Addendum to "Update on neutrino mixing in the early universe"

P. Di Bari*
IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

(Received 25 February 2003; published 4 June 2003)

In the light of the recent WMAP results we update the constraints on a class of nonstandard big bang nucleosynthesis (BBN) models with a simultaneous combination of nonstandard neutrino distributions and an extra effective number of neutrinos in the expansion rate. These models can be described in terms of the two parameters $\Delta N_\nu^{\rm tot}$, constrained by the primordial helium abundance Y_p measurement, and ΔN_ν^ρ, constrained by a combination of cosmic microwave background and primordial deuterium data. Small deviations from standard big bang nucleosynthesis are suggested. Different nonstandard scenarios can be distinguished by a measurement of the difference $\Delta N_\nu^{f_\nu}=\Delta N_\nu^{\rm tot}-\Delta N_\nu^\rho$. From the current data we estimate $\Delta N_\nu^{f_\nu}\simeq-1.4^{+0.9}_{-1.4}$, mildly disfavoring solutions with a low expansion rate, characterized by $\Delta N_\nu^{f_\nu}=0$ and negative ΔN_ν^ρ. Active-sterile neutrino mixing could be a viable explanation only for high values of $Y_p\gtrsim0.24$. The existence of large positive neutrino chemical potentials $\xi_i\sim0.05$, implying $\Delta N_\nu^\rho\simeq0$, would be a possible explanation of the data within the analyzed class of nonstandard BBN models. Interestingly, it would also provide a way to evade the cosmological bounds for "class A 3+1" four neutrino mixing models. A scenario with a decaying sterile neutrino is also considered.

DOI: 10.1103/PhysRevD.67.127301 PACS number(s): 14.60.Pq, 98.80.Cq

I. INTRODUCTION

In a previous paper [1] (see also [2]) we showed how the new cosmic microwave background (CMB) measurements of the baryon to photon ratio, η, are able to put stringent constraints on a large class of nonstandard big bang nucleosynthesis (BBN) models where, together with the usual variation of the expansion rate due to the presence of extra degrees of freedom, distortions of the electron neutrino distribution are also present. This class of models can be described in terms of two parameters [3]. The first one is the usual extra effective number of neutrinos, modifying the standard expansion rate, $\Delta N_\nu^\rho=[\Sigma_X(\rho_X/\rho_0)-3]$, where ρ_X is the energy density of the X-particle species, including the three ordinary neutrinos plus possible new ones, and $\rho_0=(7\pi^2/120)T_\nu^4$ is the energy density of one standard neutrino species. The second one is the total extra effective number of neutrinos $\Delta N_\nu^{\rm tot}$ defined, in terms of the primordial ^{4}He abundance Y_p, as $\Delta N_\nu^{\rm tot}=[Y_p^{\rm BBN}(\eta,\Delta N_\nu^\rho,\delta f_{\nu_e})-Y_p^{\rm SBBN}]/0.0137$. The difference $\Delta N_\nu^{\rm tot}-\Delta N_\nu^\rho$ is a quantity that, in the class of models that we are considering, has to be entirely ascribed to the effect of deviations of the electron electron neutrino distribution from the standard Fermi-Dirac distribution with a zero chemical potential, $\delta f_{\nu_e}=f_{\nu_e}-f^0_{\nu_e}$. If $\delta f_{\nu_e}=0$ then $\Delta N_\nu^{\rm tot}=\Delta N_\nu^\rho$ and simply [4] $Y_p^{\rm BBN}(\eta,\Delta N_\nu^\rho,\delta f_{\nu_e}=0)\simeq Y_p^{\rm SBBN}(\eta)+\gamma(\eta)\Delta N_\nu^\rho$ with η the baryon to photon ratio in units of 10^{-10}. Using the expansion given in [4], we calculated that $\gamma(\eta)\simeq0.0137$ over the pertinent range $\eta=3.5$–10. The standard BBN prediction for Y_p is described by the following expansion around $\eta=5$ [4]: $Y_p^{\rm SBBN}\simeq0.2466+0.01\ln(\eta/5)$. The presence of a nonzero δf_{ν_e} affects mainly Y_p, while its effect can be safely neglected in the deuterium abundance (D/H), also considering that we will be interested in small deviations. With this approximation the D/H abundance is described by the expression [1]

$$({\rm D/H})^{\rm BBN}(\eta,\Delta N_\nu^\rho)\simeq[3.6\times10^{-5}(\eta/5)^{-\beta}](1+\alpha\Delta N_\nu^\rho)^{\beta/2}, \tag{1}$$

with $\beta\simeq1.6$ and $\alpha=(7r_{\nu0}^4/4g_{\rho0}^{\rm SBBN})\simeq0.135$, where $r_{\nu0}$ and $g_{\rho0}^{\rm SM}$ are, respectively, the standard neutrino to photon temperature ratio and the number of degrees of freedom at present. With these expressions a simultaneous measurement of (D/H), Y_p, and η can be easily translated into a "measurement" of $\Delta N_\nu^{\rm tot}$ and ΔN_ν^ρ. We used in [1] both high[1] [5]

$$Y_p^{\rm expt}=0.244\pm0.002 \tag{2}$$

and low [6] values $Y_p^{\rm expt}=0.234\pm0.003$, while we used $({\rm D/H})^{\rm expt}=(3.0\pm0.4)\times10^{-5}$ [7]. For η we used the DASI and BOOMerANG result [8] $\eta^{\rm CMB}=6.0^{+1.1}_{-0.8}$. From low values of helium and assuming Gaussian errors, we obtained $\Delta N_\nu^{\rm tot}=-1.05\pm0.25$, while from high values of helium we obtained $\Delta N_\nu^{\rm tot}=-0.3\pm0.2$. Using the primordial deuterium abundance measurement, from the expression (1), we could estimate ΔN_ν^ρ, obtaining $\Delta N_\nu^\rho=1\pm4$. These results imply at 3σ the bounds [1] $\Delta N_\nu^{\rm tot}<0.3$ and $\Delta N_\nu^\rho\lesssim13$. In particular, the bound on $\Delta N_\nu^{\rm tot}$ was used to conclude that, for negligible neutrino asymmetries, all four neutrino mixing models are in disagreement with cosmology and thus ruled out. This was then also confirmed by the improved solar and atmospheric neutrino data from the SNO [9] and SuperK [10] experiments [11]. In the next section we will update these results in light, mainly, of the recent results from the Wilkinson Microwave Anisotropy Probe (WMAP) experiment [12] and we will see how the data suggest possible deviations from a standard picture.

*Email address: dibari@ifae.es

[1]We indicate 68% C.L. errors for all quantities unless differently stated.

II. UPDATED REFERENCE VALUES AND RESULTS

The WMAP Collaboration finds $\Omega_b h^2 = 0.0224 \pm 0.0009$ [12], corresponding to $\eta^{\rm CMB} = 6.15 \pm 0.25$. This measurement is so precise that now, when estimating $\Delta N_\nu^{\rm tot}$, the experimental error on Y_p is dominant compared to the one on η. Using high values of $Y_p^{\rm expt}$ we find at 1σ: $\Delta N_\nu^{\rm tot} = -0.35 \pm 0.15$. This means that now a 3σ range is given by $-0.8 < \Delta N_\nu^{\rm tot} < 0.1$, implying a much more stringent upper bound compared to the pre-WMAP value. Even using the range of values

$$Y_p^{\rm expt} = 0.238 \pm 0.002 \pm 0.005, \tag{3}$$

which is a compromise between low and high values and takes into account the discrepancy as a systematic uncertainty [13], we find

$$\Delta N_\nu^{\rm tot} = -0.8 \pm 0.4, \tag{4}$$

implying a 3σ range $-2.0 < \Delta N_\nu^{\rm tot} < 0.4$. Both results confirm our previous conclusion that $\Delta N_\nu^{\rm tot}$ as high as 1 is highly disfavored, thus ruling out all four neutrino mixing models *in the case of negligible neutrino asymmetries* [1]. However, now both results seem to point, at 2σ, to a negative value of $\Delta N_\nu^{\rm tot}$, suggesting the presence of nonstandard BBN effects. We can also update the estimation of ΔN_ν^ρ using the new η measurement fom CMB and a new primordial deuterium abundance measurement [14], $({\rm D/H})^{\rm expt} = (2.78^{+0.44}_{-0.38}) \times 10^{-5}$, finding $(\Delta N_\nu^\rho)^{\rm BBN} = 0.7 \pm 2.1$. As already anticipated in [1], the error has been highly reduced by the great improvement in the η determination from CMB and it is now dominated by the error on D/H. However, unlike in the determination of $\Delta N_\nu^{\rm tot}$ from $Y_p^{\rm expt}$, better future determinations of η (for example from new WMAP data or from Planck) can still further reduce the error on $(\Delta N_\nu^\rho)^{\rm BBN}$ from the current 2.1 down to 1.5. It is interesting to note that the value from BBN is comparable to the direct determination from CMB. In [15], combining the WMAP data with the 2dF redshift survey and using the value on the Hubble constant from the Hubble Space Telescope (HST) Key Project, $h = 0.72 \pm 0.08$ [16], the authors find $(\Delta N_\nu^\rho)^{\rm CMB} = 0.5^{+1.8}_{-0.9}$. Assuming that, between the nucleosynthesis and the recombination time, the quantity ΔN_ν^ρ does not change[2] and thus that $(\Delta N_\nu^\rho)^{\rm BBN} = (\Delta N_\nu^\rho)^{\rm CMB}$, one can then combine the two values. We will still assume Gaussian errors for a qualitative estimation[3] and in this way we find a CMB-deuterium combined value

$$(\Delta N_\nu^\rho)^{\rm CMB+BBN} \simeq 0.6^{+1.4}_{-0.8}. \tag{5}$$

In this way we get a much more stringent 2σ (3σ) range: $-(1.8)\ 1.0 \lesssim \Delta N_\nu^\rho \lesssim 3.4\ (4.8)$.

[2]See [1] and [17] for discussions and examples in which $(\Delta N_\nu^\rho)^{\rm CMB} \neq (\Delta N_\nu^\rho)^{\rm BBN}$.

[3]From the likelihood distribution given in [15], this does not seem to be a very good approximation at values larger than the central one, while it is reasonably good for smaller values.

III. POSSIBLE SCENARIOS

These new results show that deviations from standard BBN, if they exist, are small. This means that standard BBN is in any case, in first approximation, a very good description of all data. This result is mainly due to the fact that the deuterium abundance is in very good agreement with the CMB prediction. At the same time, the measured primordial helium abundance Y_p suggests the possible presence of small deviations whose detection is now possible mainly due to the great precision of CMB in measuring the baryon asymmetry. However, for an assessment of such a hint, it will also be necessary to reduce the large systematic uncertainties on Y_p and it will also be necessary to investigate even more accurately the robustness of the η determination from CMB. In the following we will assume that such a hint is suggestive of nonstandard BBN effects and we will discuss some possible scenarios that could explain these deviations. An important role in our discussion is played by the quantity $\Delta N_\nu^{f_\nu} = \Delta N_\nu^{\rm tot} - \Delta N_\nu^\rho$. From Eqs. (5) and (4) we can estimate

$$\Delta N_\nu^{f_\nu} \simeq -1.4^{+0.9}_{-1.4}. \tag{6}$$

A. Low expansion rate. A minimal possible way to interpret the data is to assume that there is no effect due to electron neutrino distribution distortions and thus $\Delta N_\nu^{f_\nu} = 0$ or equivalently $\Delta N_\nu^{\rm tot} = \Delta N_\nu^\rho$. In this case one can combine the result (4) from Y_p and the result (5) from deuterium plus CMB, getting $\Delta N_\nu^\rho = -0.6^{+0.40}_{-0.35}$. This result would suggest a negative value of ΔN_ν^ρ, mainly due to the low value of Y_p, implying a highly nonstandard modification of the expansion rate during the BBN time, more precisely a lower expansion rate. Usually the presence of new particle species would lead to a higher expansion rate and therefore such a possibility must rely on some drastic change of the radiation dominated picture during the BBN period. However, note that, from Eq. (6), the measurements mildly favor a value $\Delta N_\nu^{f_\nu} \neq 0$ and so this scenario is mildly disfavored by the data (at almost 90% C.L.).

B. Degenerate BBN. A well known modification of the standard BBN is to introduce neutrino chemical potentials in the thermal distributions [20], corresponding to having preexisting neutrino asymmetries or asymmetries generated at temperatures $T \gtrsim 10$ MeV by some unspecified mechanism. An electron neutrino chemical potential $(\xi_e = \mu_e / T)$ would yield $\Delta N_\nu^{f_\nu} \simeq -16 \xi_e$. The observed Y_p [cf. Eq. (3)] would then be explained by having

$$\xi_e = 0.05 \pm 0.025. \tag{7}$$

It has been shown in [18], extending the results of [19], that the existing information on neutrino mixing makes it possible to conclude that before the onset of BBN arbitrary initial neutrino chemical potentials would be almost equilibrated in such a way that $\xi_\nu \simeq \xi_\tau \simeq \xi_e$. The presence of chemical potentials would thus correspond to $\Delta N_\nu^\rho \simeq 3[\frac{30}{7}(\xi_e/\pi)^2 + \frac{15}{7}(\xi_e/\pi)^4] \simeq 3 \times 10^{-3} \ll |\Delta N_\nu^{\rm tot}|$. Therefore in this scenario the expansion rate would be practically standard and the deviations would entirely arise from a non-standard electron neutrino distribution.

C. Active-sterile neutrino oscillations. Let us assume now that at temperature $T \gg 10$ MeV all neutrino asymmetries are negligible, for example, of the order of the baryon asymmetry. It has been shown in many papers [21] that a small mixing betwen active neutrinos and new light sterile neutrinos can generate ordinary neutrino asymmetries and thus negative values of $\Delta N_\nu^{f_\nu}$ together with $\Delta N_\nu^\rho \geqslant 0$. In a simplified two-neutrino mixing the value of $\Delta N_\nu^{f_\nu}$ is highly dependent on the value of the parameter $\Delta m_{is}^2 = m_s^2 - m_i^2$. Usually the possibility of introducing active-sterile neutrino oscillations was motivated by the Liquid Scintillator Neutrino Detector (LSND) anomaly [23]. However, an explanation of the LSND anomaly in terms of active-sterile neutrino oscillations compatible with the solar and atmospheric neutrino data would yield, as already mentioned, $\Delta N_\nu^{\rm tot} = \Delta N_\nu^\rho \sim 1$ [1] (see also [24]). At the same time the new WMAP bound on the neutrino masses, $m_i \leqslant 0.23$ eV [12], is now also incompatible with such an explanation of the LSND anomaly [25], except for one constrained exception [26]. The possibility of generating a negative $\Delta N_\nu^{\rm tot}$ requires a negative value of $\Delta m^2 = m_s^2 - m_i^2$ and very small mixing angles ($\sin^2 2\theta \ll 10^{-4}$ [21,1]). Values of $m_i \leqslant 0.23$ eV thus imply $|\Delta m_{is}^2| \leqslant 5 \times 10^{-2}$ eV^2. In [22] it was shown how such a maximum value, together with very small mixing angles, would produce $\Delta N_\nu^{f_\nu} \geqslant -0.3$. For an inverted full hierarchical case the corresponding $|\Delta m_{is}^2| \sim 10^{-2}$ eV^2 and in this case $\Delta N_\nu^{f_\nu} \sim -0.13$. These values have to be considered as maximal because in reality one should consider a full multiflavor mixing and, although full calculations are still missing, one can expect that part of the electron neutrino asymmetry is actually shared with the other two flavors. This means that a small effect could reconcile the observed η_B from CMB only with high values of Y_p [cf. Eq. (2)]. In two-neutrino mixing small positive values of ΔN_ν^ρ are also possible, for larger mixing angles, but this would be at the expense of $|\Delta N_\nu^{f_\nu}|$, making it even smaller [1]. Having more than one sterile neutrino flavor would make it possible to have $\Delta N_\nu^{f_\nu} \simeq -0.3$ and positive ΔN_ν^ρ, but in this case the total $\Delta N_\nu^{\rm tot}$ would be larger than -0.3. This possibility is interesting, however, since it would be a way to distinguish active-sterile neutrino oscillations from a degenerate BBN scenario. Another way would be the detection of the effects of a possible formation of neutrino domains [27], like inhomeogeneities in the primordial deuterium abundance [27] that would give rise to gravitational waves [28].

D. Degenerate BBN and "class A 3+1" models. This is an intriguing variation of the pure degenerate BBN scenario. Suppose there are both large chemical potentials and also a mixing of new sterile neutrino flavors with the ordinary ones. If the chemical potentials are of the order given by Eq. (7), then, even for maximal mixing, the sterile neutrino production prior to the onset of BBN would be suppressed [29] and consequently the final value of $\Delta N_\nu^{\rm tot}$ would be the same as in the degenerate BBN scenario, while ΔN_ν^ρ can be in principle slightly higher because of the initial sterile neutrino highly diluted abundance. In this way it is very interesting that, as already noted in [1], the cosmological bound on four-neutrino mixing models can be evaded. Moreover, this same conclusion applies also to the (current WMAP or *any future one*) bound on the sum of neutrino masses applied to the "class A 3+1" four-neutrino mixing models. They are such that the highest mass eigenstate almost coincides with a new sterile neutrino flavor and is separated from the three lighter ones, almost coinciding with the ordinary ones (see [1] for references and details), by the LSND gap. In this case the sterile neutrino contribution to the fraction Ω_ν/Ω_m would be negligible and the bound on the sum of neutrino masses would apply only to the three active mass eigenstates whose total mass is the same as in ordinary three-neutrino models. Note also that among four-neutrino mixing models these are the only ones to be still marginally consistent with neutrino mixing experiments [30].

E. Decaying sterile neutrino. CP symmetrical decays of a sterile neutrino with a mass $m_{\rm st} \gg m_i$ into an electron neutrino plus some unknown scalar, with a lifetime τ, could yield a positive ΔN_ν^ρ and at the same time a negative $\Delta N_\nu^{\rm tot}$ analogously to the decaying MeV-ν_τ mechanism of Hansen and Villante [31], but with some important differences. The sterile neutrino abundance produced before the quark-hadron phase transition, at temperatures $T \gg 100$ MeV, is necessarily highly diluted compared to that of ordinary neutrinos. This can be regenerated at a lower temperature ~ 15 MeV $(m_{\rm st}/{\rm eV})^{1/3}$, implying $m_{\rm st} \lesssim 1$ keV, by a possible neutrino mixing with ordinary states (see [1] for details and references). If the decay temperature $T(t=\tau)$ is approximately comprised in a window (0.5–5) MeV, elastic scatterings can partially or totally kinetically equilibrate the excess of electron neutrinos and antineutrinos produced but their total number cannot be totally destroyed by partially or completely frozen annihilation before the freezing of the neutron to proton ratio. This symmetric excess of electron neutrinos and antineutrinos would yield a negative $\Delta N_\nu^{\rm tot}$ that can agree with the value (4). Note that, since the decaying neutrinos are sterile, their decays would anyway occur *out of equilibrium* even though in the ultrarelativistic regime. An interesting possibility is the case that the sterile neutrino is the LSND neutrino of class A 3+1 models, with $m_{\rm st} \sim \sqrt{\Delta m_{\rm LSND}^2}$, as for the degenerate BBN scenario in Sec. III D. Now, however, $\Delta N_\nu^\rho \lesssim 1$, because the decays can only partly destroy what is generated by the mixing. This scenario clearly suffers from fine-tuning between the lifetime of sterile neutrinos and the time window between freezing of ν_e annihilations and of the neutron to proton ratio. A way to circumvent this problem is to allow decays to be CP asymmetric as a way to realize a sort of Fukugita-Yanagida leptogenesis at low temperatures. In this case it is enough that the lifetime is shorter than the n/p freezing time (~ 10 s). This case would be very similar to the scenario of Sec. III D but with $\Delta N_\nu^\rho \lesssim 1$, the exact value depending on the mixing and on the lifetime. Note that, as in Sec. III D, the cosmological bound on the sum of neutrino masses would also be evaded, as pointed out in [32].

IV. CONCLUSIONS

In future years a better understanding of systematic uncertainties in the measured Y_p could strengthen or disprove the hint of nonstandard BBN effects. At the same time, improved data from CMB experiments should both be able to measure ΔN_ν^ρ with a precision of ~ 0.1 [33,17] and make even more robust and precise the determination of η_B. If the primordial helium anomaly is confirmed, implying negative $\Delta N_\nu^{\rm tot} < 0$, then a key quantity in discriminating among different explanations is the difference $\Delta N_\nu^{\rm tot} - \Delta N_\nu^\rho$. If this proves to be nonzero and negative, then low expansion rate scenarios will be ruled out, as already mildly suggested from current data, and a scenario with large chemical potentials would be a possible explanation if at the same time $\Delta N_\nu^\rho \sim \mathcal{O}(10^{-3}\text{–}10^{-2})$ (maybe detectable in a very optimistic case [33]). In the case that $|\Delta N_\nu^{\rm tot}| < 0.3$, then active-sterile neutrino mixing can be a viable explanation too, and if this is also accompanied by a positive value of ΔN_ν^ρ, then it will actually be favored, since degenerate BBN would be ruled out. We also pointed out that the degenerate BBN scenario could receive support from neutrino mixing experiments. This is because large neutrino asymmetries would make "class A $3+1$" four-neutrino mixing models a viable cosmological solution without any limitation from the bound on the sum of the neutrino masses. In this case one should receive a confirmation of the LSND from the MiniBoone Collaboration [34] that would realize a nice consistency between current cosmological data (but we need a better understanding of primordial helium measurements) and neutrino mixing experiments. We would be left with the tough theoretical problem of understanding the origin of large neutrino asymmetries. Current knowledge excludes the nice possibility of active-sterile neutrino oscillations themselves, but maybe a further investigation could change such a conclusion, in particular considering that full multiflavor active-sterile neutrino mixing calculations are still missing and that the role of phases in three-neutrino mixing has never been studied [1]. One possibility is that the sterile neutrino decays generate the needed electron neutrino distortions. This case could explain the current central values of $\Delta N_\nu^{\rm tot}$ [cf. Eq. (4)] and ΔN_ν^ρ [cf. Eq. (5)], but only future more accurate determinations will allow one to distinguish among the different scenarios; first of all, between the standard scenario and possible nonstandard ones.

Note added. After we submitted this paper, the second version of [25] appeared with independent similar conclusions about the possible role of large neutrino asymmetries.

P.D.B. is supported by EU network "Supersymmetry and the Early Universe," HPRN-CT-2000-00152. He thanks F. Borzumati, E. Masso, A. Pomarol, and M. Quiros for their questions which stimulated the content of Sec. III D.

[1] P. Di Bari, Phys. Rev. D **65**, 043509 (2002).
[2] P. Di Bari, hep-ph/0111056.
[3] P. Di Bari and R. Foot, Phys. Rev. D **63**, 043008 (2001).
[4] R. E. Lopez and M. S. Turner, Phys. Rev. D **59**, 103502 (1999).
[5] Y. I. Izotov and T. X. Thuan, Astrophys. J. **500**, 188 (1998).
[6] K. A. Olive and G. Steigman, Astrophys. J., Suppl. Ser. **97**, 49 (1995).
[7] J. M. O'Meara *et al.*, Astrophys. J. **552**, 718 (2001).
[8] P. de Bernardis *et al.*, Nature (London) **404**, 955 (2000); S. Hanany *et al.*, Astrophys. J. Lett. **545**, L5 (2000); N. W. Halverson *et al.*, Astrophys. J. **568**, 38 (2002).
[9] SNO Collaboration, Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011302 (2002).
[10] Super-Kamiokande Collaboration, S. Fukuda *et al.*, Phys. Lett. B **539**, 179 (2002).
[11] M. Maltoni *et al.*, Nucl. Phys. **B643**, 321 (2002).
[12] C. L. Bennett *et al.*, astro-ph/0302207; D. N. Spergel *et al.*, astro-ph/0302209.
[13] B. D. Fields and K. A. Olive, Astrophys. J. **506**, 177 (1998).
[14] D. Kirkman *et al.*, astro-ph/0302006.
[15] P. Crotty, J. Lesgourgues, and S. Pastor, astro-ph/0302337.
[16] W. L. Freedman *et al.*, Astrophys. J. **553**, 47 (2001).
[17] R. Bowen *et al.*, Mon. Not. R. Astron. Soc. **334**, 760 (2002).
[18] A. D. Dolgov *et al.*, Nucl. Phys. **B632**, 363 (2002); K. N. Abazajian *et al.*, Phys. Rev. D **66**, 013008 (2002); Y. Y. Wong, *ibid.* **66**, 025015 (2002).
[19] C. Lunardini and A. Y. Smirnov, Phys. Rev. D **64**, 073006 (2001).
[20] R. V. Wagoner *et al.*, Astrophys. J. **148**, 3 (1967); H. Reeves, Phys. Rev. D **6**, 3363 (1972); A. Yahil and G. Beaudet, Astrophys. J. **206**, 26 (1976); G. Beaudet and P. Goret, Astron. Astrophys. **49**, 415 (1976); K. A. Olive *et al.*, Phys. Lett. B **265**, 239 (1991); H. Kang and G. Steigman, Nucl. Phys. **B372**, 494 (1992); T. Kajino and M. Orito, Nucl. Phys. **A629**, 538c (1998).
[21] R. Foot, M. J. Thomson, and R. R. Volkas, Phys. Rev. D **53**, 5349 (1996); R. Foot and R. R. Volkas, *ibid.* **55**, 5147 (1997); X. Shi, *ibid.* **54**, 2753 (1996); R. Foot and R. R. Volkas, *ibid.* **56**, 6653 (1997).
[22] R. Foot, Phys. Rev. D **61**, 023516 (2000).
[23] LSND Collaboration, A. Aguilar *et al.*, Phys. Rev. D **64**, 112007 (2001).
[24] K. N. Abazajian, Astropart. Phys. **19**, 303 (2003).
[25] A. Pierce and H. Murayama, hep-ph/0302131.
[26] C. Giunti, hep-ph/0302173.
[27] P. Di Bari, Phys. Lett. B **482**, 150 (2000).
[28] A. D. Dolgov and D. Grasso, Phys. Rev. Lett. **88**, 011301 (2002).
[29] R. Foot and R. R. Volkas, Phys. Rev. Lett. **75**, 4350 (1995).
[30] M. Maltoni *et al.*, Nucl. Phys. B (Proc. Suppl.) **114**, 203 (2003).
[31] S. H. Hansen and F. L. Villante, Phys. Lett. B **486**, 1 (2000).
[32] G. Bhattacharyya *et al.*, hep-ph/0302191v2.
[33] R. E. Lopez *et al.*, Phys. Rev. Lett. **82**, 3952 (1999).
[34] MiniBoone Collaboration, R. Stefanski, Nucl. Phys. B (Proc. Suppl.) **110**, 420 (2002).