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Testing primordial abundances with sterile neutrinos

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The mixing between sterile and active neutrinos is taken into account in the calculation of Big Bang Nucleosynthesis. The abundances of primordial elements, like D, ^{3}He, ^{4}He, and ^{7}Li, are calculated by including sterile neutrinos and by using finite chemical potentials. It is found that the resulting theoretical abundances are consistent with Wilkinson Microwave Anisotropy Probe (WMAP) data on baryonic densities, and with limits of Liquid Scintillator Neutrino Detector (LSND) on mixing angles, only if ^{7}Li is excluded from the statistical analysis of theoretical and experimental results.

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I. INTRODUCTION

In recently published papers [1,2] the sensitivity of the ^{4}He primordial abundance, upon distortions of the light neutrino spectrum induced by couplings with a sterile neutrino, was analyzed. The effects due to the mixing between sterile and active neutrinos [1,2] reflect upon Big Bang Nucleosynthesis (BBN) in a noticeable manner. Previous studies on this matter can be found in Refs. [3–5], where the effects of mixing upon BBN in the presence of primordial leptonic asymmetry have been investigated, and stringent limits on the mixing due to BBN have been presented. Similar studies have been presented in Refs. [6,7]. A review on inclusion of sterile neutrino in cosmology was presented in Ref. [8].

The results of Ref. [2] may be taken as a solid starting point for a systematic analysis of the sterile-active neutrino mixing upon cosmological observables, like the primordial abundance of light elements. In addition, the mixing mechanism between sterile and active neutrinos has been studied in detail (see Ref. [9] and references therein), so that the calculation of neutrino distribution functions can readily be performed. The information about the neutrino distribution function, in the flavor basis and at a given temperature, is an essential element in the calculation of the neutron decay rate, which is a critical quantity entering BBN [10,11].

Direct physical consequences upon BBN, due to the mixing between active and sterile neutrinos, have been explored in Refs. [12,13]. Following the arguments presented in Ref. [12], and in the framework of the standard cosmological model, sterile neutrinos would produce a faster expansion rate for the Universe and a higher yield of ^{4}He. This is, indeed, a severe constraint on neutrino mixing because a higher predicted abundance of ^{4}He may be in conflict with observational data [12]. Another constraint on active-sterile neutrino mixing is the neutrino mass derived from Cosmic Microwave Background Anisotropy (CMB) [14]. The analysis of constraints presented in Ref. [15] focuses on the mixing scheme at the level of the neutrino mass hierarchy, and it suggests the adequacy of the nondegenerate mass hierarchy to set limits on the mass difference between active and sterile neutrinos, δm^2_{a-s}. The study of Ref. [15] confirms the notion about the convenience of the three active + one sterile neutrinos scheme.

In standard BBN calculations, the mixing of sterile and active neutrinos affects the leptonic fractional occupancies, which are essential quantities appearing in the expression of the weak decay rates. Thus, one needs to know, as input of the calculations, the parameters of the proposed mixing scheme, the neutrino mass hierarchy, and the leptonic densities [13]. With these elements one can calculate neutron decay rates and neutron abundances, by assuming the freeze-out of weak interactions [10,12]. The effective number of neutrino generations, N_ν, is fixed by the analysis of CMB [16–18]. Current limits on the neutrino degeneracy parameter, for light (electron) neutrinos, η_l [1], run from -0.1 to 0.3 [17,18]. For a detailed presentation of the formalism, in the context of relic-neutrino asymmetry evolution, see Ref. [13].

In this work we focus on the calculation of the abundances of D, ^{3}He, ^{4}He, and ^{7}Li in the presence of sterile-active neutrino mixing in the three flavor scenario and for the normal and inverse neutrino mass hierarchies [9]. We have compared the calculated values with data [19–21] and determined the compatibility between them by performing a χ^2 statistical analysis. Because the theoretical expressions depend on the mixing angle $\sin^2 2\phi$, the square mass difference δm^2_{14} (normal mass hierarchy) or δm^2_{34} (inverse mass hierarchy), and the baryonic density $\Omega_B h^2$, we have adopted the Liquid Scintillator Neutrino Detector (LSND) limits on the mixing angle [22–24] and the Wilkinson Microwave Anisotropy Probe (WMAP) results on the baryonic density [25] as constraints.

This article is organized as follows. In Sec. II we briefly present the essentials of the formalism. Section III is devoted to the calculation of the neutron decay rate and BBN abundances. In Sec. IV we present and discuss the results of the calculations. Conclusions are drawn in Sec. V.

II. FORMALISM

The mixing between active neutrino mass eigenstates ν_i ($i = 1, 2, 3$), leading to neutrinos of a given flavor ν_k ($k =$ light, medium, heavy), is described by the mixing matrix U [26]

$$U = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}, \quad (1)$$

where c_{ij} and s_{ij} stand for $\cos\theta_{ij}$ and $\sin\theta_{ij}$, respectively, and CP conservation is assumed [26]. To this mixing we add the mixing of a sterile neutrino with (a) the neutrino mass eigenstate of lowest mass in the normal mass hierarchy, ν_1, and (b) the one of the inverse mass hierarchy, ν_3, by defining the mixing angle ϕ, such that the new mixing matrix U is redefined as $U(\phi)$ [9],

$$U(\phi) = \begin{pmatrix} c_{13}c_{12}\cos\phi & s_{12}c_{13} & s_{13} & c_{13}c_{12}\sin\phi \\ (-s_{12}c_{23} - s_{23}s_{13}c_{12})\cos\phi & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} & (-s_{12}c_{23} - s_{23}s_{13}c_{12})\sin\phi \\ (s_{23}s_{12} - s_{13}c_{23}c_{12})\cos\phi & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} & (s_{23}s_{12} - s_{13}c_{23}c_{12})\sin\phi \\ -\sin\phi & 0 & 0 & \cos\phi \end{pmatrix}, \tag{2}$$

for the normal mass hierarchy, and,

$$U(\phi) = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}\cos\phi & s_{13}\sin\phi \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13}\cos\phi & s_{23}c_{13}\sin\phi \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13}\cos\phi & c_{23}c_{13}\sin\phi \\ 0 & 0 & -\sin\phi & \cos\phi \end{pmatrix}, \tag{3}$$

for the inverse mass hierarchy. The mixing between neutrino mass eigenstates, and particularly the inclusion of the sterile neutrino as a partner of the light neutrino, affects the statistical occupation factors of neutrinos of a given flavor. The equation that determines the structure of the neutrino occupation factors, in the basis of mass eigenstates and for an expanding Universe, can be written [27] as

$$\left(\frac{\partial f}{\partial t} - H E_\nu \frac{\partial f}{\partial E_\nu}\right) = \imath\,[H_0, f], \tag{4}$$

where t is time; H is the expansion rate of the Universe, defined as $H = \sqrt{\frac{4\pi^3 N}{45 M_{\rm Planck}^2}}T^2 = \mu_P T^2$; T is the temperature; E_ν is the energy of the neutrino; and H_0 is the unperturbed mass term of the neutrino's Hamiltonian in the rest frame. The initial condition is fixed by defining the occupation numbers at the temperature $T_0 = 3$ MeV [28],

$$\left.\begin{pmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ f_{41} & f_{42} & f_{43} & f_{44} \end{pmatrix}\right|_{T_0} = \frac{1}{1+e^{E_\nu/T_0-\eta}} \begin{pmatrix} \cos^2\phi & 0 & 0 & \sin\phi\cos\phi \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \sin\phi\cos\phi & 0 & 0 & \sin^2\phi \end{pmatrix}, \tag{5}$$

for the normal mass hierarchy, and

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

for the inverse mass hierarchy.

To obtain the solutions of Eq. (4) we have written the source term, that is the commutator in the right-hand side of Eq. (4), in terms of the square mass differences, $\delta m_{ij}^2 = m_i^2 - m_j^2$:

$$[H_0, f] = \frac{1}{2p} \begin{pmatrix} 0 & \delta m_{12}^2 f_{12} & \delta m_{13}^2 f_{13} & \delta m_{14}^2 f_{14} \\ -\delta m_{12}^2 f_{21} & 0 & \delta m_{23}^2 f_{23} & \delta m_{24}^2 f_{24} \\ -\delta m_{13}^2 f_{31} & -\delta m_{23}^2 f_{32} & 0 & \delta m_{34}^2 f_{34} \\ -\delta m_{14}^2 f_{41} & -\delta m_{24}^2 f_{42} & -\delta m_{34}^2 f_{43} & 0 \end{pmatrix}. \tag{7}$$

The value of the mixing angle θ_{13} is constrained by the upper limit given by Ref. [29] so that $\tan\theta_{13} \leqslant 10^{-3}$. The solution in the basis of mass eigenstates is

$$f_{ii} = \frac{\text{const}}{1+e^{E_\nu/T-\eta}}$$
$$f_{ij} = \frac{\text{const}}{1+e^{E_\nu/T-\eta}}\exp\left[\imath\frac{\delta m_{ij}^2}{6\mu_P}\frac{T}{E_\nu}\left(\frac{1}{T^3}-\frac{1}{T_0^3}\right)\right], \tag{8}$$

where the normalization constants are fixed by the initial conditions ($T = T_0$). The formal solution for the occupation number in the flavor basis, for the light neutrino flavor in the normal mass hierarchy, is

$$f_l = \frac{1}{1+e^{E/T-\eta}}\left\{1+\cos^2\theta_{13}\cos^2\theta_{12}\frac{\sin^2 2\phi}{2}\right.$$
$$\left.\times\left[\cos\left(\frac{\delta m_{14}^2}{6\mu_P}\frac{T}{E}\left(\frac{1}{T^3}-\frac{1}{T_0^3}\right)\right)-1\right]\right\}, \tag{9}$$

and

$$f_l = \frac{1}{1+e^{E/T-\eta}}\left\{1+\sin^2\theta_{13}\frac{\sin^2 2\phi}{2}\right.$$
$$\left.\times\left[\cos\left(\frac{\delta m_{34}^2}{6\mu_P}\frac{T}{E}\left(\frac{1}{T^3}-\frac{1}{T_0^3}\right)\right)-1\right]\right\}, \tag{10}$$

in the inverse mass hierarchy.

In the above expressions, η is the ratio between the neutrino chemical potential and the temperature. This parameter depends on the adopted value of the leptonic number L [1,2]. Explicit expressions of η versus L can be found in Ref. [1]. In the present context we have taken η as an input for the calculations (see Sec. III).

III. DECAY RATES AND NEUTRON ABUNDANCE

In the following we shall outline the main steps of the calculation of neutron decay rates, for the electroweak processes $n + e^+ \to p + \overline{\nu}$ and $n + \nu \to p + e^-$. The starting point is the calculation of the reduced rates $\lambda_\pm$ [10],

$$\lambda(n+\nu\to p+e^-)$$
$$= \lambda_- = \lambda_0\int_0^\infty dp_\nu p_\nu E_\nu p_e E_e (1-f_e)\, f_l, \tag{11}$$

$$\lambda(n+e^+\to p+\overline{\nu})$$
$$= \lambda_+ = \lambda_0\int_0^\infty dp_e p_\nu E_\nu p_e E_e(1-f_l) f_e, \tag{12}$$

and the total neutron to proton decay rate,

$$\lambda_{np}(y) = \lambda_-(y)+\lambda_+(y) = 2\lambda_0\left[e^\eta\left(1-\alpha\frac{\sin^2 2\phi}{2}\right)+1\right]$$
$$\times\frac{\Delta m_{np}^5}{y^3}\left(1+\frac{6}{y}+\frac{12}{y^2}\right)+\lambda_0\alpha\Delta m_{np}^5\frac{\sin^2 2\phi}{2}e^\eta$$
$$\times\int_0^\infty dq q^2 (q+1)^2 e^{-qy} g(q,y), \tag{13}$$

at lowest order in the quantity e^η. For the sake of convenience we have introduced the more compact notation $f_l = (1 + e^{E_\nu/T-\eta})^{-1}\{1-\alpha\frac{\sin^2 2\phi}{2}+\frac{\sin^2 2\phi}{2}g(E_\nu,T)\}$, with $\alpha = c_{13}^2 c_{12}^2$ for the normal mass hierarchy and $\alpha = s_{13}^2$ for the inverse mass hierarchy, respectively. The function $g(E_\nu, T)$ is the factor that contains the temperature T and the energy E_ν in Eqs. (9) and (10), and the variable y is defined as $y = \frac{\Delta m_{np}}{T}$. The details of the calculations have been discussed elsewhere [30], for the case of two neutrino mass eigenstates. The final expression for the neutron to proton decay rate is obtained by fixing the normalization λ_0, of Eq. (13), from the neutron half-life

$$\frac{1}{\tau} = \frac{4\lambda_0\Delta m_{np}^5}{255}, \tag{14}$$

and the result is

$$\lambda_{np}(y) = \frac{255}{2\tau}\left[e^\eta\left(1-\alpha\frac{\sin^2 2\phi}{2}\right)+1\right]\left(\frac{1}{y^3}+\frac{6}{y^4}+\frac{12}{y^5}\right)$$
$$+\frac{255}{4\tau}\alpha\frac{\sin^2 2\phi}{2}e^\eta\int_0^\infty dq q^2 (q+1)^2 e^{-qy} g(q,y), \tag{15}$$

in units of s^{-1}. Following Ref. [10], the neutron abundance, until the freeze-out of weak interactions, is expressed in terms of the neutron to proton decay rate, λ_{np} of Eq. (15), as

$$X_{\text{neutrons}} = \int_0^\infty dw\, e^{w+\eta}\left(\frac{1}{1+e^{w+\eta}}\right)^2$$
$$\times e^{-(\mu_P\Delta m_{np}^2)^{-1}\int_w^\infty du u(1+e^{-u-\eta})\lambda_{np}(u)}. \tag{16}$$

The quantity X_{neutrons} is, therefore, a function of λ_{np} and, consequently, of the occupation factors f_l, which contain the information about the mixing between active and sterile neutrinos. The next step consists of the calculation of primordial nuclear abundances. The method to calculate the BBN abundances was presented in Ref. [11]. It is a semianalytic approach based on the balance between production and destruction of a given nuclear element, which requires the knowledge of X_{neutrons}. For details we refer the reader to Ref. [11].

The above-presented framework shows that the calculation of primordial abundances may indeed be taken as a tool to test leptonic mechanisms, like the mixing between sterile and active neutrinos, as it has been pointed out by Kishimoto, Fuller, and Smith [2].

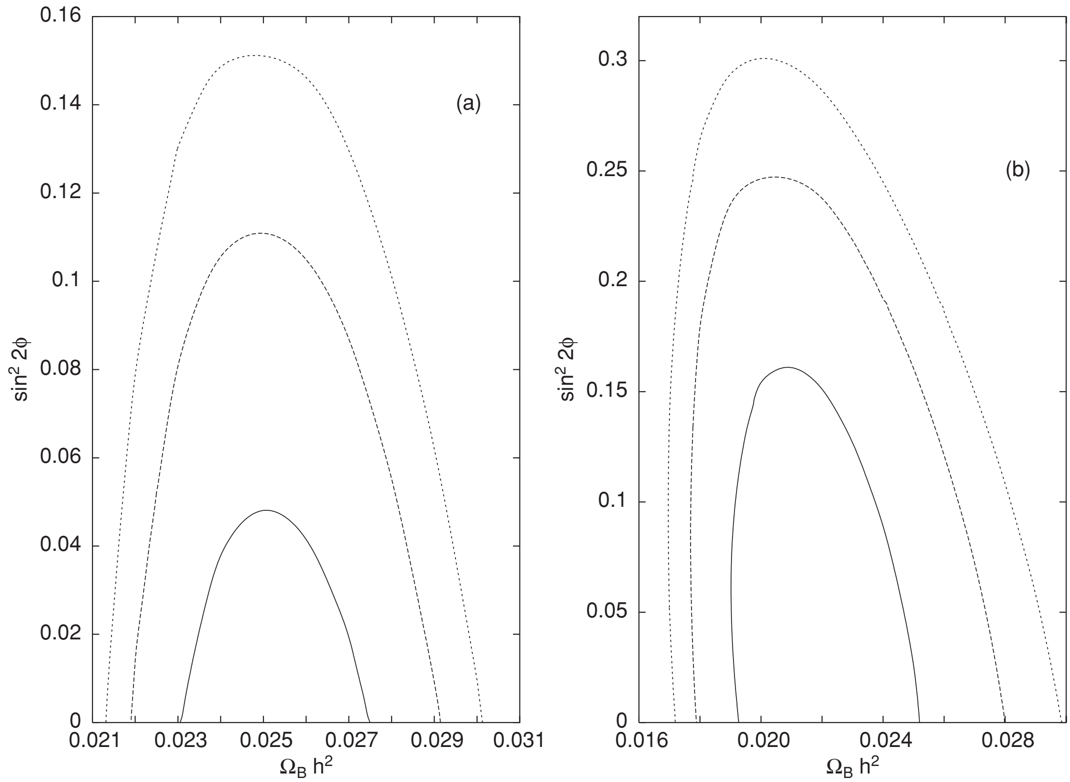

FIG. 1. Statistical analysis of the calculated nuclear abundances. The curves are the contour plots for results with comparable χ^2 values. The contours correspond to increasing values of χ^2, from bottom to top. The calculations were performed by taking the sterile-active neutrino mixing, $\sin^2 2\phi$, and the baryonic density, $\Omega_B h^2$, as variables. Figure 1(a) shows the results obtained by the χ^2 analysis of theoretical and experimental values, including data on ^{7}Li. Figure 1(b) shows the results of the statistical analysis performed with the exclusion of ^{7}Li. The results shown in the figure have been obtained with the solution corresponding to the normal mass hierarchy.

IV. RESULTS AND DISCUSSION

To perform the calculations we have adopted the oscillation parameters determined from Sudbury Neutrino Observatory (SNO), Super Kamiokande (SK), and CHOOZ measurements [29]. The mixing with the sterile neutrino, represented by the mixing angle ϕ, is taken as an unknown variable, within the limits fixed by the LSND data [22–24]. The mass splitting δm^2_{14} (or δm^2_{34}) was taken from the analysis given by Keränen *et al.* [9]. The actual value is fixed at $\delta m^2 = 10^{-11}$ eV^2. We have then calculated the neutron abundance, by applying the formalism of the previous section. The primordial abundances of D, ^{3}He, ^{4}He, and ^{7}Li have been calculated as described in Ref. [11]. The baryonic density $\Omega_B h^2$ (see Ref. [30]) was varied within the limits $0.010 < \Omega_B h^2 < 0.035$. Concerning the value of η we have varied it in the interval determined by the allowed values of the potential lepton number, $\mathcal{L} = 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}$, that is $0.0 \leqslant \mathcal{L} \leqslant 0.4$ [1,2]. In the present calculations we have adopted the values $0.0 \leqslant \eta \leqslant 0.07$, which are consistent with the densities $0.0 \leqslant L_{\nu_e} \leqslant 0.05$ [1].

To determine the allowed values of the mixing angle ϕ we have performed a χ^2 minimization, after computing the primordial abundances. The data have been taken from Refs. [19–21]. The results are shown in Figs. 1(a) and 1(b). The curves are the contour plots for results with comparable values of χ^2. Figure 1(a) shows the results obtained by the χ^2 analysis of theoretical and experimental values [19–21], including data on ^{7}Li. Figure 1(b) shows the results of the statistical analysis performed with the exclusion of ^{7}Li. In the first case, Fig. 1(a), the absolute minimum is located at $\sin^2 2\phi = 0.000 \pm 0.026$, and $\Omega_B h^2 = 0.0253 \pm 0.0015$; both sets of results have been obtained by using the solution (9) for the occupations. The smallness of the mixing angle does not contradict LSND results [22–24], but the value of the baryonic density is outside the limits determined by WMAP [25]; that is, $(\Omega_B h^2)_{\mathrm{WMAP}} = 0.0223 \pm 0.0008$. This disagreement between theory and data may be caused by large uncertainties in the ^{7}Li data. As pointed out by Richard *et al.* [31], the validity of the data on ^{7}Li may be questioned by the uncertainties inherent to the physics of ^{7}Li in the interior of the stars, i.e, the turbulent transport in the radiative zone of stars. In contrast, the situation improves if the data on ^{7}Li are removed at the time of performing the statistical analysis [Fig. 1(b)]. For this case, the best value of the mixing angle is $\sin^2 2\phi = 0.018 \pm 0.098$, and the baryonic density corresponding to the minimum, $\Omega_B h^2 = 0.0216 \pm 0.0017$, is indeed consistent with the WMAP data. The anomalous feature associated with the inclusion of ^{7}Li in the set of data persists if other elements are removed from the data. We have verified it by systematically removing, one at a time, the abundances of D, ^{3}He, and ^{4}He and keeping the data on ^{7}Li. In all cases the location of the minimum lies closer to the one of Fig. 1(a). For the case of inverse mass

TABLE I. Best values of the mixing angle and of the baryonic density, determined from the χ^2 analysis of the calculated abundances, as functions of the parameter η. Left and right sides of the table show the results obtained with and without considering the data on ^{7}Li, respectively.

η	All data		All data but ^{7}Li	
	$\Omega_B h^2$	$\sin^2 2\phi$	$\Omega_B h^2$	$\sin^2 2\phi$
0.00	0.0253 ± 0.0015	0.000 ± 0.026	0.0216 ± 0.0017	0.018 ± 0.098
0.01	0.0250 ± 0.0014	0.000 ± 0.010	0.0216 ± 0.0020	0.002 ± 0.022
0.02	0.0248 ± 0.0014	0.000 ± 0.015	0.0218 ± 0.0020	0.004 ± 0.030
0.03	0.0246 ± 0.0012	0.000 ± 0.034	0.0216 ± 0.0018	0.008 ± 0.080
0.04	0.0244 ± 0.0016	0.000 ± 0.039	0.0216 ± 0.0019	0.018 ± 0.090
0.05	0.0244 ± 0.0016	0.000 ± 0.056	0.0216 ± 0.0017	0.052 ± 0.090
0.06	0.0244 ± 0.0016	0.000 ± 0.101	0.0216 ± 0.0018	0.108 ± 0.090

hierarchy the occupation factor (10) is strongly constrained by the value of θ_{13} and the difference with respect to the thermal occupation factor vanishes. It means that the contour plot shows, for the inverse mass hierarchy, parallel lines to the vertical axis ($\sin^2 2\phi$), because all possible values of $\sin^2 2\phi$ are allowed by Eq. (10) when $\sin^2 \theta_{13} \to 0$. For both the normal and inverse hierarchy solutions, Eqs. (9) and (10), particle number conservation was enforced, on the average, by the factor μ_P [see its definition following Eq. (4)]. Because of the high temperature we have not included collision terms in Eq. (4).

Similar results, related to the abundance of ^{7}Li, have been obtained in the calculations of nuclear abundances in the context of cosmological models [32–34] and also in the case of a two neutrino mixing [30].

To investigate the dependence of the above results on the parameter η, we show in Fig. 2 the values of the mixing angle $\sin^2 2\phi$, obtained from the χ^2 analysis, as functions of the chemical potential. The calculations have been performed by excluding the data on ^{7}Li. Our present results are very much in agreement with the results reported in Ref. [10], because the values shown in Fig. 2 display a small variation in a relatively large domain of values of η.

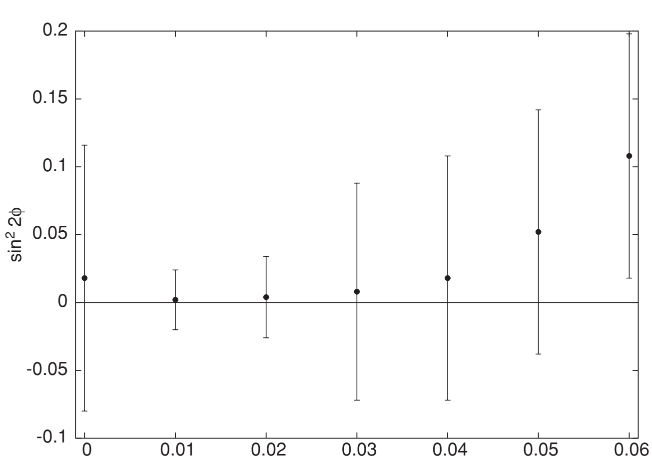

FIG. 2. Best values of the mixing angle, $\sin^2 2\phi$, determined from the χ^2 analysis of the calculated abundances, as functions of the parameter η.

Finally, the best values of the baryonic density and the mixing angle, both with and without including ^{7}Li in the analysis, are shown in Table I as functions of η. In agreement with the expectations of Ref. [10], and with our own, both sets of results do not differ much, or at least they do not show a pronounced dependence, with respect to the chemical potential.

V. CONCLUSIONS

In this work we have calculated BBN abundances by including the mixing between active and sterile neutrinos. As pointed out by Kishimoto, Fuller, and Smith [2], the BBN abundances are sensitive to active-sterile neutrino mixing. Indeed, Kishimoto, Fuller, and Smith [2] have demonstrated the sensitivity of the ^{4}He abundance on the distortion of the light neutrino spectrum produced by the mixing with a sterile neutrino. In our case, the statistical analysis of the compatibility between theoretical and observed nuclear abundances indicates the existence of a clear sensitivity of the results upon active-sterile neutrino mixing as well. In performing our analysis, we have considered the WMAP baryonic density together with the LSND constraint on the sterile-active neutrino mixing. The comparison between calculated and observed abundances indicates some sort of anomaly in the abundance of ^{7}Li. Similar difficulties, related to the determination of the abundance of ^{7}Li, have been reported previously [31] in the context of the physics of the interior of stars. We found that the consideration of the abundance of ^{7}Li, in the presence of active-sterile neutrino mixing, excludes the WMAP value of the baryonic density. This exclusion is not observed when the other nuclear abundances are not included in the analysis.

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