h_{50}^2 \leq 0.06\ (7) \quad (^7\text{Li (standard depletion)})$$

If instead of constraining ourselves to the Standard Model with 3 massless neutrinos we allow additional particles, then there is an extra parameter in standard BBN - the energy density of the Universe around 1 MeV. We parameterize the additional energy density in terms of the energy density of a massless neutrino species ΔN_ν. The greater the energy density the earlier n/p freezes out, and thus the larger Y_p . An upper bound to Y_p thus constrains the additional degrees of freedom at 1 MeV:

$$\Delta N_\nu \leq \frac{Y_p^{max} - 0.236}{0.014} = 0.29\ (65) \quad (Y_p \leq 0.240\ (5))$$

The import of this equation to model builders is that models with scalars in thermal equilibrium at 1 MeV are ok by BBN at $2-\sigma$ if the maximum Y_p inferred from observation is relaxed to 0.245, a move that may be supported by Skillman's new data.

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