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General BBN Bounds on Electron-Sterile Neutrino Oscillations

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Abstract. I discuss BBN with late electron-sterile neutrino oscillations, effective after electron neutrino freezing. The primordial production of ^{4}He in the presence of oscillations is numerically calculated for different initial population of the sterile neutrino $0 \leq \delta N_s < 1$. General BBN bounds on oscillation parameters are presented, corresponding to $\sim 5\%$ overproduction of the primordial ^{4}He and different initial population of the sterile neutrino, namely $\delta N_s = 0; 0.5; 0.7; 0.9$. The cosmological constraints corresponding to initially partially filled sterile state are relaxed, compared to the case of initially zero population of the sterile neutrino.

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1 Introduction

Electron-sterile neutrino oscillations $\nu_e \leftrightarrow \nu_s$, effective after neutrino decoupling, influence processes in the early universe and in particular, could lead to ^{4}He overproduction. Following this, we derive cosmological bounds on neutrino oscillations parameters investigating the general case of initially partially filled state of the sterile neutrino.

Some current findings make our work an issue of present interest. *First*: The recent measurements of primordial ^{4}He point to an effective number of neutrino flavours $N_{eff} = (3.68 - 3.80)^{+0.80}_{-0.70}$ [1]. The analysis of CMB data, derived from 7yr WMAP observations show $N_{eff} = 4.34^{+0.86}_{-0.88}$ at 68% CL [2]. Thus, the current data provide values for N_{eff}, which are higher than previously estimated and higher than the theoretically predicted by the standard model number of neutrino species $N_{eff} = 3.046$. *Second*: Solar, atmospheric and terrestrial neutrino oscillations experiments provide evidence for the existence of the neutrino oscillations. The neutrino oscillations data from LSND [3] and MiniBooNE [4] suggest existence of 1 or even 2 light sterile neutrinos, which participate into oscillations with the flavour neutrinos [5]. Also, the recent re-analysis of global

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short-baseline neutrino oscillation data points to the existence of two sterile neutrinos [6]. This can be an explanation of the cosmologically required additional relativistic density.

2 Recent Status of the Primordial ^{4}He Knowledge

Primordially produced ^{4}He is the preferred light element for obtaining limits on non-standard physics, because it is calculated and measured with remarkable precision. Some recent theoretical estimations of Y_p and determinations from astrophysical observations in metal poor HII regions are presented in Table 1.

Table 1. Recent observational estimations and theoretical predictions of primordial ^{4}He production

Y_p(theor)	References	Y_p(obs)	References
0.2486 ± 0.0002	[7]	0.2565 ± 0.0010(stat.) ± 0.0050(syst.)	[1]
0.2482 ± 0.0007	[8]	0.2561 ± 0.0108(stat. + syst.)	[10]
0.2479 ± 0.0002	[9]	0.2573 ± 0.0033(stat. + syst.)	[11]
		0.250 ± 0.003(stat. + syst.)	[12]

The data point to a higher central value of the observed Y_p compared to the theoretical predictions and only several percent uncertainty, which makes actual the consideration of ^{4}He overproduction $\delta Y_p/Y_p \geq 5\%$ due to $\nu_e \leftrightarrow \nu_s$ oscillations.

3 BBN and Electron-Sterile Neutrino Oscillations

3.1 Neutrino oscillations effects on primordial ^{4}He

From Standard BBN theory is known that the primordial ^{4}He abundance δY_p depends mainly on the neutron-to-proton ratio at freeze-out and neutron mean liftime τ_n, $Y_p \sim 2(n/p)_f/(1 + (n/p)_f) \exp(-t/\tau_n)$. The freeze-out occurs when the week processes rates Γ_ω become comparable to the expansion rate H(t): $\Gamma_\omega \sim G_F^2 E_\nu^2 N_\nu \leq H(t) \sim \sqrt{G_N g_{\text{eff}}} T^2$. Thus Y_p is a strong function of relativistic degrees of freedom g_{eff} at BBN epoch, entering through H(t), and neutrino energy spectrum, neutrino number densities and neutrino-antineutrino asymmetry, entering through Γ_ω.

Contrary to the flavour neutrino oscillations which effect BBN negligibly, active-sterile neutrino oscillations can exert strong effect on primordial ^{4}He production. As far as $\nu_e \leftrightarrow \nu_s$ neutrino oscillations can fill the initially empty or partially filled sterile state, $0 \leq \delta N_s < 1$, they lead to an increase of the effective number of neutrino species $N_{\text{eff}} = 3 + \delta N_s$ and the relativistic degrees of freedom during BBN $g_{\text{eff}} = 10.75 + 7/4\delta N_s$. This speeds up the expansion of the Universe,

$H(t) \sim g_{\rm eff}^{1/2}$, causes earlier n/p-freezing, at times when neutrons are more abundant and hence leads to overproduction of ^{4}He [13, 14]. This *dynamical effect* gives up to 5% ^{4}He overproduction when one additional neutrino type is brought into equilibrium by oscillations.

The *kinetic effect* of oscillations on BBN may be stronger in case of oscillations between ν_e and initially partially populated ν_s $(0 \leq \delta N_s < 1)$, effective after neutrino decoupling, which cause significant and continuous deviation from the equilibrium spectrum of ν_e [15] and growth of neutrino-antineutrino asymmetry [16]. The spectrum distortion affects nucleon kinetics and hence Γ_ω and causes overproduction of ^{4}He. The distortion is the greatest if $\delta N_s = 0$ (initially empty sterile state) at the start of oscillations and decreases with the increase of δN_s. Detailed analysis of the interplay of the effects is presented in [17, 18].

We perform numerical analisys to study $\nu_e \leftrightarrow \nu_s$ oscillations effects on Y_p described in [19]. We calculate neutrino evolution using a set of nonlinear integro-differential equations at each neutrino momentum, describing neutrino depletion, spectrum distortion and oscillations generated asymmetry effects and accounting for the contribution of them on neutrons to nucleons freezing ratio.

3.2 BBN bounds on oscillation parameters

In the following we discuss the case of $\nu_e \leftrightarrow \nu_s$ oscillations and different initial degrees of ν_s population, namely $\delta N_s = 0; 0.5; 0.7$ and 0.9. Accounting for all oscillations effects on BBN, we have calculated different iso-helium contours. Using ^{4}He contour corresponding to overproduction $\delta Y_p/Y_p = 5.2\%$ we have derived cosmological constraints on oscillations parameters δm^2 and $\sin^2 2\theta$ for the non-resonant $\delta m^2 < 0$ and resonant $\delta m^2 > 0$ cases.

Our numerical analysis has shown that BBN bounds, corresponding to more than 5% ^{4}He overproduction can be considerably relaxed for $\delta N_s > 0.5$ (see Figure 1). As it is expected, when $\delta N_s = 1$, the constraints alleviate, because the sterile state is initially full and the kinetic effect due to spectrum distortion disappears.

The analytical fits to the exact constraints for $\delta N_s = 0$ and $\delta Y_p/Y_p = 5.2\%$ are:

$$\delta m^2 (\sin^2 2\theta)^7 \leq 3.1 \times 10^{-9}\ \text{eV}^2 \quad \text{for} \quad \delta m^2 < 0$$

and

$$\mid \delta m^2 \mid < 1.7 \times 10^{-9} \qquad \text{for} \quad \delta m^2 > 0 \text{ and large } \theta.$$

These bounds are slightly relaxed compared to the bounds corresponding to 3% ^{4}He overproduction, derived in [17] and presented by the lowest curve in Figure 1.

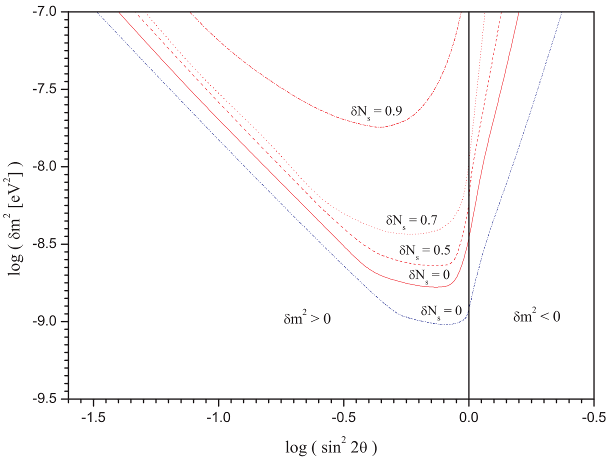

Figure 1. The resonant ($\delta m^2 > 0$) and non-resonant ($\delta m^2 < 0$) iso-helium contours for $\delta Y_p/Y_p = 5.2\%$ and $\delta N_s = 0$, $\delta N_s = 0.5$, $\delta N_s = 0.7$ and $\delta N_s = 0.9$ are presented. The case for $\delta Y_p/Y_p = 3\%$ and $\delta N_s = 0$ - the lowest curve is presented for comparison.

4 Summary and Conclusions

Here we have shortly reviewed the production of primordial ^{4}He in presence of $\nu_e \leftrightarrow \nu_s$ neutrino oscillations and their effects on BBN processes. Accounting for the neutrino oscillations effects, we have numerically calculated the BBN production of ^{4}He for $0 \leq \delta N_s < 1$ values. We have derived BBN bounds corresponding to iso-helium contour $\delta Y_p/Y_p = 5.2\%$ and $\delta N_s = 0, 0.5, 0.7$ and 0.9. Our analysis has shown that for 5.2% ^{4}He overproduction the cosmological constraints relax in comparison with 3% ^{4}He and with increasing δN_s. In case of $\delta Y_p/Y_p > 5\%$ the relaxation becomes significant for $\delta N_s \geq 0.5$.

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