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COSMOLOGICAL CONSTRAINTS ON NEUTRINO OSCILLATIONS FOR INITIALLY NON-ZERO STERILE STATE

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Abstract. We discuss cosmological constraints on neutrino active-sterile oscillations for the specific case when the sterile neurino is partially- filled initially. We provide numerical analysis of the BBN production of He-4, Y_p, in the presence of electron-to-sterile neutrino oscillations, effective after neutrino decoupling. We account for all known oscillations effects on cosmological nucleosyntesis. We obtain isohelium contours corresponding to different levels of He-4 overproduction, $\delta Y_p/Y_p$, for non-zero initial population of the sterile state δN_s. We present the cosmological constraints on oscillation parameters corresponding to $\delta N_s = 0.0$ and 0.5 and $\delta Y_p/Y_p = 3\%$ and 5%. The cosmological constraints for the cases $\delta N_s \leq 0.5$ are slightly strengthened in comparison to $\delta N_s = 0$ case.

1. INTRODUCTION

There are many different experiments indicating and/or confirming the existence of neutrino oscillations:

solar neutrino oscillations experiments: Homestake, Kamiokande, SuperKamioKa, Gallex, SAGE, SNO;

atmospheric neutrino oscillations experiments: SuperKamioKa, Makro, Soudan 2, IMB;

terrestrial neutrino oscillations experiments: LSND, KamLAND, K2K.

In the case of non-zero neutrino masses the mass eigenstates ν_i are distinct from the flavour ones ν_f:

$$\nu_i = U_{if}\nu_f, \qquad f = e, \mu, \tau \tag{1}$$

and transitions between neutrinos of different types, known as neutrino oscillations, take place.

Neutrino oscillations may influence the physical processes in the early Universe evolution, such as baryogenesis, leptogenesis, nucleosynthesis, etc. Vice versa, Big Bang Nucleosynthesis (BBN) explains successfully the data on the primordial abundances of D, He-3, He-4 and Li-7 and that is why it could be used as a probe for the physics of the early Universe and the neutrino oscillations, in particular.

The most stringent constraints on neutrino oscillations parameters were obtained from BBN considerations. In particular, LMA and LOW active-sterile solar oscillation solutions and atmospheric active-sterile solutions were excluded many years before the global analysis of experimental neutrino data pointed to the preference of flavour oscillations for solving these neutrino anomalies (for a review on these issues see Kirilova 2004). However, these constraints were obtained assuming zero sterile neutrino state population before neutrino oscillations epoch.

Here we discuss BBN constraints on neutrino oscillations parameters obtained in the more general case of sterile neutrino state initially partially occupied. This issue is interesting because sterile neutrinos ν_s may be present at the onset of BBN epoch — they may be produced in GUT models, in models with large extra dimensions, Manyfold Universe models, mirror matter models, or in $\nu_{\mu,\tau} \leftrightarrow \nu_s$ oscillations in 4-neutrino mixing schemes. Hence, the degree of population of ν_s may be different depending on the ν_s production model.

The general case of non-zero sterile neutrino population was discussed in ref. (see Kirilova, 2004b). The kinetic effect of oscillations was shown to be sensitive to the initial population of ν_s. Hence, it is desirable to generalize the cosmological constraints on neutrino oscillation parameters, as well.

2. PODUCTION OF PRIMORDIAL HELIUM-4 AND NEUTRINO OSCILLATIONS

2.1. PRIMORDIAL HE-4 - THEORY AND OBSERVATIONS

Y_p, predicted by BBN, is calculated with great precision (see e.g. Lopez and Turner, 1999; Esposito et al., 2000; Cyburt et al., 2003; Cuoco et al., 2003). The theoretical uncertainty is less than 0.1% ($|\delta Y_p| < 0.0002$) within a wide range of values of the baryon-to-photon ratio η. The predicted He-4 value is in relatively good agreement with the observational data for He-4 and is consistent with the abundances of the other light elements. Contemporary helium values, inferred from astrophysical observational data, are 0.238–0.245 (see Olive et al., 1997; Izotov and Thuan, 1998). Using η indicated either by D measurements or by CMB, taking the central Helium value of the 2 measurements 0.238 and assuming the systematic error of 0.005 the agreement between different helium measurements is at 2σ level and the uncertainty is only around 2%.

Measurements of primordial helium from CMB data are possible. Hopefully, future Planck CMB measurements will be capable of determining the helium mass fraction within $\delta Y \sim 0.01$ in a completely independent way (see Trotta and Hansen, 2003).

Thus ^{4}He is the most abundantly produced, most precisely measured and calculated element among the primordially formed elements, and therefore, it is the preferred one for obtaining limits on nonstandard physics.

Its primordial yield essentially depends on the freezing of the weak reactions governing the neutron to proton transitions. Their freeze-out occurs when in the process of expansion the weak processes rates become comparable to the expansion rate:

$$\Gamma_w \sim G_F^2 E_\nu^2 N_\nu \leq H(t) \sim \sqrt{g_{eff}}\, T^2 \tag{2}$$

So, the primordially produced mass fraction of He-4 $Y_p \sim 2(n/p)_f/(1+n/p)_f$ is a strong function of relativistic degrees of freedom at BBN epoch, which enter through H, and also depends on the electron neutrino characteristics, namely its energy spectrum, number densities and the neutrino-antineutrino asymmetry, entering through Γ_w.

2.2. OSCILLATIONS EFFECTS

Flavor neutrino oscillations effect BBN negligibly because the energy spectrum distributions of different flavor neutrinos are almost equal (see g.e. Dolgov, 1981).

Active-sterile oscillations effect (a) expansion rate through exciting additional neutrino types, and (b) the weak interactions rate due to shifting neutrino densities and energy spectrum from BBN equilibrium values, thus directly influencing the kinetics of nucleons during the weak freeze-out and correspondingly the primordial production of helium-4.

(a) Due to its strong dependence on g_{eff}, He-4 is known as the best speedometer and its abundance is used to constrain the number of the relativistic particles during BBN (see Shvartsman, 1969; Steigman et al., 1986), usually parameterized by δN_ν. As far as oscillations between active and sterile neutrinos can bring the initially empty (or partially filled) sterile state into equilibrium, they lead to an increase of the number of neutrino species in equilibrium N_ν during BBN. This speeds up the expansion of the universe, $H(t) \sim g_{eff}^{1/2}$, and causes earlier n/p-freezing, $T_f \sim (g_{eff})^{1/6}$, at times when neutrons were more abundant (see e.g. Dolgov, 1981) and an overproduction of helium-4. This effect gives up to 5% ^{4}He overproduction (if one additional neutrino type is brought into equilibrium by oscillations, $\delta N_s = 1$).

(b)The effect of oscillations may be much stronger than $\delta N_s = 1$ in case of oscillations effective after ν decoupling, proceeding between partially populated sterile neutrino state $0 \leq \delta N_s < 1$ and electron neutrino (see e.g. Kirilova, 1988; Kirilova and Chizhov, 1996; Chizhov and Kirilova, 1997; Kirilova, 2002). The non-equilibrium initial condition, for most of the oscillations parameters of the model, leads to considerable and continuous deviations from the equilibrium ν_e spectrum (spectrum distortion) because the oscillation rate depends on energy according to $\Gamma \sim \delta m^2/E$.

The distortion leads to both a depletion of the active neutrino number density and a decrease of the Γ_w. Thus it influences the nucleon kinetics, causing an earlier n/p-freezing and an overproduction of ^{4}He yield.

The spectrum distortion is the greatest, if the sterile state is empty at the start of oscillations, $\delta N_s = 0$. It decreases with the increase of the degree of population of the sterile state at the onset of oscillations (see Kirilova, 2004b) as illustrated in the following figures.

Besides this leading kinetic effect of oscillations there is known an additional subdominant effect, namely the production of neutrino-antineutrino asymmetry: Neutrino-antineutrino asymmetry may be generated during the resonant transfer of neu-

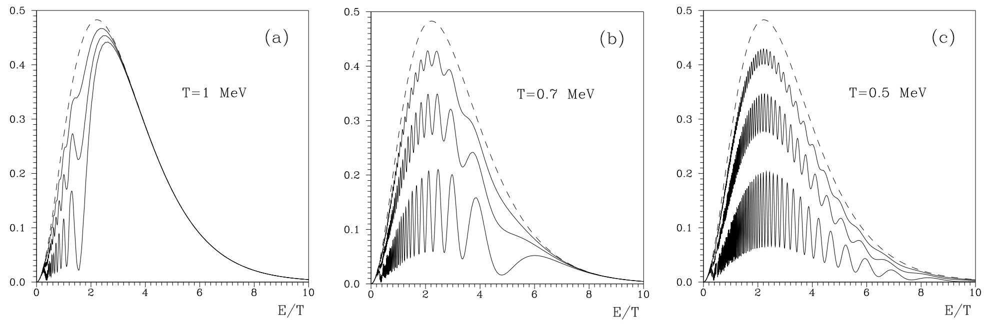

Figure 1: The figures illustrate the spectrum distortion at different degrees of population of the steriles, namely $\delta N_s = 0$ (lower curve), $\delta N_s = 0.5$ and $\delta N_s = 0.8$ (upper curve). The dashed curve gives the equilibrium spectrum for comparison. It is obvious that the distortion of the spectrum is considerable and with time, involves the whole neutrino ensemble.

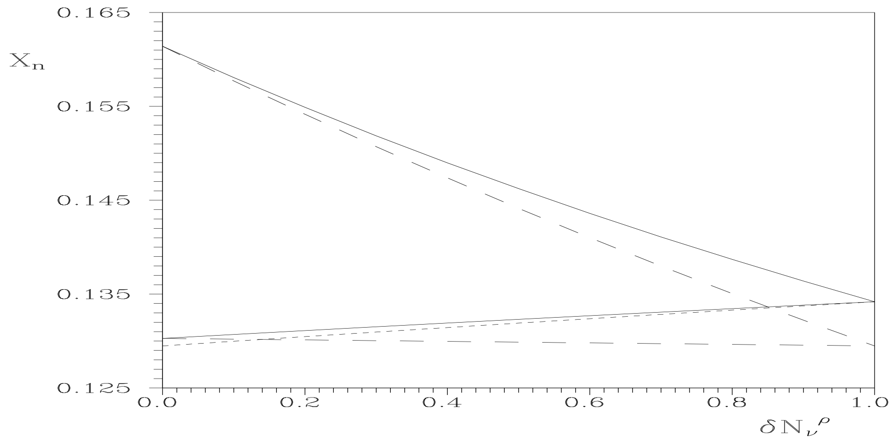

Figure 2: The solid curves show frozen neutron number density relative to nucleons $X_n^f = N_n^f/N_{nuc}$ as a function of the sterile neutrino initial population, at $\delta m = \pm 10^{-7}$ eV^2, $\sin^2 2\theta = 10^{-1}$. The dashed curves represent the kinetic effect, while the dotted curve shows the effect of energy density increase. The upper curves correspond to the resonant case and the lower the non-resonant one.

trinos (see e.g. Kirilova and Chizhov, 1996; Foot et al., 1996). This dynamically produced asymmetry suppresses oscillations at small mixing angles, leading to less overproduction of He-4 compared to the case without the account of asymmetry growth, and hence alleviating BBN constraints on oscillation parameters.

Non-zero initial sterile neutrino population influences neutrino effects on BBN -(i) it increases the expansion rate, (ii) in the $\nu_e \leftrightarrow \nu_s$ oscillations case, the presence of ν_s at the onset of oscillations influences the kinetic effects of $\nu_e \leftrightarrow \nu_s$ on BBN. Larger δN_s decreases the kinetic effects, because the element of initial non-equilibrium between the active and the sterile states is less expressed (see e.g. Kirilova, 2004). The dependence of the dynamical, kinetic and the total effect of on δN_s value is presented at Fig. 2.

Neutrino spectrum distortion effect is very strong even when there is a considerable population of the sterile neutrino state before the beginning of the electron–sterile oscillations. The kinetic effects are the strongest for $\delta N_s = 0$, they disappear for $\delta N_s = 1$, when ν_e and ν_s states are in equilibrium, and the total effect reduces to the SBBN with an additional neutrino

The cosmological constraints on oscillations parameters for the case of $\delta N_s \neq 0$ are changed.

3. COSMOLOGICAL CONSTRAINTS ON OSCILLATION PARMETERS

3.1. COSMOLOGICAL CONSTRAINTS ON OSCILLATION PARMETERS – $\delta N_S = 0$ CASE

Observational data on primordial ^{4}He abundance put stringent limits on the allowed oscillation parameters (see e.g. Barbieri and Dolgov, 1990; 1991).

In the discussed electron-sterile oscillation case the combined iso-helium contours for the nonresonant and the resonant case, for different levels of helium overproduction were calculated (see e.g. Chizhov and Kirilova, 1998; 2000; Kirilova and Chizhov; 2001), accounting for all oscillations effects on BBN. The dashed curves on the last figure present $\delta Y_p = (Y_{osc} - Y_p)/Y_p = 3\%, 5\%$ isohelium contours.

The analytical fits to the exact constraints are:

$$\delta m^2 (\sin^2 2\vartheta)^4 \leq 1.5 \times 10^{-9} \mathrm{eV}^2 \quad \delta m^2 > 0 \tag{3}$$

$$|\delta m^2| < 8.2 \times 10^{-10} \mathrm{eV}^2 \quad \delta m^2 < 0, \;\; large \;\; \vartheta, \tag{4}$$

The cosmological constraints exclude almost completely LOW solution to the solar neutrino problem, besides the LMA solution and sterile atmospheric solution, excluded in previous works. This result is consistent with the global analysis of the neutrino experiments data, which do not favour $\nu_e \leftrightarrow \nu_s$ solutions as dominant solutions.

3.2. COSMOLOGICAL CONSTRAINTS ON OSCILLATION PARMETERS – $\delta N_S \neq 0$ CASE

$\delta N_s \neq 0$ present before $\nu_{\mu,\tau} \leftrightarrow \nu_s$ just leads to an increase of the total energy density of the Universe, and it is straightforward to re-scale the existing constraints.

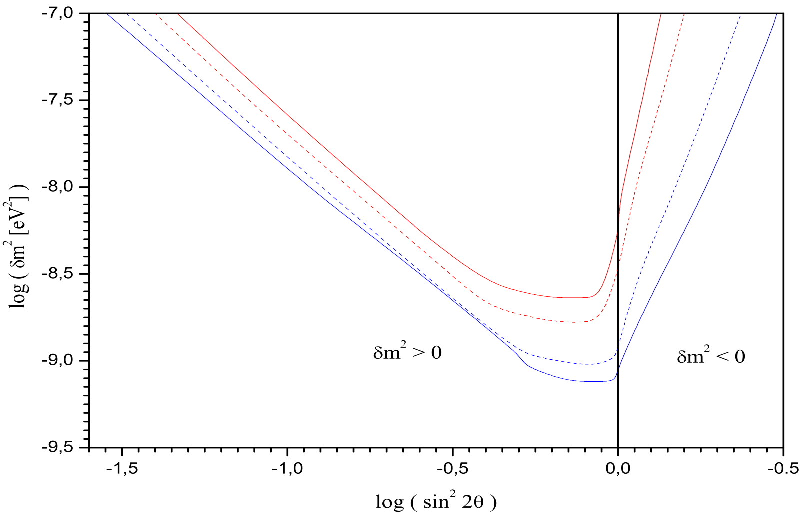

Figure 3: The dashed contours present BBN constraints for $\delta N_s = 0$, the solid — $\delta N_s = 0.5$ corresponding to $\delta Y_p/Y_p = 3\%$ (lower curves) and 5% (upper curves).

In the $\nu_e \leftrightarrow \nu_s$ oscillations case, however, the presence of ν_s at the onset of oscillations influences in addition the kinetic effects of $\nu_e \leftrightarrow \nu_s$ on BBN. Hence a precise study of the cosmological constraints for that case is needed.

We have calculated cosmological constraints corresponding to $\delta N_s = 0.5$ initial population of the sterile neutrino and for different levels of helium overproduction. As far as contemporary accuracy of helium observations allows at most 5% deviation from the standard BBN predicted value, we present the 5% isohelium contour as the maximum allowed one (see Kirilova and Panayotova, 2004).

Our numerical analysis has shown that up to $\delta N_s = 0.5$ the cosmological constraints corresponding to 3% and 5% He overproduction are slightly changed and remain stringent, as before (see e.g. Kirilova, 2004; Kirilova and Panayotova, 2004). Hence, even for partially filled sterile state the cosmological constraints give the most stringent limit on oscillation parameters.

The cosmological constraints in the case of non-empty initially sterile state exclude almost completely LOW solution to the solar neutrino problem as well as the LMA solution and sterile atmospheric solution. They are in agreement with the analysis of the experimental data from the solar and terrestrial neutrino oscillation experiments. However, the cosmological constraints are more restrictive by several orders of magnitude concerning the neutrino squared mass differences.

4. CONCLUSIONS

We have studied BBN constraints on neutrino active-sterile oscillations for the specific case when the sterile neurino is partially filled initially.

We have provided numerical analysis of the BBN production of He-4, Y_p, in the presence of electron-to-sterile neutrino oscillations, effective after neutrino decoupling, accounting for all known oscillations effects on cosmological nucleosyntesis.

We have obtained isohelium contours corresponding to different levels of He-4 overproduction, $\delta Y_p/Y_p$, for non-zero initial population of the sterile state δN_s.

We have calculated the cosmological constraints on oscillation parameters corresponding to $\delta N_s = 0.0$ and 0.5 and $\delta Y_p/Y_p = 3\%$ and 5%.

The cosmological constraints for the cases $\delta N_s \leq 0.5$ are slightly changed in comparison to $\delta N_s = 0$ case. I.e. even in case the sterile state was initially non-empty the cosmological constraints on oscillation parameters remain the most stringent ones.

The results are important for reveiling neutrino properties, and in particular, for defining the role of the sterile neutrino in resolving the solar and atmospheric neutrino anomalies.

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