International Journal of Modern Physics E
Vol. 23, No. 3 (2014) 1450014 (11 pages)

DOI: 10.1142/S0218301314500141

Sterile neutrinos and Big Bang Nucleosynthesis in the 3 + 1 scheme

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Received 20 December 2013
Revised 10 February 2014
Accepted 18 February 2014
Published 14 March 2014

We study the effects of adding a sterile neutrino to three active neutrinos ($3+1$ scheme) in the calculation of primordial abundances. Taking the normalization constant (a) of the occupation factor of the sterile neutrino and the active-sterile mixing angle (ϕ) as free parameters, we calculate the neutrino distribution function and primordial abundances of light nuclei. We set constrains on these parameters by using the available data on the abundances of D, ^{4}He and ^{7}Li. Results are consistent with small values of a and ϕ. The extracted value of the baryon-to-photon ratio (η_B), which is constrained by the Wilkinson Microwave Anisotropy Probe (WMAP) value η_B^{WMAP}, and Planck observations, depends strongly on the inclusion of the lithium data in the fit.

Keywords: Sterile neutrino; 3 + 1 scheme; primordial abundances.

PACS Number(s): 98.80.Ft, 26.35.+c, 14.60.Pq, 98.80.-k

1. Introduction

The analysis of the data obtained by the Wilkinson Microwave Anisotropy Probe (WMAP)[1] and by Planck[2] provides, with great accuracy, the value of the baryon density, and the effective number of neutrinos, among other cosmological parameters. The baryon density, or the baryon-to-photon ratio, is the only free parameter of the model which describes the Big Bang Nucleosynthesis (BBN). The results

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obtained by the WMAP Collaboration[1] and by Planck,[2] are consistent with the observed primordial abundances of D and ^{4}He, but there exists a disagreement with the observed abundance of ^{7}Li. Some authors have suggested that a better understanding of turbulent transport in the radiative zones of stars is needed for a better determination of the abundance of primordial lithium,[3] and others have suggested that there exists a stellar lithium depletion that depends on the mass of the star.[4,5] The nuclear physics aspects of the abundance of ^{7}Li have been revisited recently.[6–8] As a main consequence of these studies, the influence of nuclear reaction and nuclear structure mechanisms upon the solution of the ^{7}Li problem was emphasized. However, the problem persists and the observed abundance of primordial lithium is smaller than the predicted BBN abundance. Several authors set constraints on the effective number of neutrino species using WMAP data and other experiments.[9–11]

The observation of neutrino oscillations[12–19] solves the solar neutrino problem[20] and leads to further advances in neutrino related processes such as nuclear double-beta decay[21–23] and neutrino astrophysics.[24–27] Other experiments, such as the Liquid Scintillator Neutrino Detector (LSND)[28] and the Mini Booster Neutrino Experiment (MiniBooNE)[29] have reported on anomalies which may be interpreted as possible signals of extra-neutrino species. The results from the WMAP collaboration,[30] the Sloan Digital Sky Survey[31] and several measurements of the Cosmic Microwave Background (CMB) anisotropy[32,33] indicate an effective neutrino number higher than the predicted by the standard model. There exists, in the literature, some works that combine the data obtained by short-baseline neutrino oscillation experiment and the cosmological data to obtain information about the masses and mixing-scenario ($3+1$, $3+2$ or $3+1+1$) of the neutrinos species.[34,35]

There exists several papers on the sensitivity of the helium abundance upon the distortion of the light-neutrino spectrum induced by active-sterile neutrino oscillations,[36–40] and about the effects of the active-sterile neutrino mixing on the calculated primordial abundances.[41] In the publications by Bell *et al.*,[42] Di Bari[43] and Foot *et al.*[44] the effect of neutrino oscillations on the neutrino asymmetry was studied. Hannestad, Tamborra and Tram[45,46] studied the full thermalization assumption during BBN in the $1+1$ scheme for different values of the lepton asymmetry. In work of Jacques *et al.*,[47] the $3+2$ scenario and partial thermalization of the sterile states during cosmological epochs have been analyzed.

In previous works, we have studied the effect of the inclusion of one and two sterile neutrinos in the primitive Universe.[48–50] In particular, we have analyzed the effects of active-sterile neutrino oscillations in the two-state scheme,[49] in the $3+1$ scheme[48] and in the $3+2$ scheme.[50] We have computed neutrino occupation factors and single-beta decay rates in order to obtain the primordial abundances using the semi-analytical method[51] and the numerical code.[52,53]

In this work, we perform our calculations in the $3+1$ scheme, with a variable normalization of the sterile neutrino sector. We compute the light-neutrino occupation factor and then, the neutron-to-proton decay rates in order to obtain the abundances of the light elements produced during the BBN time sequel. For the computation of the light-neutrino occupation factor we use three different approaches: (i) we solve the quantum kinetic equations (QKE) numerically with a neutrino interaction term;[42] (ii) we solve the QKE with a neutrino interaction term and without a damping factor;[42] (iii) we solve the evolution equation in an expanding Universe without considering neutrino interactions. Using observable data we set constrains on the mixing angle and on the normalization constant of the occupancy factor for the sterile neutrino.

This paper is organized as follows. In Sec. 2, we describe the formalism to include active-sterile neutrino oscillations during BBN. In Sec. 3, we present and discuss the results of the calculation of BBN abundances under the assumption of non-constant values of η_B, a and ϕ. Finally, the conclusions are drawn in Sec. 4.

2. Formalism

The mixing between three active neutrino mass-eigenstates and one sterile neutrino is expressed by the matrix[54]

$$U(\phi) = \begin{pmatrix} c_{12}c_{13}\cos\phi & s_{12}c_{13}\cos\phi & s_{13}\cos\phi & \sin\phi \\ -s_{12}c_{23} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} & 0 \\ s_{12}s_{23} - c_{12}s_{13}c_{23} & -c_{12}s_{23} - s_{12}s_{13}c_{23} & c_{13}c_{23} & 0 \\ -c_{12}c_{13}\sin\phi & -c_{13}s_{12}\sin\phi & -s_{13}\sin\phi & \cos\phi \end{pmatrix},$$

where ϕ is the mixing-angle of the lowest mass-eigenstate with the sterile neutrino (in this notation s_{ij} stands for $\sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$). Since we want to test the change in the electron neutrino component due to the sterile neutrino, we have assumed that the mixing angles between the sterile neutrino and the two other mass-eigenstate (related to the muon and the tau neutrino) are null. According to the recently reported data, we have taken a nonzero value for the mixing angle θ_{13}.[55–57]

The inclusion of a new kind of neutrino affects the statistical occupation factor of neutrinos of a given flavor, in particular the electron–neutrino (which is the neutrino involved in the calculation of the neutron-to-proton decay rate). For this reason, one must perform the calculation of the new occupation factors. In the next subsections, we solve the evolution equations for the neutrino occupation factors for two different cases: (i) including a neutrino interaction term; (ii) without considering neutrino interactions.

2.1. *Including neutrino interactions*

Following the formalism of Bell *et al.*,[42] in a two-flavor system, the QKE which govern the evolution of P_0 and $\mathbf{P}$ (quantities related to the neutrino density) are

$$\begin{aligned}\frac{\partial \mathbf{P}(p)}{\partial t} &= \mathbf{V}(p) \times \mathbf{P}(p) + (1 - P_z(p))\frac{\partial \ln P_0(p)}{\partial t}\hat{z} \\ &\quad - \left(\kappa(p) + \frac{\partial \ln P_0(p)}{\partial t}\right)(P_x(p)\hat{x} + P_y(p)\hat{y}),\end{aligned}$$

$$
\begin{aligned}
\frac{\partial P_0(p)}{\partial t} &= R(p), \\
\rho(p) &= \frac{1}{2} P_0(p)\,(1 + \mathbf{P}(p)\cdot\sigma),
\end{aligned}
\tag{1}
$$

where σ are the Pauli matrices and

$$
\begin{aligned}
\mathbf{V}(p) &= \beta(p)\hat{x} + \lambda(p)\hat{y}, \\
\beta(p) &= \frac{\delta m^2}{2p}\sin 2\phi, \\
\lambda(p) &= -\frac{2\zeta(3)\sqrt{2}A_e}{\pi^2}\frac{G_F T^4 p}{m_W^2} - \frac{\delta m^2}{2p}\cos 2\phi.
\end{aligned}
\tag{2}
$$

In the last expression no neutrino asymmetry was considered. In the notation of Ref. 42, T is the temperature, G_F is the Fermi constant, m_W is the W-boson mass, δm^2 is the mass-squared difference between the eigenstates 1 and 4, $A_e = 17$, and ζ is the Riemann zeta function. Other quantities entering Eq. (1) are the damping function $\kappa(p)$, which is written

$$
\kappa(p) = \frac{1}{2}\frac{G_F^2 T^4 y_e}{3.15} p, \tag{3}
$$

$y_e = 0.1$ (from the thermal equilibrium condition), and the repopulation function $R(p)$.[42]

We are interested in solving these equation with the conditions imposed by BBN. These equations can be solved analytically, considering that the damping factor κ, of Eq. (3), vanishes, under the conditions discussed in Bell *et al.*[42] The solutions obtained in this manner are illustrative of the effects of oscillations between the neutrino mass eigenstates. The solutions corresponding to $\kappa \neq 0$ can be obtained numerically. As we are discussing in the next section, we have performed both types of calculations in order to determine the combine effects of damping and oscillations upon de primordial abundances. In both cases, numerically and analytically, we have taken the repopulation factor $R(p) = 0$ (this gives a constant value for P_0). Therefore, for the analytical approach, we can write the neutrino number density as a function of time as

$$
\begin{aligned}
f_{ee} &= f_{ee}(0)P_{ee} + f_{ss}(0)P_{se}, \\
f_{ss} &= f_{ee}(0)P_{es} + f_{ss}(0)P_{ss},
\end{aligned}
\tag{4}
$$

where P_{ee} and P_{se} are the probabilities, and $f_{ij}(0)$ are the occupation factors at temperature T_0 (see below).

2.2. *Without including neutrino interactions*

Following the formalism used by Kirilova,[36] we solve the equation

$$
\left(\frac{\partial f}{\partial t} - HE_\nu \frac{\partial f}{\partial E_\nu}\right) = \imath[\mathcal{H}_0, f], \tag{5}
$$

where f represents the 4×4 matrix of the occupation factors, t is the time, H is the expansion rate of the Universe ($H = \mu_P T^2$), E_ν is the neutrino energy and $\mathcal{H}_0$ is the unperturbed mass term of the neutrino's Hamiltonian in the rest frame. We assume that at the temperature $T_0 = 2\,\mathrm{MeV}$ the occupation factors for all neutrinos in the flavor eigenstates are standard Fermi–Dirac distributions. However, for the sterile neutrino, we assume that its occupation factor is multiplied by a constant factor a[11] which varies between 0 and 1. This assumption leads to the initial condition

$$\left.\begin{pmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ f_{41} & f_{42} & f_{43} & f_{44} \end{pmatrix}\right|_{T_0} = \frac{1}{1+e^{E_\nu/\mathrm{T}_0}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \frac{a-1}{1+e^{E_\nu/T_0}} \begin{pmatrix} \sin^2\phi & 0 & 0 & \frac{1}{2}\sin 2\phi \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2}\sin 2\phi & 0 & 0 & \cos^2\phi \end{pmatrix}. \tag{6}$$

The solutions of Eq. (5), in the flavor basis, are written

$$\begin{aligned} f_{ee} &= \left[1 - \frac{1}{2} c_{12}^2 c_{13}^2 \sin^2 2\phi (1-a)(1-\cos\Delta)\right] \frac{1}{1+e^{E_\nu/T}}, \\ f_{\mu\mu} &= \left[1 - \frac{1}{2} s_{12}^2 c_{13}^2 \sin^2 2\phi (1-a)(1-\cos\Delta)\right] \frac{1}{1+e^{E_\nu/T}}, \\ f_{\tau\tau} &= \left[1 - \frac{1}{2} s_{13}^2 \sin^2 2\phi (1-a)\,(1-\cos\Delta)\right] \frac{1}{1+e^{E_\nu/T}}, \\ f_{ss} &= \left[a + \frac{1}{2} \sin^2 2\phi (1-a)(1-\cos\Delta)\right] \frac{1}{1+e^{E_\nu/T}}, \end{aligned} \tag{7}$$

with $\Delta = \frac{m_1^2 - m_4^2}{6\mu_P} \frac{T}{E_\nu} (\frac{1}{T^3} - \frac{1}{T_0^3})$, where m_i is the mass of the neutrino in the ith eigenstate. If the parameter a is zero, the active-sterile neutrino mixing modifies the distribution function of all type of neutrinos. If the active-sterile mixing angle is null, the distribution functions are not modified respect to the Fermi–Dirac distributions. We have considered a fixed square mass-difference[58,59] of 1 eV^2.

With the occupation factors (6) we have calculated the primordial abundances as a function of the mixing between active and sterile neutrinos, using an adapted version of Kawano's code,[52,53] as described in our previous work.[50]

3. Results

The input of the calculations is the set of oscillation parameters determined from SNO, SK, GNO, CHOOZ DAYA BAY, RENO and DOUBLE CHOOZ experiments,[12,17,18,55–57,60] the active-sterile neutrino mixing angle, ϕ, and the occupation constant a of Eq. (7). We have considered the mean value of the oscillation term which includes the mass splitting.

As a first step, we have studied the effects upon the primordial abundances when the parameter a varies between 0 and 1, for a null value of the active-sterile mixing angle. The calculations were performed with and without including neutrino interactions, both for $\kappa = 0$ and $\kappa \neq 0$. The baryon density is fixed at the value determined from WMAP data.[1] The abundances of D and ^{4}He increase with the parameter a and the ^{7}Li abundance decreases. The results are quite similar for the calculation performed with $\kappa = 0$. The effect of the variation of the parameter a can raise up to 15% for the abundances of D and ^{4}He, and 10% for ^{7}Li. The effect due to the variation of the mixing angle is noticeable, and the larger the mixing angle, the larger is the calculated primordial abundance of a given nuclei. The effect of the mixing can raise up to 8%.

The general trend of the variation may be summarized by saying that the abundances of D and ^{4}He increase, by increasing the value of a, while the abundance of ^{7}Li decreases if a increases. The effects due to the changes in a are larger than those due to changes in ϕ. The results for both set of results (those obtained with and without including neutrino oscillations) are quite similar.

Next, we have considered observational data to set constrains on the free parameters of the model, namely a and $\sin^2 2\phi$. WMAP data are able to constraint the baryon density $\Omega_B h^2$ (related to the baryon-to-photon ratio η_B) with great accuracy, however there is still some degeneracy between the model parameters. For this reason we have performed two different analysis, the first by considering η_B fixed at the WMAP value, and the second one by considering η_B as an extra free parameter. To determine the best value of the mixing angle $\sin^2 2\phi$, a and the baryon-to-photon ratio η_B, we have performed a χ^2 minimization.

The observational data for D have been extracted from Refs. 61–64. We use the data from Refs. 65–70 for ^{4}He and, for ^{7}Li we have considered the data given by Refs. 4, 71–74. Regarding the consistency of the data, we have followed the treatment of Ref. 75 and increased the errors by a fixed factor $\Theta_{^4\mathrm{He}} = 2.15$ and $\Theta_{^7\mathrm{Li}} = 1.50$, for the other cases the errors were not changed.

3.1. *Results with η_B fixed*

We have computed the abundance of light nuclei for different values of a, and by fixing the value of the baryon density at the value[1] $\eta_B^{\mathrm{WMAP}} = (6.187 \pm 0.156) \times 10^{-10}$. We performed a statistical analysis in order to obtain the best-fit value of the parameters for different cases. The results are presented in Table 1. The first two cases shown in the table are the results of Eq. (1) and the last set are the ones obtained by using the occupation factors of Eq. (7). The same structure is conserved in the subsequent tables. In the cases corresponding to a zero mixing angle ($\phi = 0$), the variable to be determined is the renormalization parameter a.

Table 1. Best-fit parameter value of a and 1σ errors. The mixing angle ϕ has been fixed at the value $\phi = 0$ (no mixing).

Including neutrino interaction ($\kappa \neq 0$)		
Data	$a \pm \sigma$	$\frac{\chi^2}{N-1}$
$D + {}^4He + {}^7Li$	$0.51^{+0.08}_{-0.04}$	27.94
$D + {}^4He$	$0.21^{+0.08}_{-0.04}$	2.43
Including neutrino interaction ($\kappa = 0$)		
Data	$a \pm \sigma$	$\frac{\chi^2}{N-1}$
$D + {}^4He + {}^7Li$	$0.64^{+0.04}_{-0.09}$	26.52
$D + {}^4He$	$0.21^{+0.04}_{-0.06}$	1.45
Without including neutrino interaction		
Data	$a \pm \sigma$	$\frac{\chi^2}{N-1}$
$D + {}^4He + {}^7Li$	$0.63^{+0.04}_{-0.07}$	26.39
$D + {}^4He$	0.25 ± 0.07	1.53

There is no good global fit for the whole data set, however, better fits can be found by excluding the data on ^{7}Li. If the other elements are removed from the data, the anomalous feature associated with the inclusion of the lithium data persists. It means that the value of $\frac{\chi^2}{N-1}$ remains much larger than unity if the lithium data are present in the sample, regardless the inclusion or removal of the data of any of the other elements, either D or ^{4}He.

The next step was to vary both a and $\sin^2 2\phi$. The results are presented in Table 2.

Once again, there is no good fit for the whole data set, however, if one excludes the lithium data the fit improves considerably. The values obtained for the parameter a are the same obtained from the previous analysis and the resulting mixing angle is always small.

3.2. *Results with η_B variable*

Next, we allow η_B to vary in performing the calculation of the primordial abundances for different value of a. The results of the statistical analysis are presented in Table 3.

Somehow better fits than those of the previous sub-section, are found for the complete set of data, but if one removes the lithium data the value of χ^2 decreases considerably. One can also notice that, when the ^{7}Li data is excluded from the data set, the value of the baryon-to-photon ratio is in excellent agreement, within 1σ, with the value obtained by the analysis of the WMAP data (η_B^{WMAP}).[1] If one uses the whole data set to perform the analysis, the obtained value of η_B agrees with

Table 2. Best-fit parameter values and 1σ errors. The fit has been performed by varying the mixing angle ϕ, and the renormalization parameter a.

Data	$a \pm \sigma$	$\sin^2 2\phi \pm \sigma$	$\frac{\chi^2}{N-2}$
Including neutrino interaction ($\kappa \neq 0$)			
$\mathrm{D} + {}^4\mathrm{He} + {}^7\mathrm{Li}$	$0.53^{+0.06}_{-0.09}$	0.10 ± 0.10	29.84
$\mathrm{D} + {}^4\mathrm{He}$	0.22 ± 0.06	$0.00^{+0.12}$	2.69
Including neutrino interaction ($\kappa = 0$)			
$\mathrm{D} + {}^4\mathrm{He} + {}^7\mathrm{Li}$	0.62 ± 0.07	$0.00^{+0.02}$	28.18
$\mathrm{D} + {}^4\mathrm{He}$	0.18 ± 0.04	$0.00^{+0.08}$	1.04
Without including neutrino interaction			
$\mathrm{D} + {}^4\mathrm{He} + {}^7\mathrm{Li}$	0.62 ± 0.07	$0.00^{+0.02}$	28.18
$\mathrm{D} + {}^4\mathrm{He}$	0.25 ± 0.07	$0.00^{+0.09}$	1.04

the WMAP value at the level of 7σ. The value for the parameter a decreases with respect to the value obtained previously, when all the data are used in the statistical test, meanwhile it increases its value when we eliminate the lithium data.

Finally, we compute the abundances using a, ϕ and η_B as free parameters. The results of the χ^2 analysis are presented in Table 4.

Table 3. Best-fit parameter values and 1σ errors. The baryon-to-photon ratio η_B is given in units of 10^{-10}. The fit has been performed by varying η_B and a, and taken $\phi = 0$ for the mixing angle.

Data	$\eta_B \pm \sigma$	$a \pm \sigma$	$\frac{\chi^2}{N-2}$
Including neutrino interaction ($\kappa \neq 0$)			
$\mathrm{D} + {}^4\mathrm{He} + {}^7\mathrm{Li}$	5.74 ± 0.13	$0.21^{+0.08}_{-0.04}$	25.52
$\mathrm{D} + {}^4\mathrm{He}$	6.44 ± 0.15	$0.39^{+0.07}_{-0.08}$	0.96
Including neutrino interaction ($\kappa = 0$)			
$\mathrm{D} + {}^4\mathrm{He} + {}^7\mathrm{Li}$	5.67 ± 0.10	0.17 ± 0.07	23.05
$\mathrm{D} + {}^4\mathrm{He}$	$6.29^{+0.10}_{-0.07}$	$0.32^{+0.09}_{-0.08}$	0.95
Without including neutrino interaction			
$\mathrm{D} + {}^4\mathrm{He} + {}^7\mathrm{Li}$	5.63 ± 0.06	$0.19^{+0.04}_{-0.07}$	23.04
$\mathrm{D} + {}^4\mathrm{He}$	6.32 ± 0.11	0.37 ± 0.11	0.96

Table 4. Best-fit parameter values and 1σ errors. The baryon-to-photon ratio η_B is given in units of 10^{-10}. In performing the fits we have allowed all parameters (η_B, ϕ, a) to vary.

Data	$\eta_B \pm \sigma$	$a \pm \sigma$	$\sin^2 2\phi \pm \sigma$	$\frac{\chi^2}{N-3}$
Including neutrino interaction ($\kappa \neq 0$)				
$D + {}^4He + {}^7Li$	5.70 ± 0.13	$0.17^{+0.07}_{-0.05}$	$0.02^{+0.10}_{-0.02}$	27.54
$D + {}^4He$	6.40 ± 0.16	0.36 ± 0.07	$0.01^{+0.12}_{-0.01}$	0.78
Including neutrino interaction ($\kappa = 0$)				
$D + {}^4He + {}^7Li$	5.61 ± 0.10	$0.06^{+0.10}_{-0.06}$	0.10 ± 0.05	24.90
$D + {}^4He$	6.29 ± 0.19	0.31 ± 0.18	$0.06^{+0.15}_{-0.06}$	0.86
Without including neutrino interaction				
$D + {}^4He + {}^7Li$	5.60 ± 0.12	$0.03^{+0.27}_{-0.03}$	0.15 ± 0.08	24.91
$D + {}^4He$	6.32 ± 0.15	$0.31^{+0.49}_{-0.31}$	$0.09^{+0.23}_{-0.09}$	0.86

Relatively good fits are obtained if the primordial abundance of ${}^7Li$ is not used in the analysis. For this case, the value of η_B is in good agreement with the value of WMAP. The value for the parameter a is slightly smaller than the ones shown in Tables 1–3, when all the data are used in the statistical test, and the mixing angle acquires a relatively high value (but null within 3σ). We have also performed the same analysis considering different values for the mass-square difference in Eq. (4), and found that the larger is δm^2, the lower are the values of the mixing angle and the parameter a.

4. Conclusion

In this work, we have calculated the primordial abundances of light nuclei considering the presence of an extra sterile neutrino. We have computed the occupation factor for the light neutrino, the neutron-to-proton decay rates and the primordial abundances of the light elements produced during the first three minutes of the Universe. We have found a sensitivity of the abundances to active-sterile neutrino mixing, in agreement with results reported in previous works.[39,48–50]

It was shown that the larger the mixing angle, the larger become the primordial abundances. Also, if the parameter a increases its value, the primordial abundances of D and ${}^4He$ increase, while the abundance of ${}^7Li$ decreases.

It was found that, if the whole data set is used in the analysis, the extracted value of η_B is not in agreement with the value obtained by WMAP, however, if the lithium data is removed from the data set, the best-fit value of η_B is in good agreement with η_B^{WMAP}. The value for the parameter a remains lower than 0.65

in all cases. When the value of the baryon-to-photon ratio is fixed, we found that the statistical analysis favors small values of the mixing angle (in agreement with previous works[50]). The statistical errors of the fits, for the mixing angle ϕ, show that its value is consistent with zero, suggesting that the primordial abundances are mostly affected by the change in η_B and in a rather than by changes in the mixing angle.

Acknowledgments

Support for this work was provided by the PIP 0740 of the National Research Council (CONICET) of Argentina, and by the ANPCYT of Argentina. The authors are members of the Scientific Research Career of the CONICET.

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