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Telling Three from Four Neutrinos with Cosmology

Kevork N. Abazajian

NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory,
Batavia, Illinois 60510-0500, USA

Abstract

New results, namely the independent determination of the deuterium abundance in several quasar absorption systems, refined calculations of the predicted primordial helium abundance, and the complementary determination of the cosmological baryon density by observations of anisotropies in the cosmic microwave background (CMB), allow for a reevaluation of the constraints on the relativistic particle content of the universe at primordial nucleosynthesis. Expressed in terms of the neutrino energy density, we find $1.5 < N_\nu < 3.5$ (95% CL). In particular, we show that phenomenological four neutrino models including a sterile state (not participating in $SU(2)_L \times U(1)_Y$ interactions) unavoidably thermalize a fourth neutrino, and are highly disfavored in the standard minimal model of primordial nucleosynthesis, if the systematic uncertainty in the primordial helium abundance is small. We describe plausible extensions of the minimal model which evade this constraint.

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1 Introduction

With the simplifying conditions of isotropy, homogeneity, thermal equilibrium, and the particle content of the standard model of particle physics, big bang nucleosynthesis (BBN) is a one parameter model dependent only on the baryon-to-photon ratio, η, at that epoch. The appeal of this simple yet successful standard model [1] has motivated a predictive ability, for example, in the number of leptons in the standard model of particle physics [2].

Email address: `aba@fnal.gov` (Kevork N. Abazajian).

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The light nuclides D, ^{3}He, ^{4}He and ^{7}Li are produced in measurable quantities in the first three minutes of the standard cosmology. Considerable attention has been devoted to the analysis of uncertainties in the predicted abundances of the light elements and their consistency with the observed light element abundances [3–6]. Though systematic uncertainties likely dominate the helium abundance measurements [6–8] and may be present in observations of the deuterium-to-hydrogen ratio D/H in high-redshift quasar systems [9], and ^{7}Li may be partially depleted by stellar processes [10], standard BBN is remarkably successful predictor for the abundances of these light elements with abundances that differ by nine orders of magnitude.

There exist a variety of ways of modifying the standard BBN paradigm, including altering the spatial distribution of baryon number, out-of-equilibrium decays of massive particles, or new neutrino physics (for a summary, see Ref. [11]).

We focus our attention on a minimal extension to BBN by a modification of the neutrino sector, and specifically to models which attempt to simultaneously account for the indications of neutrino mixing and masses from the atmospheric neutrino results of Super-Kamiokande [12], the observations of the transformed solar neutrino flux [13,14], and the Liquid Scintillator Neutrino Detector (LSND) signal [15]. A class of models that can accommodate all of these results introduce a fourth mass eigenstate [16]. As is well known, the fourth flavor state must be sterile, *i.e.*, not participating in $SU(2)_L \times U(1)_Y$ interactions, due to its being both light ($m \ll 1$ GeV) and not observed in the invisible width of the Z^0 boson [6]. In current manifestations of four neutrino mixing models, the sterile neutrino is not necessarily closely associated with a single mass eigenstate, since the atmospheric and solar observations each disfavor large sterile components. However, recent global analyses [16] of the available neutrino oscillation data, including short baseline limits [17], leave four-neutrino models viable. There are several ways that light sterile neutrinos can be accommodated in neutrino mass models. For a review see, *e.g.*, Ref. [18].

The standard contribution to the energy density by the three active neutrinos can be augmented by the complete or partial equilibration of the sterile mode. The increased energy density in units of the energy density in one neutrino and its antiparticle ($\rho_{\bar{\nu}\nu} = 7\pi^2 T^4/120$) is then $N_\nu = 3 + \Delta N_\nu$, where $\Delta N_\nu = \rho_s/\rho_{\bar{\nu}\nu}$ is the relative contribution of the sterile state. Here, we use ΔN_ν strictly as a parameterization of extra (or missing) relativistic energy density. Sterile neutrinos in the early universe can also give rise to lepton asymmetry generation [19], which can alter or strongly suppress sterile neutrino thermalization, or, if the asymmetry is generated in the $\nu_e/\bar{\nu}_e$ sector, alter beta-equilibrium and thus light element abundance production, primarily in the production of ^{4}He.

Letting N_ν be a free parameter of BBN, its primary effect is altering the predicted ^{4}He abundance Y_p. The remaining parameter, the baryon content η, is (over) constrained by D/H, ^{3}He and ^{7}Li. In one analysis, Lisi, Sarkar and Villante [20] used four permutations of primordial light element abundance determinations to derive limits roughly in the range $2 < N_\nu < 4$. In one combination of light element abundance determinations (their data set A), the 99.7% CL region allowed $N_\nu \sim 4.5$. This value is widely cited as allowing for an additional neutrino (or relativistic degree of freedom) at BBN. Though this limit was correct, it relied on the possibility of a "high" primordial deuterium abundance. Since that work, deuterium has been observed or bounded to have a "low" value in six high-redshift quasar absorption systems (QAS) by three groups [9,21], and the "high" deuterium QAS observation [22] has not been verified in other systems and is disputed [23]. The baryon-to-photon ratio η is related to the cosmological baryon density Ω_b (as a fraction of the cosmological critical density) as $\eta \simeq 2.74 \times 10^{-8}\,\Omega_b h^2$, where h is the present Hubble parameter in units of 100 km s^{-1} Mpc^{-1}. The work by Cyburt, Fields & Olive [5] took the possibility of two values of the baryon density, that given by D/H+BBN and CMB, $\Omega_b h^2 \simeq 0.02$, and a value of $\Omega_b h^2 \simeq 0.01$ preferred by one inferred primordial value of Y_p [24] and the ^{7}Li abundance [25] (if undepleted). Ref. [5] finds that these densities give 95% CL upper bounds of $N_\nu < 3.6$ and $N_\nu < 3.9$, respectively.

Motivated by the six quasar absorption system measurements of a "low" D/H and the analysis of the observations of the CMB anisotropy experiments DASI, BOOMERanG, and MAXIMA, we adopt that the inferred value of the cosmic baryon density from D/H plus standard BBN $\Omega_b h^2(\mathrm{D/H})$ and the shape of the acoustic peaks in the CMB angular power spectrum $\Omega_b h^2(\mathrm{CMB})$, are approaching the actual value of $\Omega_b h^2$, within statistical and systematic uncertainties. The forthcoming analysis of the Microwave Anisotropy Probe (MAP) satellite's observations will potentially reduce the uncertainty in $\Omega_b h^2$ to approximately 10% [26]. In Section 2, we analyze in detail the constraints arising from accurate calculations of the primordial helium abundance, the inferred primordial helium abundance, and that using either $\Omega_b h^2(\mathrm{D/H})$ or $\Omega_b h^2(\mathrm{CMB})$ and show that a thermalized fourth neutrino is highly disfavored by standard BBN. In Section 3, we analyze current four neutrino mixing schemes and their behavior in the early universe and show that thermalization of a fourth neutrino state is unavoidable. In Section 4, we describe various means and methods of extending the standard model to evade this constraint.

2 The BBN Prediction of the Number of Neutrinos

The consistency of BBN as a predictor of the light element abundances already been explored in some detail [3–6]. We instead focus on the current uncertainties in the cosmic baryon density $\Omega_b h^2$ and the observed primordial ^{4}He abundance Y_p, the light nuclide whose abundance is most sensitive to the energy content of the universe at the BBN epoch.

The baryon content of the universe can be estimated in a variety of ways, of which the most precise measures currently are the deuterium abundance at high redshift and the shape of the acoustic peaks in the CMB [27]. Deuterium has been observed in high-redshift metal-poor neutral hydrogen systems which are seen as absorbers in the spectrum of back-lighting quasars. The deuterium in these extremely metal-poor systems is inferred to be close to the primordial value due to minimal stellar processing which produces metals and only destroys deuterium. Due to the extreme sensitivity of D/H to the baryon content at BBN, the baryon density required to produce the observed deuterium abundance is rather precisely determined [4,9]:

$$\Omega_b h^2(\mathrm{D/H}) = 0.020 \pm 0.002 \ (95\%\mathrm{CL}). \tag{1}$$

The baryon content also alters the amplitude of acoustic oscillations in the primordial plasma at CMB decoupling and the relative height of the first three acoustic peaks (for a review of the physics of the CMB, see Ref. [28]). The first three acoustic peaks in the angular power spectrum of the CMB have been detected in the analysis of CMB anisotropy measurements by the DASI [29], BOOMERanG [30] and MAXIMA [31] experiments. The results of these experiments' analyses find

$$\begin{aligned}
&\Omega_b h^2\,(\mathrm{D}) = 0.022^{+0.004}_{-0.003} && (95\%\mathrm{CL})\\
&\Omega_b h^2\,(\mathrm{B}) = 0.022^{+0.004}_{-0.003} && (95\%\mathrm{CL})\\
&\Omega_b h^2(\mathrm{M}) = 0.033 \pm 0.013 && (68\%\mathrm{CL}) \qquad (2)
\end{aligned}$$

respectively. The BOOMERanG value above is that given by their Bayesian approach. For concreteness in our analysis, we quantify the uncertainty in the cosmic baryon density inferred from the CMB with the likelihood function given in Ref. [29] by DASI+DMR.

If analyses of the CMB anisotropy measurements change and provide a value for $\Omega_b h^2$ that is higher than that inferred from standard BBN, then this could have been an indication for a model with large and disparate neutrino degeneracy parameters known as degenerate BBN [32]. However, if the favored large mixing angle (LMA) neutrino mixing parameters of the solution to the solar neutrino problem are verified (*e.g.*, by the KamLAND experiment [33]), then synchronized neutrino flavor transformation in the early universe stringently limit neutrino degeneracies [34] and degenerate BBN is no longer a rescue.

In order to precisely predict the abundance of ^{4}He from standard BBN for varying baryon density and neutrino number, Lopez and Turner [35] included finite-temperature radiative, Coulomb and finite-nucleon-mass corrections to the weak rates; order-α quantum-electrodynamic correction to the plasma density, electron mass, and neutrino temperature; and incomplete neutrino decoupling. Ref. [35] provides a fitting formula for their results of the predicted helium abundance as a function of η, N_ν and neutron lifetime τ. We employ this fitting formula for the predicted ^{4}He abundance, taking into account the typographical correction of signs noted in Ref. [4]. After all of the above corrections are applied, the uncertainty in the predicted helium abundance is dominated by the neutron lifetime uncertainty, which is now known better than 0.1% [6]. Therefore, we can safely ignore the theoretical errors, as they are dwarfed by observational uncertainty, which we now address.

The primordial helium abundance Y_p has been estimated in observations of hydrogen and helium emission lines from regions of hot, ionized metal-poor gas in dwarf galaxies (HII regions). By extrapolating the helium abundance and metallicity relationship for these regions to zero metallicity, Olive, Steigman and Skillman [24] find

$$Y_p(\mathrm{OSS}) = 0.238 \pm 0.002\ (\mathrm{stat.}) \pm 0.005\ (\mathrm{sys.})\,, \tag{3}$$

while Izotov and Thuan [36] find

$$Y_p(\mathrm{IT}) = 0.244 \pm 0.002\ (\mathrm{stat.})\,. \tag{4}$$

Uncertainties regarding the ionization structure and temperature uniformity of the HII regions as well as underlying stellar absorption are sources of significant systematic error. Refs. [8,24] estimate systematic effects in the primordial helium abundance are 2%. Ref. [7] finds that systematic effects can lead to 2-4% uncertainties that tend to *overestimate* Y_p. In an attempt to avoid bias, in this work we adopt the central value of

$$Y_p = 0.241 \pm 0.002\ (\mathrm{stat.}) \pm \sigma_{\mathrm{sys}}\,, \tag{5}$$

and characterize the systematic uncertainty as the disparity between competing claims

$$\sigma_{\mathrm{sys}} = |Y_p(\mathrm{OSS}) - Y_p(\mathrm{IT})|\,, \tag{6}$$

or approximately 3%. The shape of systematic uncertainty in likelihood space is certainly not well defined, therefore we make the simplifying ansatz of a Gaussian distribution, as done, *e.g.*, in Ref. [5], and combine the statistical and systematic errors in quadrature.

We produce probability distribution functions (p.d.f.'s) for N_ν versus $\Omega_b h^2$, using Gaussian distributions for Y_p [Eq. (5)] and $\Omega_b h^2$(D/H) [Eq. (1)], and the likelihood function given in Ref. [29] for $\Omega_b h^2$(DASI). We find, using either the information from deuterium or the CMB on $\Omega_b h^2$:

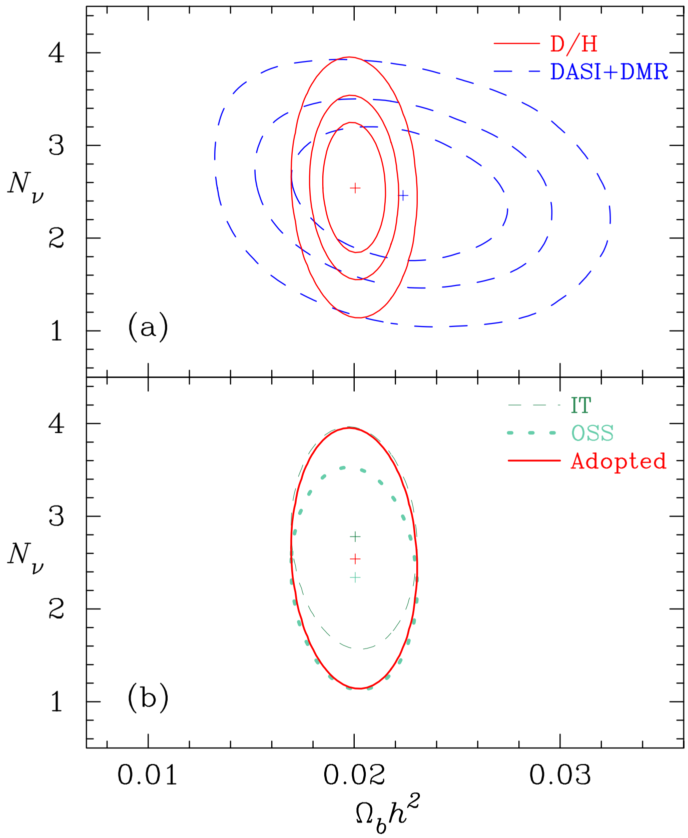

Fig. 1. Shown are the contours of 68%, 95% and 99% CL (inner to outer contours) when using the baryon density inferred from the deuterium abundance (D/H) at high-redshift (solid lines) *or* that from the DASI+DMR analysis of CMB anisotropies (dashed lines), in frame (a). In both cases, we use our our adopted determination of the primordial ^{4}He abundance. In frame (b), we show the 99% CL contours using the Izotov & Thuan (IT), Olive, Steigman & Skillman (OSS) and our adopted value and uncertainty of the primordial ^{4}He abundance along with the D/H determination of $\Omega_b h^2$. The uncertainty in N_ν does not depend on the choice between IT and OSS as much as the size of systematic uncertainty. See text for details.

$$N_\nu(\mathrm{D/H}) = 2.55 \pm 0.70 \quad (68\%\ \mathrm{CL}) \tag{7}$$

$$N_\nu(\mathrm{DASI}) = 2.46 \pm 0.74 \quad (68\%\ \mathrm{CL}), \tag{8}$$

which is consistent with the standard BBN prediction. We show the shapes of the likelihood contours in Fig. 1 (a). To illustrate the difference between adopting the IT or OSS helium values, we plot the 99% likelihood contours for the choices Y_p(OSS), Y_p(IT) (using the systematic uncertainty of ±0.005) and our choice (5). As seen in Fig. 1 (b) the range of uncertainty does not depend on the choice of the central value but the size of systematic effects.

For a sterile neutrino to be thermalized with the bath of the early universe, the active neutrinos must be thermalized initially. This constitutes prior information that may *loosen* the constraints shown in Fig. 1. Prior information

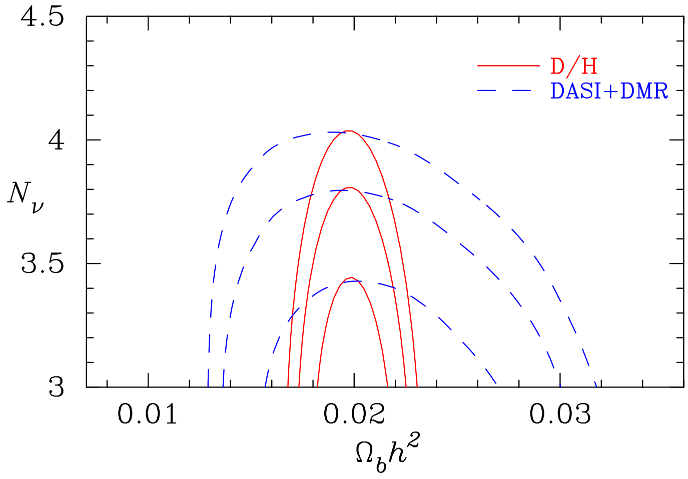

Fig. 2. Shown are the contours of 68%, 95% and 99% CL (inner to outer contours) given the prior condition that the active neutrinos are thermalized, our adopted value of primordial ^{4}He abundance, and $\Omega_b h^2$ determined by D/H (solid lines) or the CMB observations by DASI+DMR (dashed lines). See text for details.

can be included in a Bayesian approach [6], integrating the p.d.f. only in the physically allowed region, $N_\nu > 3$, which we have done using a Monte Carlo integration. We show the confidence level intervals for this case in Fig. 2. As seen there, a fully populated fourth neutrino is excluded at approximately the 99% CL.

Measurements of CMB anisotropies by the MAP satellite may measure $\Omega_b h^2$ to 10%, giving a precise value independent of BBN. If consistent with $\Omega_b h^2$ inferred from D/H and BBN, then $\Omega_b h^2$ becomes a “nuisance parameter” that can be marginalized and the confidence level for N_ν is simply the integral of the p.d.f.,

$$\mathrm{CL}(N_\nu) = \int_3^{N_\nu} p(N'_\nu|Y_p)\, dN'_\nu. \tag{9}$$

3 Four Neutrino Models in the Early Universe

There is now convincing evidence for neutrino flavor states to be composed of large amplitudes of more than one mass state from two experiments: Super-Kamiokande [12] and the Sudbury Neutrino Observatory (SNO) [14]. There is also an indication of a neutrino oscillation signal at short baselines from the Liquid Scintillator Neutrino Detector (LSND) experiment [15]. To accommodate all three of these results, a four neutrino model must be invoked (or CPT is violated; see below). The mass and flavor state bases are related by a unitary transformation

$$\nu_\alpha = \sum_i^4 U_{\alpha i} \nu_i\,, \tag{10}$$

where $\alpha = e, \mu, \tau, s$ denotes the flavor state and i is the mass state. The matrix $U_{\alpha i}$ generally has 6 rotation (mixing) angles and 3 CP violating phases. The transformation probability has the form:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\ \sin^2\left(\delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\ \sin\left(\delta m^2_{ij}\frac{L}{2E}\right), \tag{11}$$

which provides rich neutrino oscillation phenomenology and experimental possibilities [37]. Here $\delta m^2_{ij} \equiv m_i^2 - m_j^2$, L is the distance from where the flavor ν_α was created, and E is its energy. For reviews of neutrino phenomenology see, *e.g.*, Refs. [38].

For neutrino physics in the early universe, we are interested in the magnitude of mixing amplitudes of active neutrinos converting to sterile states. It has been known for some time that a sterile neutrino coupling with a single active neutrino via the unitary neutrino mass matrix must have mixing parameters [39,40]

$$\delta m^2_{\alpha s}\sin^4 2\theta_{\mathrm{BBN}} \lesssim \begin{cases} 5\times 10^{-6}, & \text{for } \alpha = e \\ 3\times 10^{-6}, & \text{for } \alpha = \mu,\tau \end{cases}, \tag{12}$$

in order to not fully thermalize the sterile neutrino prior to BBN via nonresonant collisional processes. Such constraints (12) certainly do not directly apply to multiple neutrino mixing schemes including a sterile which nature may have given us. Multiple mixing angles and the phenomenon of lepton number generation via neutrino mixing complicate the BBN bound.

We adopt a rotation angle ordering for U so that $(\nu_e, \nu_\mu, \nu_\tau, \nu_s) = (\nu_1, \nu_2, \nu_3, \nu_4)$ when all mixing angles are set to zero. Four neutrino mixing scheme constraints have been examined recently in detail by Di Bari [41], which we summarize and expand on here in view of the recent global analyses of four-neutrino models by Maltoni, Schwetz and Valle [16]. The effective amplitude of active-sterile neutrino mixing between flavor α and the sterile can be written as

$$A_{\alpha;s} = 4|U_{\alpha 4}|^2|U_{s4}|^2 \simeq \sin^2 2\theta_{\mathrm{BBN}}\,. \tag{13}$$

Therefore, BBN constraints for active-sterile mixing through a pair of neutrino mass eigenstates ν_4, ν_i are

$$\delta m^2_{4i} A_{\alpha;s} \lesssim \begin{cases} 5\times 10^{-6}, & \text{for } \alpha = e \\ 3\times 10^{-6}, & \text{for } \alpha = \mu,\tau \end{cases}, \tag{14}$$

for nonresonant sterile production, where $\delta m^2_{4i} > 0$. This constraint (14) applies primarily to the active-sterile mixing that leads the oscillation, *i.e.*, that which has the shortest oscillation length or largest δm^2_{ij}. Small vacuum mixing amplitudes in the leading oscillation mode may avoid thermalization, and so secondary oscillation modes with larger mixing amplitudes may thermalize the sterile.

3.1 3+1

Models referred to as (3+1) may satisfy all experimental indications of neutrino oscillations with a triplet of mass eigenstates that provide the atmospheric and solar mass-scales, and a sterile-dominated mass eigenstate with a large mass-scale splitting with the triplet providing the LSND result via indirect $\bar{\nu}_\mu \to \bar{\nu}_e$ mixing through the sterile. In order to satisfy the mixing amplitude that would provide the LSND signal, the amplitude must be [16]

$$\begin{aligned} A_{\mu;e} &= 4|U_{e4}|^2|U_{\mu4}|^2 \\ &> 3\times10^{-4} \qquad (99\%\ \mathrm{CL})\,, \end{aligned} \tag{15}$$

at a $\delta m^2_{\rm LSND} \simeq 2\ \mathrm{eV}^2$ from Fig. 8 of Ref. [16]. Indirect mixing of this form has two mixing amplitudes that may thermalize the sterile. In this case, the mixing amplitudes $A_{\mu;s}$ and $A_{e;s}$ may participate in the thermalization. Consider the slightly less-constrained [cf. (14)] $A_{\mu;s} = 4|U_{\mu4}|^2|U_{s4}|^2$. The amplitude

$$|U_{s4}|^2 > 0.54 \quad (99\%\ \mathrm{CL})\,, \tag{16}$$

is bounded from below from constraints on the fraction of sterile neutrinos participating in atmospheric oscillations (see Fig. 3 of Ref. [16]).

Evading constraints from BBN on $A_{\mu;s}$ and $A_{e;s}$ would require minimizing both $|U_{e4}|$ and $|U_{\mu4}|$ while satisfying (15). This gives $|U_{e4}|^2 = |U_{\mu4}|^2 \simeq 10^{-2}$. Combined with the limit (16), the BBN constrained combination has the minimum value

$$\delta m^2_{\rm LSND} A_{\mu;s} \gtrsim 3\times10^{-4} \tag{17}$$

which exceeds the limits (14) by at least two orders of magnitude and invariably thermalizes the sterile. This constraint comes from the conservative case where $\delta m^2_{4i} > 0$. The inverted case $\delta m^2_{4i} < 0$ is resonant and more stringently constrained. Therefore, (3+1) models are strongly disfavored by standard BBN.

3.2 2+2

Four neutrino models may also accommodate all indications for neutrino mixing with mass eigenstates in a pair of doublets that provide the solar and atmospheric mass scales and a large mass gap between the doublets providing the LSND mass scale. The global analysis by Maltoni *et al.* [16] finds that such (2+2) models are consistent within 99% CL either with the sterile neutrino completely participating in the atmospheric or solar solutions. Therefore, it is possible to choose a very small amplitude mixing between the doublet not participating in sterile oscillations and the sterile state such that the large LSND mass splitting does not populate the sterile neutrino. On the other hand, unitarity constrains the sterile state to be present among some linear combination of mass eigenstates. Whether (2+2) scenarios are compatible with the exclusion of large sterile components in both the atmospheric and solar neutrino observations is controversial [42], but there exists no global neutrino oscillation analysis including the latest SNO neutral current results [14].

Whether the sterile flavor is in the atmospheric doublet or solar doublet is not of concern for the early universe. In either case, the sterile flavor will be thermalized. For our notation, we employ the mass scheme used in Ref. [16], where the (2+2) model has the solar scale between ν_1 and ν_4 and the atmospheric scale between ν_2 and ν_3, with the hierarchy only being determined by the condition for resonance in the sun, $m_1 < m_4$. One can avoid the effects of thermalization of the largest mass scale by setting the inter-doublet mixings to zero, $U_{s1} = U_{s3} = 0$, but by unitarity $|U_{s2}|^2 + |U_{s4}|^2 = 1$, whereby the sterile neutrino participates in large part in the solar scale, atmospheric scale or both. Having a complete sterile solution for either scale has already been known to thermalize the sterile neutrino [39,40]. One could consider democratically separating the sterile into both the atmospheric and solar scales to minimize its presence in both, so that $|U_{s2}|^2 = |U_{s4}|^2 = 1/2$. However, the amplitudes $A_{\mu;s} = 4|U_{\mu 2}|^2|U_{s2}|^2$ and $A_{e;s} = 4|U_{e4}|^2|U_{s4}|^2$ still grossly exceed the BBN bounds (14) since the magnitudes $|U_{e4}|^2 = |U_{e1}|^2 \tan^2\theta_{\rm LMA}$ and $|U_{\mu 2}|$ must be large to accommodate the large to maximal mixing angle solutions of the solar and atmospheric neutrino problems. Therefore, (2+2) models are also strongly disfavored by standard BBN.

3.3 Self-Suppression

The possibility that a four neutrino mass scheme could be arranged in such a way as to evade sterile-thermalization constraints were considered by Bell, Foot & Volkas [43] and Shi, Fuller & Abazajian [44]. One could potentially either self-generate a lepton number and suppress the large-mixing-amplitude thermalization or offset the effects of sterile thermalization by altering the electron neutrino-antineutrino asymmetry through alteration of beta-equilibrium,

$$\begin{aligned}
&{\rm n} + \nu_e \leftrightarrow {\rm p} + e^- \\
&{\rm n} + e^+ \leftrightarrow {\rm p} + \bar\nu_e \,.
\end{aligned} \qquad (18)$$

In the models considered in Refs. [43,44], the direct thermalization bounds (14) were avoided by placing the sterile neutrino in the small-mixing-angle solution to the solar neutrino problem, a region of parameter space still viable at the time and outside of the constraint region (14).

In addition, Refs. [43,44] explored methods of generating asymmetries between electron neutrinos and antineutrinos by resonant lepton number generation [19]. The resonance condition in the early universe requires $m_4 < m_i$, where m_i is a mass eigenstate (more) closely associated with an active flavor. A positive electron neutrino number will suppress the ^{4}He abundance by shifting the rates (18), which would be necessary if standard BBN is inconsistent by having too high of a predicted ^{4}He abundance for a given $\Omega_b h^2$. As shown above, standard BBN remains consistent within observational uncertainty. The sign of resonantly generated electron neutrino/antineutrino asymmetry can be chaotic [45], or at least not well determined [46], having an significant chance (50% if chaotically random) of being negative and actually *increasing* Y_p by altering beta-equilibrium in the opposite direction. If the sign of the asymmetry *is* randomly chaotic, then causally disconnected regions will have different sign asymmetries, which leads to an enhancement of the transformation of active neutrinos into sterile neutrinos at the boundaries of regions of different sign [47] and potentially placing more stringent constraints on four neutrino mass schemes [48].

There is considerable evidence now that the solar solution lies in the LMA region of parameter space [14]. Therefore, as discussed in the previous sections, thermalization of the sterile is unavoidable in either the (3+1) or (2+2) scenarios. And, importantly, it was shown by Di Bari [41] that thermalization of the sterile in these four neutrino models suppresses lepton number generation, and electron neutrino/antineutrino asymmetries are not effective in avoiding the BBN bounds (14).

4 Constraint Evasion and New Physics

The simplifying and appealing principle of Occam's razor has proven to be a powerful tool as a predictor in science, yet nature does not always take the most simple form. The minimal model for four neutrino mixing or the standard BBN described above may certainly not be the entire framework of the early universe or particle physics. Importantly, if all experimental indications for neutrino oscillations remain, *viz.*, if the MiniBooNE detector [49] verifies the LSND signal, K2K [50] and MINOS [51] verify the atmospheric oscillation solution and KamLAND detects the LMA signal [33], then new physics must be at play beyond standard three-neutrino mixing and standard BBN. There exist a number of ways of accommodating such a scenario, several of which are described below. The aesthetic value of these scenarios are left to the judgment of the reader.

Pre-existing lepton asymmetry — A lepton number in the active neutrino flavors will suppress sterile neutrino population by magnifying the associated lepton potential and dwarfing the vacuum mixing amplitude [52]. This lepton number would have to be produced by an unspecified mechanism earlier than the population of the sterile neutrino would take place.

A fifth mass eigenstate — Appropriate insertion of a mass eigenstate with a major sterile component with $m_5 < m_i$ ($i = 1...4$) in degenerate neutrino mass models may resonantly generate lepton number sufficiently prior to sterile thermalization as to suppress it. This possibility was explored in Ref. [41].

Majoron fields — One mechanism for generating neutrino mass involves a massless Nambu-Goldstone boson (a majoron) from models where either the total or partial lepton number is spontaneously broken [53]. In such models, a coherent majoron field creates potentials for the neutrinos proportional to the gradient of the field [54] and suppresses sterile thermalization in a similar way as a pre-existing lepton asymmetry. Interestingly, this mechanism arises from the neutrino mass model itself.

A low reheating temperature universe — There is no direct evidence that the neutrino background is thermalized. As explored in Refs. [55], the highest temperature of the universe could have been only 0.7 MeV. The neutrino background may never have been thermalized, but the observed light element abundances could still be created. In this case, sterile neutrinos may modify the nucleosynthesis processes by partial population but are not directly excluded.

Baryon-antibaryon inhomogeneity — Detailed calculations of diffusion and nucleosynthesis in universes containing baryon number asymmetries [56] have found that small-scale antibaryon domains are not excluded by BBN and the observed light element abundances [57], and may lift constraints on relativistic energy density present at BBN to $N_\nu \lesssim 7$, even with total baryon densities consistent with CMB observations [58].

Extended quintessence — Non-minimally coupled quintessence models (where the quintessence field is not only coupled to gravity) that provide a negative-pressure vacuum energy density to explain the acceleration phase that the universe may be entering can alter BBN [59]. In certain cases of such "extended quintessence" scenarios, the quintessence field may behave to decrease the expansion rate during the freeze-out of beta equilibrium (18), and therefore *decrease* the predicted helium abundance. This reduction of the expansion rate could offset the increase in the expansion rate due to the presence of an extra neutrino degree of freedom and allow for four-neutrino models.

CPT violating neutrinos — There exists a radical proposal that fits all indications for neutrino oscillation and invokes CPT violation in the neutrino sector [60]. The success of this model lies in the fact that LSND's indication for neutrino oscillation lies primarily in the antineutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ channel [15], is motivated by braneworld scenarios with extra dimensions, and gives dramatic predictions for the MiniBooNE [49] and KamLAND [33] experiments. This model has no effect on standard BBN since in the standard case the neutrinos and antineutrinos are equally thermally populated and therefore CPT violating neutrino oscillations do not disturb the detailed balance of thermal equilibrium, leading to no direct conflicts between light element abundances and standard BBN.

5 Discussion and Conclusions

In minimal models of big bang nucleosynthesis with no new physics, we have shown that four neutrino models explaining current indications for neutrino oscillations are disfavored at the 99% CL. This conclusion depends on systematic effects not being larger than that expected ($\sim 3\%$) in determining the ^{4}He abundance in ionized HII regions and that the baryon density inferred by the D/H abundance in six high-redshift quasar absorption systems and the anisotropies in the cosmic microwave background are approaching the true cosmic value of $\Omega_b h^2$.

The MAP satellite will verify or disprove the value of $\Omega_b h^2$ inferred by the above methods to high precision in the near future [26]. If consistency remains in cosmological determinations of the baryon density, then $\Omega_b h^2$ would then become a "nuisance" parameter in determining the cosmological energy density at standard BBN. The primordial helium abundance is currently the best probe of the energy density of the universe present at BBN, yet there remain no concrete proposals in the literature for the reducing systematic uncertainties present in determining the primordial ^{4}He abundance, which is the dominant uncertainty in constraining the energy density present in the universe at the age of one second via standard BBN.

In addition, we have summarized several scenarios that evade the standard BBN model constraints presented here. Remarkably, if all experimental indications for neutrino oscillations are confirmed, new physics must be present not only in the particle content of the neutrino sector but also in the early universe.

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