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Neutrinos and Big Bang Nucleosynthesis

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Abstract

The early universe provides a unique laboratory for probing the frontiers of particle physics in general and neutrino physics in particular. The primordial abundance of the relic nuclei produced during the first few minutes of the evolution of the Universe depend on the electron neutrinos through the charged-current weak interactions among neutrons and protons, and on all flavors of neutrinos through their contributions to the total energy density which regulates the universal expansion rate. The latter contribution also plays a role in determining the spectrum of the temperature fluctuations imprinted on the Cosmic Background Radiation (CBR) some 400 thousand years later. Using deuterium as a baryometer and helium-4 as a chronometer, the neutrons play a key role in determining the abundance of helium (4He) emerging from BBN when the universe is ~20 minutes old. For example, since the 4He yield is largely fixed by the supply of neutrons available at BBN, an asymmetry between $n_1$ and $n_2$ (neutrino “degeneracy”) will drive the relative abundance of neutrons up or down, thereby increasing or decreasing the relic abundance of 4He. On the other hand, all flavors of neutrinos were relativistic at BBN (few MeV $\lesssim E \lesssim 30$ keV), contributing significantly to the total density, which determines the expansion rate of the universe at that epoch. The competition between the universal expansion rate (the Hubble parameter, $H$) and the nucleon and weak interaction rates is key to regulating the relic abundances of the light nuclides (D, 4He, 7Li) synthesized during BBN.

This latter effect of (light, relativistic) neutrinos on the expansion rate also plays a role some 400 kyr later, at “recombination” (protons and electrons combine to form neutral hydrogen) when the Cosmic Background Radiation (CBR) is set free from the tyranny of electron scattering to propagate throughout the Universe. By influencing the age of the Universe and the size of the sound horizon at recombination, the neutrinos help to fix the scales of the CBR temperature anisotropies observed by WMAP and other CBR detectors; see, e.g., [4] and references therein. Here, however, neutrino degeneracy plays no role except, perhaps, by increasing the neutrino energy density and, thereby, affecting the expansion rate. This latter effect is, generally, subdominant.

Since neutrinos influence the early evolution of the Universe at these two, widely separated epochs (~20 minutes and ~400 kyr later), the relics from BBN (light nuclides) and the temperature anisotropies imprinted on the CBR provide two, largely independent windows on neutrino physics. These connections and what we have learned from them are reviewed here. For further details and references, see [5, 6]; this review is largely based on these two papers. After introducing some notation in the next section, the constraints from the CBR are reviewed in §3. §4 provides an overview of BBN and of the current status of the comparisons between the observational data and the predictions of the standard model (SSB) as well as of some general extensions of the the standard model (non-standard BBN). In §5 the constraints from the CBR and from BBN are combined to identify the allowed ranges of the baryon and neutrino parameters.

We conclude in §6 with a summary and with an identification of the successes of the standard models of particle physics and cosmology and of some of the challenges confronting them.

1. Introduction

During its early evolution the universe was hot and dense, passing brief epochs as a universal particle accelerator and as a cosmic nuclear reactor. As a consequence, through its evolution the entire universe provides a valuable alternative to terrestrial accelerators and reactors as probes of fundamental physics at the highest energies and densities. Several decades of progress have validated this Particle Astrophysics and Particle Cosmology approach to testing and constraining models of High Energy Physics and Cosmology, for early work see, e.g., [1, 2, 3]. This strategy has proven especially useful in connection with the physics of neutrinos (e.g., masses, mixing, number of flavors, etc.).

Neutrinos play two different, but equally important roles in Big Bang Nucleosynthesis (BBN). On the one hand, electron-type neutrinos (and antineutrinos), through their charged current, weak interactions help to regulate the neutron-proton ratio, which plays a key role in determining the abundance of helium 4He) emerging from BBN when the universe is ~20 minutes old. For example, since the 4He yield is largely fixed by the supply of neutrons available at BBN, an asymmetry between $n_1$ and $n_2$ (neutrino “degeneracy”) will drive the relative abundance of neutrons up or down, thereby increasing or decreasing the relic abundance of 4He. On the other hand, all flavors of neutrinos were relativistic at BBN (few MeV $\lesssim E \lesssim 30$ keV), contributing significantly to the total density, which determines the expansion rate of the universe at that epoch. The competition between the universal expansion rate (the Hubble parameter, $H$) and the nuclear and weak interaction rates is key to regulating the relic abundances of the light nuclides (D, 4He, 7Li) synthesized during BBN.

2. Notation

To set the scene for the discussion to follow, it is useful to first introduce some notation. We are interested in three, key parameters: the baryon density, the number of “equivalent” neutrons, and a measure of a neutrino-antineutrino asymmetry.

As the universe expands, the baryon density decreases. A dimensionless measure of the baryon density is provided by the ratio of baryons to photons in the CBR. Following $e^\pm$ annihilation, this ratio is preserved during the subsequent evolution of the universe. The parameter $\eta$ is defined by the present (i.e., post-BBN, post-recombination) value of this ratio: $\eta \equiv \rho_B/\rho_\gamma$, where $\rho_B \equiv 10^{10}\eta \rho_\gamma$. An equivalent measure of the baryon density is provided by the baryon density parameter, $\Omega_B$, the ratio (at present) of the baryon density to the critical density. In terms of the present value of the Hubble parameter, $H_0 \equiv 1000$ km s$^{-1}$ Mpc$^{-1}$, these two measures are related by

$$\Omega_B \equiv 10^{10}(\rho_B/\rho_\gamma) \chi \approx 274\Omega_B h^2.$$ (1)

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In the standard model of particle physics there are three families of light neutrinos, $N_i = 3$ which, in the standard model of cosmology, are relativistic at BBN and also at recombination. The early evolution of the universe is “radiation dominated”, i.e., the energy density is dominated by the contributions from relativistic particles, including the neutrinos. The universal expansion rate, as measured by the Hubble parameter, depends on the density: $H \propto \rho^{1/3}$. Any additional (non-standard) contributions to the energy density (such as, e.g., from additional flavors of neutrinos) will result in a speed-up of the expansion rate,

$$S = H'/H = (\rho'/\rho)^{1/3} > 1.$$  \hspace{1cm} (2)

Any non-standard contribution to the density may be written in terms of what would be the energy density due to an equivalent number of “extra” neutrinos $\Delta N_i$ ($N_i = 3 + \Delta N_i$). Prior to $e^0$ annihilation, this may be written as

$$\rho' \equiv 1 + 7\Delta N_i / 43.$$  \hspace{1cm} (3)

Thus, either $S$, the expansion rate factor or $\Delta N_i$, the number of equivalent neutrinos, provide equally good measures of the early universe expansion rate. While it is easy to imagine extra contributions to the energy density from new physics beyond the standard model, it must be noted that it is possible for $\Delta N_i$ to be negative, leading to a slower than standard, early universe expansion rate ($S < 1$). For example, models where the decay of a massive particle, produced earlier in the evolution of the universe, reheats the universe to a temperature which is not high enough to (re)populate a thermal spectrum of the standard neutrinos ($T_{\text{reheat}} \lesssim 7 \text{ MeV}$), will result in $\Delta N_i < 0$ and $S < 1$ [7].

For any neutrino flavor $i$, an asymmetry (“neutrino degeneracy”) between the numbers of $\nu_i$ and $\bar{\nu}_i$, relative to the number of CBR photons, can be quantified by the net lepton number $L_i$, the neutrino chemical potential $\mu_i$, or, by the dimensionless degeneracy parameter $\zeta_i \equiv \mu_i / T_i$:

$$L_i \equiv \frac{n_{\nu_i} - n_{\bar{\nu}_i}}{n_i} = \frac{\pi^2}{12} (\zeta_i + \frac{\zeta_i^2}{2}) = \frac{\pi^2}{2} (\zeta_i + \frac{\zeta_i^2}{2}).$$  \hspace{1cm} (4)

Although we are interested in lepton asymmetries which are orders of magnitude larger than the baryon asymmetry ($B \sim 10^{-10}$), the values of $\zeta_i$ ($\bar{\nu}_e, \mu, \tau$) considered here are sufficiently small ($|\zeta_i| \lesssim 0.1$) so that the “extra” energy density contributed by such degenerate neutrinos is negligible:

$$\Delta N_i(\zeta_i) \approx \frac{30}{\pi^2} \left(\frac{\zeta_i}{T_i}\right)^2 + \frac{15}{\pi^2} \left(\frac{\zeta_i}{T_i}\right)^4 \lesssim 0.01.$$  \hspace{1cm} (5)

In this case, the results to be presented below for $\zeta_i \neq 0$ will correspond to $N_i = 3$ ($S = 1$). In fact, if the three active neutrinos ($\nu_e, \nu_{\mu}, \nu_{\tau}$) mix only with each other, all individual neutrino degeneracies will equilibrate via neutrino oscillations to, approximately, the electron neutrino degeneracy before BBN begins [8]. Thus, the magnitude of the electron neutrino degeneracy constrained by BBN is of special interest when limiting the total net lepton asymmetry of the universe: $L \approx 3L_e$, $\Delta N_e(\zeta_e) \approx 3\Delta N(\zeta_e)$.

For the standard models of particle physics and cosmology, $\Delta N_e = 0$ ($S = 1$) and $\zeta_e \equiv \zeta_\nu \equiv \zeta_\mu \equiv \zeta_\tau = 0$, and the value (range of values) of $\eta$ identified by BBN and the CBR should agree, restricting the allowed deviations from zero of $\Delta N_i$ and/or $\zeta_i$.

### 3. CBR

In Figures 1 and 2 are shown the CBR temperature anisotropy angular power spectra for different choices of the baryon density ($\Omega_B h^2$) and of $N_i$ (Fig. 2). Non-zero values of $\Delta N_i$ change the energy density in radiation, which shifts the redshift of the epoch of equal matter (Cold Dark Matter and Baryons) and radiation densities. This results in changes to the angular scales and the amplitudes of the “acoustic” peaks in Figures 1 & 2; see, e.g., [5] and further references therein. WMAP is a much more sensitive baryometer than it is a chronometer. While the best fit values for the baryon density and $N_i$ are $\Omega_B h^2 = 0.05$ and $N_i = 3.0$ (for $S = 0.98$) respectively, the $2\sigma$ range for the baryon density parameter is $5.6 \leq \Omega_B h^2 \leq 7.3$, whereas for $N_i$, it is $0.9 \leq N_i \leq 8.3$ (0.81 $\leq S \leq 1.36$) [6]. Thus, although the WMAP best fit value of $N_i$ is less than the standard model value of 3, it is clear that this difference is not at all statistically significant. It will be interesting to see if the much tighter CBR constraint on the baryon density parameter ($\sim 6$–$8\%$) consistent with the value of this parameter identified by BBN.
4. BBN

Since the relic abundances of D, 3He, and 3Li produced during BBN are rare limited (nuclear reaction rates), each of these nuclides is a candidate baryometer. Among these, deuterium is the baryometer of choice for several reasons. The BBN-predicted abundance of D is sensitive to the baryon density ($\Omega_B \equiv 10^5(D/H) \propto n^{-1.15}$). The post-BBN evolution of D is simple in that whenever gas is incorporated into stars, D is completely destroyed. Thus, observations of the deuterium abundance anywhere, at any time, provide a lower bound to the primordial D abundance (and, therefore, an upper bound to $\Omega_B$). It is expected that if D can be observed in regions which have experienced minimal stellar processing, the deuterium abundance inferred from such data should be very close to the BBN abundance.

The good news is that there are data from observations of neutral D and neutral H in high redshift, low heavy element (“metallicity”) abundance QSO absorption line systems (QSOALS); see Figure 3. As may be seen from Fig. 3, the bad news is that there are only five such systems with good enough data to derive meaningful D abundances [9]. And, even for these, specially selected targets, there is the possibility of confusion between D and H absorption spectra which are identical, save for the wavelength/velocity shift between them. That is, small amounts of hydrogen at the “wrong” redshift (“interlopers”) can masquerade as deuterium. Further, since the hydrogen absorption in such systems is saturated, it is often difficult to identify the number of systems which contribute to the total absorption and in such systems is saturated, it is often difficult to identify the error budget. Indeed, for the data summarized by Kirkman et al. [9] and shown in Fig. 3, $\chi^2$ exceeds 16 for 4 degrees of freedom! Following Kirkman et al., the error bars are inflated here to account for this excessive dispersion, and a primordial abundance $\Omega_B = 2.6 \pm 0.4$ is adopted. For SBBN this estimate for the abundance of primordial D corresponds to $\Omega_B = 6.1 \pm 0.7$. This is in excellent (spectacular!) agreement with the independently estimated abundance above in $3/3$ from the CBR. In Figure 4 are shown the likelihood distributions for $\eta$ derived from the CBR (WMAP) and from SBBN (D). 3He is a much less useful baryometer than is D. In the first place, its BBN-predicted abundance is less sensitive to the baryon density parameter ($3He/H \propto g^{1/2}$). In addition, as gas is incorporated into stars and the stellar-processed material is returned to the interstellar medium when they die, 3He is produced, destroyed and, some survives. This complicated history makes it much more difficult to account for the post-BBN evolution of 3He. Finally, 3He is only observed within the Galaxy [10] and, therefore, its abundance samples only a limited range in metallicity. Nonetheless, while there is a clear oxygen abundance gradient with location within the Galaxy (higher in the center, lower in the suburbs, indicating more stellar processing in the interior), the 3He abundance shows no such gradient (either with position or with metallicity). However, the Bania, Rood, and Balser [10] recommended value of $\gamma_3 = 10^5(3He/H) = 1.1 \pm 0.2$ corresponds to $\Omega_B = 5.6 \pm 0.7$, in broad agreement with the SBBN-D and CBR-WMAP determinations. So far, so good.

In contrast to deuterium (and to 3He), the abundance of 4He has increased in the post-BBN universe as stars have burned hydrogen to helium (and beyond). Therefore, to avoid model-dependent evolutionary uncertainties, it is best to concentrate on determining the 4He abundance (mass fraction, $Y_4$) in the most metal-poor sample available and to let the data speak for themselves concerning any correlation between the helium and heavy element abundances. The best such data come from observing the emission lines formed when ionized helium and hydrogen capture electrons in regions of hot, ionized gas (He II regions). There exists at present, thanks largely to the work of Izotov and Thuan [11], a very large sample of helium abundance determinations in low metallicity, extragalactic.

\[ D = 10^5(3He/H) \propto n^{-1.15} \]

\[ Y_4 = 10^5(4He/H) \]

\[ \Omega_B = 2.6 \pm 0.4 \]

\[ \gamma_3 = 10^5(3He/H) = 1.1 \pm 0.2 \]

\[ \Omega_B = 5.6 \pm 0.7 \]

\[ Y_4 = 10^5(4He/H) \]
When using the infrared flux method effective temperatures, Thuan [11] derive such a small uncertainty, that their central metallicity halo stars suggests this effect may not be large among the observed values of [Li] derived from the lowest destroy or dilute prestellar lithium, the very small dispersion mixing of the stellar surface material with the interior would oldest stars in the Galaxy, they have had the most time to modify rather than to the cosmology. Since the low metallicity halo stars the higher lithium abundance; they find [Li]P this were the true primordial 7Li abundance, then the SBBN abundance data are, within the errors, consistent with the predictions of SBBN and the CBR (and to ignore this challenge to the standard models of particle physics Indeed, all of the current observational estimates of the abundance / in conflict with the CBR-WMAP and \( \frac{Y_p}{Y_e} \) ≈ \( 0.238 \pm 0.005 \) [13] is adopted. The \( ^3\)He abundance determinations are most likely examples of extant technique, yet inaccurate determinations of an important cosmological parameter. It has long been known that there are a variety of systematic uncertainties which are likely to interfere with an accurate \( Y_p \) determination. In a very recent, detailed on all of the well-known systematic uncertainties, Olive & Skillman [14] suggest the true errors likely exceed previous estimates by factors of 2–3 or more (\( \Delta Y_p / Y_p \approx 0.013 \)). Given such large uncertainties, it is not surprising that the extant \( ^4\)He abundance data are, within the errors, consistent with the predictions of SBBN and the CBR (and/or SBBN plus D) determined baryon density. Nonetheless, it might be premature to ignore this challenge to the standard models of particle physics and of cosmology. Perhaps the tension between \( D \) and \( ^4\)He is an early warning of new physics beyond the standard models. Before pursuing this option in the next section, \( ^7\)Li is considered here.

As with \( ^3\)He, there is conflict in the comparisons between the SBBN predictions and the \( ^7\)Li relic abundance estimates derived from observations. Here, too, the potential for systematic errors looms large. \( ^7\)Li is produced in the Galaxy by cosmic ray spallation/fusion reactions and observations of super-lithium rich red giants provide evidence that (at least some) stars can be net producers of lithium. Therefore, to infer the BBN yield of \( ^7\)Li, the data should be limited to those from the most metal-poor halo stars in the Galaxy. For the WMAP baryon density, the SBBN expected \( ^7\)Li abundance is \( [\text{Li}]_P \approx 12 + \log([\text{Li}]/[\text{H}])_0 \approx 2.69 \pm 0.16 \). In contrast, for a selected data set of the lowest metallicity halo stars, Ryan et al. [15] derive a primordial abundance of \( [\text{Li}]_P \approx 2.0 \pm 0.1 \). In deriving the stellar lithium abundances, the adopted stellar temperature plays a key role. When using the infrared flux method effective temperatures, studies of halo and Galactic Globular Cluster stars [16] suggest a higher abundance: \( [\text{Li}]_P \approx 2.24 \pm 0.01 \). Very recently, Melendez & Ramirez [17] have reanalyzed 62 halo stars using an improved infrared flux method effective temperature scale, confirming the higher lithium abundance; they find \( [\text{Li}]_P \approx 2.37 \pm 0.05 \). If this were the true primordial \( ^7\)Li abundance, then the SBBN value of the baryon density parameter would be \( \Omega = 0.10 \pm 0.04 \), in conflict with the CBR-WMAP and/or SBBN-D estimates. Indeed, all of the current observational estimates of the abundance of primordial lithium are significantly lower than the SBBN expectation.

As with \( ^3\)He, the problem may be traced to the astrophysics rather than to the cosmology. Since the low metallicity halo stars used to derive the primordial abundance of lithium are the oldest stars in the Galaxy, they have had the most time to modify (by dilution and/or destruction) their surface abundances. While mixing of the stellar surface material with the interior would destroy, or dilute prestellar lithium, the very small dispersion among the observed values of \([\text{Li}]_P\) derived from the lowest metallicity halo stars suggests this effect may not be large

![Image](image_url)
Consistent with the WMAP CBR data, values of $/afii9797$ and $/afii9821$ are subdominant to that on $/afii9841$. The best fit parameter choices which resolve the tension between $/afii94$ and $/afii94$ He, while preserving the good agreement with the WMAP data are $\eta_{10} = 6.2 (\eta_{10}^H = 0.23)$ and $\eta_{10} = 0.044$. In Figure 6 are shown the $1\sigma$ and $2\sigma$ contours consistent with the WMAP data and with BBN and the CBR; see, for example, [5]. Fixing the $/afii94$ and $/afii94$ He abundances, Kneller & Steigman find two approximate, but quite accurate, BBN relations among these three parameters.

$$590(\gamma - 1) \approx 116\eta_{10} - 697,$$

and

$$145\gamma \approx 106(\gamma - 1) + 6.31.$$  

Consistent with the WMAP CBR data, values of $\Delta N$, and $\gamma$, in the ranges $-2 \leq \Delta N \leq 5$ and $-0.1 \leq \gamma \leq 0.3$ are permitted [6]. However, even with this freedom it is still not possible to reconcile the BBN-predicted and the observed relic lithium abundances [19]. For the values of these parameters which are consistent with BBN and the CBR, $\Delta N$, $\gamma$, and $\xi$ are all close to 0.

6. Summary and conclusions

BBN and the CBR probe the evolution of the Universe (and its constituents) at two, widely separated epochs in its early evolution. Confronting the predictions of BBN and the CBR with the relic abundance and WMAP data enables independent tests of the standard models of particle physics and cosmology. Qualitatively, the standard models pass these tests with flying colors, permitting BBN and CBR constraints to be put on new neutrino physics ($N \neq 3$; $\xi \neq 0$). When considered in quantitative detail however, there are some challenges to the standard models at the $\sim 2\sigma$ level. Many would take this as evidence for success and declare victory. However, if these tensions are taken at face value, they might be alerting us to problems with the astrophysics, the astrophysics, the cosmology, the particle physics or, combinations of them. It is not unlikely that the apparent conflicts may result from the data, its analysis, and/or the extrapolations to the early universe. While the community awaits the new surprises to be encountered at the LHC, a Linear Collider, or the next generation of terrestrial or space-based telescopes, it should be kept in mind that these challenges could be pointing the way to new physics, especially new neutrino physics, beyond the standard models of particle physics and/or cosmology.

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