CERN-TH/2002-217

Overproduction of primordial helium-4 in the presence of neutrino oscillations

D. P. Kirilova[1]

Theory Division, CERN, Geneva, Switzerland and
Institute of Astronomy, Bulgarian Academy of Sciences,
blvd. Tsarigradsko Shosse 72, Sofia, Bulgaria

Abstract

The maximum overproduction of helium-4 in cosmological nucleosynthesis with active–sterile neutrino oscillations, $\nu_e \leftrightarrow \nu_s$, efficient after decoupling of electron neutrino, is analyzed. The kinetic effects on primordial nucleosynthesis due to neutrino spectrum distortion, caused by oscillations, are precisely taken into account.
The maximum overproduction of primordial ^{4}He as a function of oscillation parameters is obtained from the analysis of the kinetics of the nucleons and the oscillating neutrinos, for the full range of parameters of the discussed oscillation model. A maximum relative increase of ^{4}He, up to 14% for non-resonant oscillations and up to 32% for resonant ones is registered. Cosmological constraints on oscillation parameters are also discussed.

[1]Regular Associate of the Abdus Salam ICTP, Trieste, Italy

1 Introduction

In this work I study the maximum overproduction of ^{4}He in Big Bang Nucleosynthesis (BBN) with electron–sterile neutrino oscillations $\nu_e \leftrightarrow \nu_s$.

The positive indications for oscillations, obtained by the neutrino experiments (SuperKamiokande, SNO, Soudan 2, LSND, etc.) turned the subject of neutrino oscillations into one of the hottest points of astrophysics and neutrino physics. The solar neutrino problem, the atmospheric neutrino anomaly and the positive results of LSND experiments may be naturally resolved by the phenomenon of neutrino oscillations, implying nonzero neutrino mass and mixing. Although sterile neutrino impact in oscillations explaining atmospheric and solar neutrino anomalies, is strongly constrained from the analysis of experimental oscillations data, still some small fraction of ν_s may participate in oscillations. Hence, it is interesting to study cosmological effects of such oscillations.

Cosmological nucleosynthesis with neutrino oscillations was studied in numerous publications, discussed in detail in [1, 2]. In these publications the central goal was to obtain cosmological constraints on oscillation parameters.

The overproduction of ^{4}He itself was not studied in detail until now. Such a study may be of interest for constructing of alternative cosmological models, for constraining galactic chemical evolution, it may be useful for non-standard models predicting active-sterile oscillations, like models with extra dimensions, mirror world particles, etc.

Here I address that question of the possible maximal overproduction of ^{4}He due to oscillations. For that purpose the case of $\nu_e \leftrightarrow \nu_s$, oscillations, effective after the electron neutrino decoupling from the plasma (i.e for $\delta m^2 \sin^2 2\vartheta \leq 10^{-7}\mathrm{eV}^2$), is the most suitable. In that case due to the fact that sterile neutrino state is usually less populated than the active one at the start of oscillations, the oscillations may cause strong distortion of the electron neutrino spectrum, which affects the kinetics of the nucleons freezing before nucleosynthesis, and hence, the primordial production of ^{4}He. And, as will be shown by the numerical analysis, this kinetic effect of oscillations, may be much bigger than the one corresponding to an increase in the total energy density due to an additional neutrino flavor δN_ρ, mainly considered in literature.

We analyze ^{4}He primordial production, taking into account all known effects of $\nu_e \leftrightarrow \nu_s$ oscillations on the primordial synthesis of ^{4}He. The production of ^{4}He was calculated in the non-resonant and resonant oscillation cases. In both cases strong overproduction of ^{4}He was found possible - up to 14% and 32%, correspondingly. Thus in the discussed model of non-equilibrium oscillations the maximum overproduction of ^{4}He corresponds to an increase of the neutrino effective degrees of freedom $\delta N_{kin}^{max} \sim 6$.

The oscillation effects on BBN and their description are briefly reviewed in the next section. The kinetic approach, the results on ^{4}He primordially produced abundance in the presence of oscillations, and the cosmological constraints on oscillation parameters are discussed in the last section.

2 Cosmological Nucleosynthesis with Neutrino Oscillations

2.1 Standard Cosmological Nucleosynthesis

According to the standard BBN, during the early hot and dense epoch of the Universe, the light elements D, ^{3}He, ^{4}He, ^{7}Li were synthesized successfully. The most reliable and abundant data are now available for ^{4}He. This fact and its relatively simple chemical evolution make ^{4}He the preferred element for the analysis of the oscillations effect on BBN.

The contemporary values for the mass fraction of ^{4}He, Y_p, inferred from observational data, are in the range 0.238–0.245 (the systematic errors are supposed to be around 0.007) [3].

Primordially produced ^{4}He abundance Y_p, is calculated with great precision within the standard BBN model [4]. According to the standard BBN ^{4}He is a result of a complex network of nuclear reactions, proceeding after the neutron-to-protons freezing. It essentially depends on the freezing ratio $(n/p)_f$. The latter is a result of the freezing of the weak processes:

$$\begin{aligned} \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \tilde{\nu}_e, \end{aligned} \qquad (1)$$

which maintained the equilibrium of nucleons at high temperature ($T > 1$ MeV). Their freeze-out occurred when in the process of Universe cooling the rates of these weak processes, Γ_w, became comparable and less than the expansion rate $H(t)$:

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

Thus, the produced ^{4}He is a strong function of the number of the effective degrees of freedom at BBN epoch, $g_{eff} = 10.75 + 7/4\delta N_\rho$.

Y_p depends also on the electron neutrino spectrum and number density, and on the neutrino-antineutrino asymmetry, which enter through Γ_w. In the standard BBN model three neutrino flavors, zero lepton asymmetry and equilibrium neutrino number densities and spectrum distribution are postulated:

$$n_{\nu_e}(E) = (1 + \exp(E/T))^{-1}.$$

Almost all neutrons, present at the beginning of nuclear reactions, are sucked into ^{4}He. So, the primordially produced mass fraction of ^{4}He can be approximated by

$$Y_p \sim 2(n/p)_f/(1 + n/p)_f \exp(-t/\tau_n).$$

where τ_n is the neutron mean lifetime.

The theoretical uncertainty of the precisely calculated Y_p is less than 0.1% ($|\delta Y_p| < 0.0002$) within a wide range of η. So, in the standard BBN scenario, where τ_n, and g_{eff} are fixed, Y_p, as well as the rest cosmologically produced light elements are functions of only one parameter - the baryon-to-photon ratio η.

Deuterium measurements in pristine environments towards low metallicity quasar absorption systems at very high $z \sim 3$ provide us with the most precision determination of the baryon density [5], giving the value: $\eta = (5.6 \pm 0.5) \times 10^{-10}$. Recently, the baryon density was also determined from observations of the anisotropy of the cosmic microwave background (CMB) by DASI [6], BOOMERANG [7, 8], CMB [9] and MAXIMA experiments [10]. For the combined analysis of the data see also [11, 12]. The CMB anisotropy data is in remarkable agreement with the baryon density determined from deuterium measurements and BBN.

So, the predicted primordial ^{4}He abundance Y_p is in accordance with the observational data and is consistent with deuterium measurements.

2.2 Effects of neutrino oscillations on nucleosynthesis

In case neutrino oscillations are present in the Universe primordial plasma, they lead to changes in the Big Bang Nucleosynthesis, depending on the oscillation channels and the way they proceed. The effect of flavor neutrino oscillations on BBN is negligibly small because the temperatures and hence, the densities of the neutrinos with different flavors are almost equal.

Active-sterile oscillations, however, are capable to shift neutrino number densities and spectrum from their equilibrium values. Besides, they may change neutrino-antineutrino asymmetry and excite additional neutrino types. Thus, the presence of neutrino oscillations invalidates the main BBN assumptions about three neutrino flavors, zero lepton asymmetry and equilibrium neutrino energy distribution.

Qualitatively, the oscillations effects on the nucleosynthesis of ^{4}He may be illustrated as follows:

- excitation of additional degrees of freedom

It is known that active-sterile oscillations may keep sterile neutrinos in thermal equilibrium [13] or bring them into equilibrium in case they have already decoupled. The presence of light steriles in equilibrium leads to an increase of the effective degrees of freedom during BBN and to faster Universe expansion $H(t) \sim g_{eff}^{1/2}$ and earlier n/p-freezing, $T_f \sim (g_{eff})^{1/6}$, at times when neutrons were more abundant [13, 14]:

$$n/p \sim \exp\left[-(m_n - m_p)/T_f\right]$$

This effect leads to 5% ^{4}He overproduction corresponding to one additional neutrino type brought into equilibrium by oscillations.

- distortion of the neutrino spectrum

Much stronger effect of oscillations may be achieved in case of oscillations between initially empty sterile neutrino state and electron neutrino. The non-equilibrium initial condition leads to spectrum distortion of the active neutrino due to oscillations.

Since oscillation rate is energy dependent $\Gamma \sim \delta m^2/E$ the low energy neutrinos start to oscillate first, and later the oscillations become noticeable for the more energetic neutrinos. Due to that, the neutrino energy spectrum $n_\nu(E)$ may strongly deviate from its equilibrium form [15]. This spectrum distortion affects the kinetics of nucleons freezing - it leads to an earlier n/p-freezing and an overproduction of ^{4}He yield.

The effect can be easily understood having in mind that the distortion leads both to a *depletion of the active neutrino number densities* N_ν [16]:

$$N_\nu \sim \int \mathrm{d}E E^2 n_\nu(E)$$

and to a *decrease of the mean neutrino energy*, which reflects into a decrease of the weak rates $\Gamma_w \sim E_\nu^2 N_\nu$, and hence, to an overproduction of ^{4}He primordial abundance.

The decrease of the electron neutrino energy due to oscillations into low temperature sterile neutrinos, has also an additional effect: Due to the threshold of the reaction converting protons into neutrons, when neutrinos have lower energy, protons are preferably produced in reactions (1), which may lead to an underproduction of ^{4}He [17]. However, this turns to be a minor effect.

The effect of spectrum distortion was numerically analyzed for hundreds combinations of mass differences and mixing angles in previous studies of active-sterile oscillations [15, 18, 19, 20]. It was proved important both in the resonant [19] and in the non-resonant oscillations case [20].

In the discussed here scenario it is the dominant effect and leads to overproduction of the primordial ^{4}He abundance.

- neutrino-antineutrino asymmetry growth

The idea of neutrino-antineutrino asymmetry generation during the resonant transfer of neutrinos was first proposed in ref. [21]. Dynamically produced asymmetry exerts back effect to oscillating neutrino and may change its oscillation pattern [22, 23], it may suppresses oscillations at small mixing angles, leading to weakening the oscillations effect on BBN, i.e. *less overproduction of* ^{4}*He.* [2]

The effect of the oscillations generated asymmetry on ^{4}He for the discussed here model was analyzed for hundreds of $\delta m^2 - \vartheta$ combinations in [19].

[2]There were independent studies of the asymmetry growth in active-sterile oscillations for the case of large mass differences along the lines of the pioneer work [24].

3 Helium-4 overproduction due to $\nu_e \leftrightarrow \nu_s$ neutrino oscillations

We have provided an exact study of all the oscillation effects on the primordial production of ^{4}He.

3.1 The required kinetic approach

For the analysis of the non-equilibrium picture of active–sterile neutrino oscillations, producing non-equilibrium neutrino number densities, distorting neutrino spectrum and generating neutrino-antineutrino asymmetry a self-consistent numerical analysis of the evolution of the nucleons and the oscillating neutrinos in the high temperature Universe was provided.

Exact kinetic equations for the nucleons and for the neutrino density matrix *in momentum space* [18] were used. This allowed to describe precisely the kinetic effects of oscillations on helium production due to spectrum distortion *at each neutrino momentum.*

The equation for the neutron number densities in momentum space n_n reads:

$$\begin{aligned}
&(\partial n_n/\partial t) = H p_n \ (\partial n_n/\partial p_n) + \\
&+ \int \mathrm{d}\Omega(e^-,p,\nu)|\mathcal{A}(e^- p \to \nu n)|^2 \left[n_{e^-} n_p (1-\rho_{LL}) - \right. \\
&\left. - n_n \rho_{LL} (1-n_{e^-})\right] \\
&- \int \mathrm{d}\Omega(e^+,p,\tilde{\nu})|\mathcal{A}(e^+ n \to p\tilde{\nu})|^2 \left[n_{e^+} n_n (1-\bar{\rho}_{LL}) - \right. \\
&\left. - n_p \bar{\rho}_{LL} (1-n_{e^+})\right]. \qquad (2)
\end{aligned}$$

where $\mathrm{d}\Omega(i,j,k)$ is a phase space factor and $\mathcal{A}$ is the amplitude of the corresponding process, neutrino ρ_{LL} and antineutrino number densities $\bar{\rho}_{LL}$ at each integration step of eq. (2) are taken from the simultaneously performed integration of the set of equations for neutrino density matrix (see ref. [18]).

The equation provides a simultaneous account of the different competing processes, namely: neutrino oscillations (entering through ρ_{LL} and $\bar{\rho}_{LL}$), Hubble expansion (first term) and weak interaction processes (next terms).

The numerical analysis was performed for the temperature interval [2 MeV, 0.3 MeV].

We have found that for a wide range of oscillation parameters the spectrum distortion of electron neutrino is considerable during the period of nucleons freezing. Hence, usually the kinetic effect of oscillations due to electron neutrino energy spectrum distortion plays the dominant role in the overproduction of helium. In Fig. 1 the evolution of the energy spectrum of the electron neutrino through the period of nucleons freezing is illustrated. In the Figs.1a,1b and 1c the energy spectra at different characteristic temperatures, correspondingly $T = 1$ MeV, $T = 0.7$ MeV and $T = 0.5$ are presented. By the dashed curve the equilibrium spectrum at the given temperature is given for comparison. The spectra are calculated for oscillation parameters $\delta m^2 = 10^{-7}$ eV^2 and $\sin^2 2\vartheta = 0.1$.

It is seen that oscillations affect non trivially the neutrino spectrum and distort strongly its equilibrium form. So, it is not possible to describe correctly the spectrum distortion due to oscillations simply by shifting the effective temperature of the neutrino and accounting only for the depletion of its total number density, considering its spectrum equilibrium as in refs. [26, 27].

For the proper description of the spectrum distortion in the case of non-equilibrium electron-sterile oscillations, studied here, the evolution of the neutrino ensembles should be explored using neutrino density matrix in momentum space, allowing to describe the evolution of neutrino at each momentum.

The neutrino-antineutrino asymmetry in the resonant case grows up to 5 orders of magnitude from its initial value (taken to be of the order of the baryon asymmetry). So, this asymmetry influences BBN only indirectly - through oscillations. This oscillations generated asymmetry leads to a decrease in the produced ^{4}He compared with the case without asymmetry account. However, its effect comprises only up to about a 10% of the total effect.

3.2 Maximum helium-4 overproduction

The overproduction of the primordial ^{4}He, $\delta Y_p = Y_p^{osc} - Y_p$ in the presence of $\nu_e \leftrightarrow \nu_s$ oscillations was calculated for mass differences $\delta m^2 \leq 10^{-7}$ eV^2 and $0 \leq \vartheta \leq \pi/4$. Several hundreds of $\delta m^2 - \vartheta$ combinations were explored.

We have used the data from the precise calculations of the n/p-freezing provided for the non-resonant case in [20] and for the resonant case in [19]. As far as it is the essential for the production of ^{4}He. The neutron decay was accounted adiabatically till the beginning of nuclear reactions at about 0.09 MeV.

We have found that the effect of oscillations becomes very small (less than 1%) for small mixings: as small as $sin^2 2\vartheta = 0.1$ for $\delta m^2 = 10^{-7}$ eV^2, and for small mass differences: $\delta m^2 < 10^{-10}$ eV^2 at maximal mixing. For very small mass differences $\delta m^2 \leq 10^{-11}$ eV^2, or at very small mixing angles $\sin^2 2\vartheta \leq 10^{-3}$, the effect on nucleosynthesis becomes negligible.

In the non-resonant case the oscillation effect increases with the increase of the oscillation parameters, hence it is maximal at maximal mixing and greatest mass differences. In Fig. 2 (the lower curve) the maximal relative increase in the primordial ^{4}He as a function of neutrino mass differences at maximal mixing: $\delta Y_p^{max}/Y_p = \delta Y_p^{osc}/Y_p(\delta m^2)_{|\theta=\pi/4}$ is presented.

It is seen that for maximal mixing, the oscillation effect becomes greater than 5% (the one corresponding to one additional neutrino type) already at $|\delta m^2| \geq 3 \times 10^{-9}$ eV^2 (in the resonant case) and $\delta m^2 \geq 6 \times 10^{-9}$ eV^2 (in the non-resonant one). It continues to grow up with the increase of the mass differences, and at $|\delta m^2| \sim 10^{-7}$ eV^2 is several times bigger: $\delta N_{kin}^{max} \sim 3$ in the non-resonant case and $\delta N_{kin}^{max} \sim 6$ for the resonant one.

Further increase of the mass differences, however, will lead to oscillations effective before electron neutrino decoupling, and therefore, to a smaller spectrum distortion effect, because the interactions with the plasma will lead to faster thermalization of the sterile state. Hence, the effect on helium will decrease with further increase of $|\delta m^2|$ and finally reach an overproduction of 5% again, corresponding to a full thermalization of the sterile state and its equilibrium spectrum.

In Fig. 3 we present a combined plot (for the resonant and the non-resonant oscillation case) of δY_p dependence on the mixing angle for $\delta m^2 = 10^{-7}$ eV^2 and $\delta m^2 = 10^{-8}$ eV^2. While in the non-resonant case the oscillations effect increases with the increase of the mixing (see l.h.s of Fig.3.), in the resonant case for a given δm^2 there exists some resonant mixing angle, at which the oscillations are enhanced by the medium (due to the MSW effect), and hence, the overproduction of ^{4}He is greater than that corresponding to the vacuum maximal mixing angle. This behavior of the helium production on the mixing angle is illustrated in the r.h.s. of the figure.

The upper curve in Fig.2 shows the maximal relative increase in the resonant oscillations case as a function of mass differences. Each maximum ^{4}He value corresponds to the resonant mixing angle for the concrete mass difference: $\delta Y_p^{max}/Y_p = Y_p^{osc}(\delta m^2, \vartheta_{\delta m}^{res})$. As can be seen from Figs. 2 and 3, a considerable overproduction can be achieved: in the resonant case up to 32% and in the non-resonant one – up to 14%. So, the net effect of spectrum distortion of electron neutrino due to oscillations on the production of ^{4}He may be considerable and several times larger than the effect due to excitation of one additional neutrino type.

Several words are due to cosmological constraints on neutrino oscillation parameters, calculated in the discussed model of oscillations. Due to the strong kinetic effect of neutrino spectrum distortion caused by active-sterile oscillations discussed, the obtained constraints in that model of oscillations are more stringent than those obtained in pioneer works, not accounting for the kinetic effects of oscillations. Hence, according to these more precise studies of spectrum distortion effects of oscillations, the $\delta Y_p/Y_p < 3\%$ limit excludes almost completely the LOW electron-sterile solution to the solar neutrino problem [25], in addition to the excluded sterile LMA solution in previous investigations. I.e. it is more than an order of magnitude more restrictive to the mass differences.

This study has shown that considerable Y_p overproduction may result from the electron neutrino spectrum distortion due to $\nu_e \leftrightarrow \nu_s$ oscillations. The overproduction is maximal for the case of initially empty sterile neutrino state, considered here. The dependence of ^{4}He overproduction on the degree of population of the sterile neutrino state before $\nu_e \leftrightarrow \nu_s$ oscillations is considered in a separate paper [28]. Bigger initial population of ν_s leads to a smaller spectrum distortion of ν_e, and hence smaller kinetic effect on primordial nucleosynthesis δN_{kin} and higher energy density due to the increase of the number of degrees of freedom δN_ρ. The interplay between the two effects, however, is such that the overproduction of ^{4}He is smaller than in the case when initially $\delta N_\rho = 0$, discussed here.

4 Conclusions

The primordial production of ^{4}He in the presence of $\nu_e \leftrightarrow \nu_s$ oscillations, effective after electron neutrino decoupling was analyzed. A precise quantitative study of the maximum overproduction of ^{4}He, accounting for all oscillations effects is provided. It was shown that the considerable spectrum distortion of the electron neutrino caused by oscillations, which effects the kinetics of the neutron-proton transitions during nucleons freezing, plays the dominant role in the overproduction of ^{4}He.

Enormous overproduction of ^{4}He (up to 32% in the resonant case and 14% in the non-resonant case) was found possible in case the sterile neutrino state was empty at the start of oscillations.

The results of this analysis can be useful for constraining nonstandard physics, predicting active-sterile neutrino oscillations, like extra-dimensions, producing oscillations, supernova bursts employing oscillations, etc.. It can be of interest also for models of galactic chemical evolution.

Acknowledgments

I thank M. V. Chizhov for the help during the preparation of this paper. This work has been completed during my visiting position at TH CERN. I appreciate also the Regular Associateship at the Abdus Salam ICTP, Trieste.

References

[1] Kirilova, D. P., and Chizhov, M. V., 2001, CERN-TH/2001-020, astro-ph/0108341

[2] Dolgov A., hep-ph/0202122.

[3] Izotov, Y. I., and Thuan, T. X., Ap. J. 500 (1998) 188.

[4] Lopez, R., and Turner, M. S., Phys. Rev. D 59 (1999) 103502.

[5] Meara J. et al., Ap.J. 552 (2001) 718.

[6] Pryke S. et al., ApJ 5681 (2002) 46.

[7] Netterfield C. et al., ApJ 571 (2002) 604.

[8] Bernardis P. et al., ApJ 564 (2002) 559.

[9] Padin S. et al., ApJ Letters 549 (2001) L1.

[10] Stompor B. et al., ApJ 561 (2001) L7.

[11] Wang X., Tegmark M., Zaldarriaga M., Phys.Rev. D65 (2002) 123001

[12] Douspis M. et al., Astr.Astrop. 379 (2001) 1.

[13] Dolgov, A. D., Sov. J. Nucl. Phys. 33 (1981) 700.

[14] Fargion, D., and Shepkin, M., Phys. Lett. B 146 (1984) 46.

[15] Kirilova, D. P., 1988, JINR E2-88-301, Dubna, Russia.

[16] Barbieri, R., and Dolgov, A., Phys. Lett. B 237 (1990) 440.

[17] Dolgov A.,Kirilova D., Int.J.Mod.Phys.A3 (1988) 267.

[18] Kirilova, D. P., and Chizhov, M. V., Phys. Lett. B 393 (1997) 375.

[19] Kirilova, D. P., and Chizhov, M. V., Nucl. Phys. B 591 (2000) 457.

[20] Kirilova, D. P., and Chizhov, M. V., Phys. Rev. D 58 (1998) 073004.

[21] Mikheyev, S., and Smirnov, A., 1986, in VI Moriond Meeting on Massive Neutrinos in Particle Physics and Astrophysics, eds. O. Fackler and J. Tran Thanh Van, Editions Frontiers, Tignes, p. 355.

[22] Kirilova, D., and Chizhov, M.,1996, in 17 International Conference on Neutrino Physics and Astrophysics, NEUTRINO 96, eds. K. Enqvist, K. Huitu, and J. Maalampi, World Scientific, Helsinki, p. 478.

[23] Kirilova, D. P., and Chizhov, M. V., 1999, hep-ph/9908525.

[24] R. Foot, M. J. Thomson and R. R. Volkas, Phys. Rev. D 53 (1996) R5349

[25] Kirilova, D. P., and Chizhov, M. V., Nucl. Phys. B Proc. Suppl. 100 (2001) 360.

[26] Shi X., Schramm D. N., and Fields B. D., *Phys. Rev.* **D 48**, 2563 (1993).

[27] Shi X., and Fuller G. M., *Phys. Rev.* **D 59**, 063006 (1999).

[28] Kirilova D., CERN-TH-2002-209

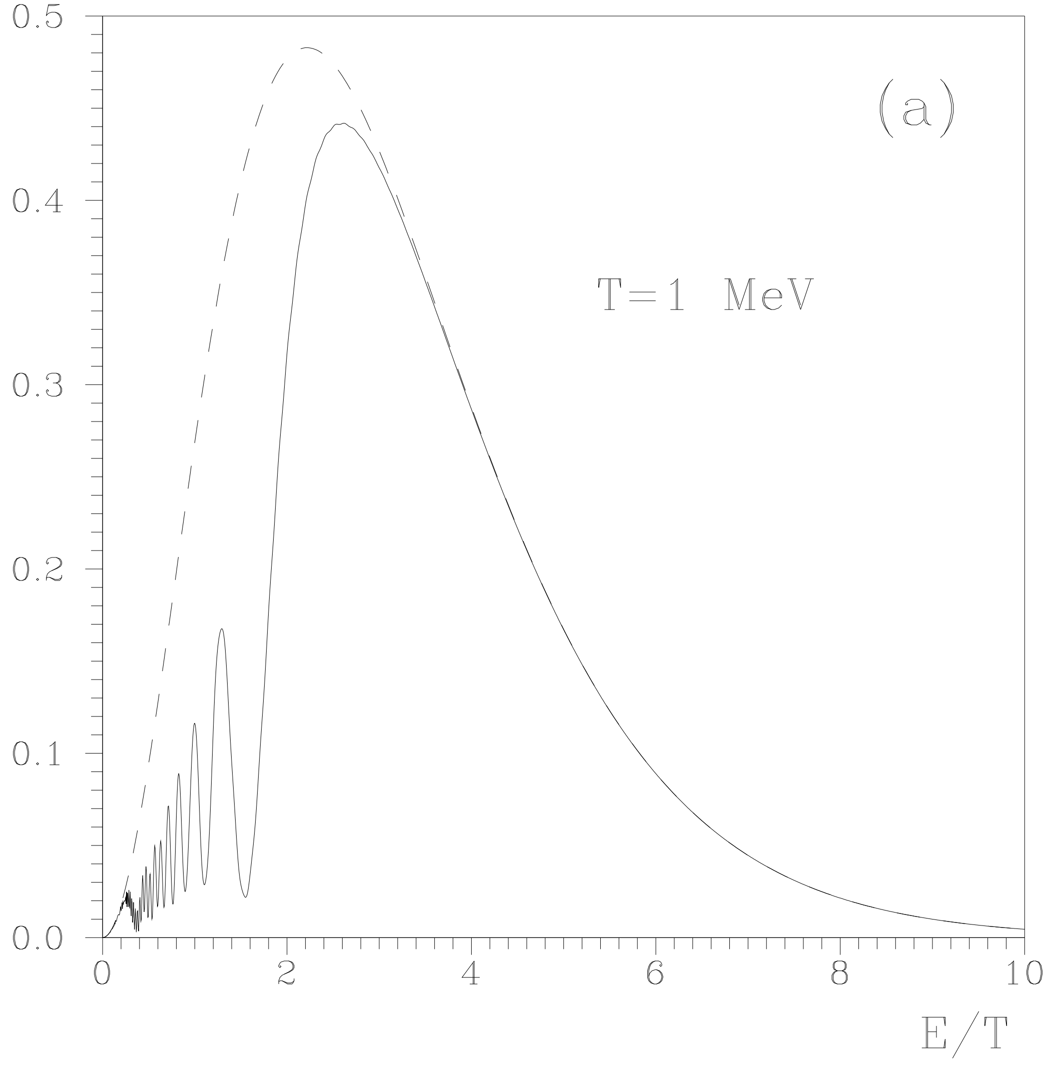

Figure 1a: The figure illustrates the degree of distortion of the electron neutrino energy spectrum $x^2\rho_{LL}(x)$, where $x = E/T$, caused by oscillations with mass difference $|\delta m^2| = 10^{-7}$ eV^2 and $\sin^2 2\vartheta = 0.1$ at a characteristic temperature 1 MeV. The dashed curve gives the equilibrium neutrino spectrum for comparison.

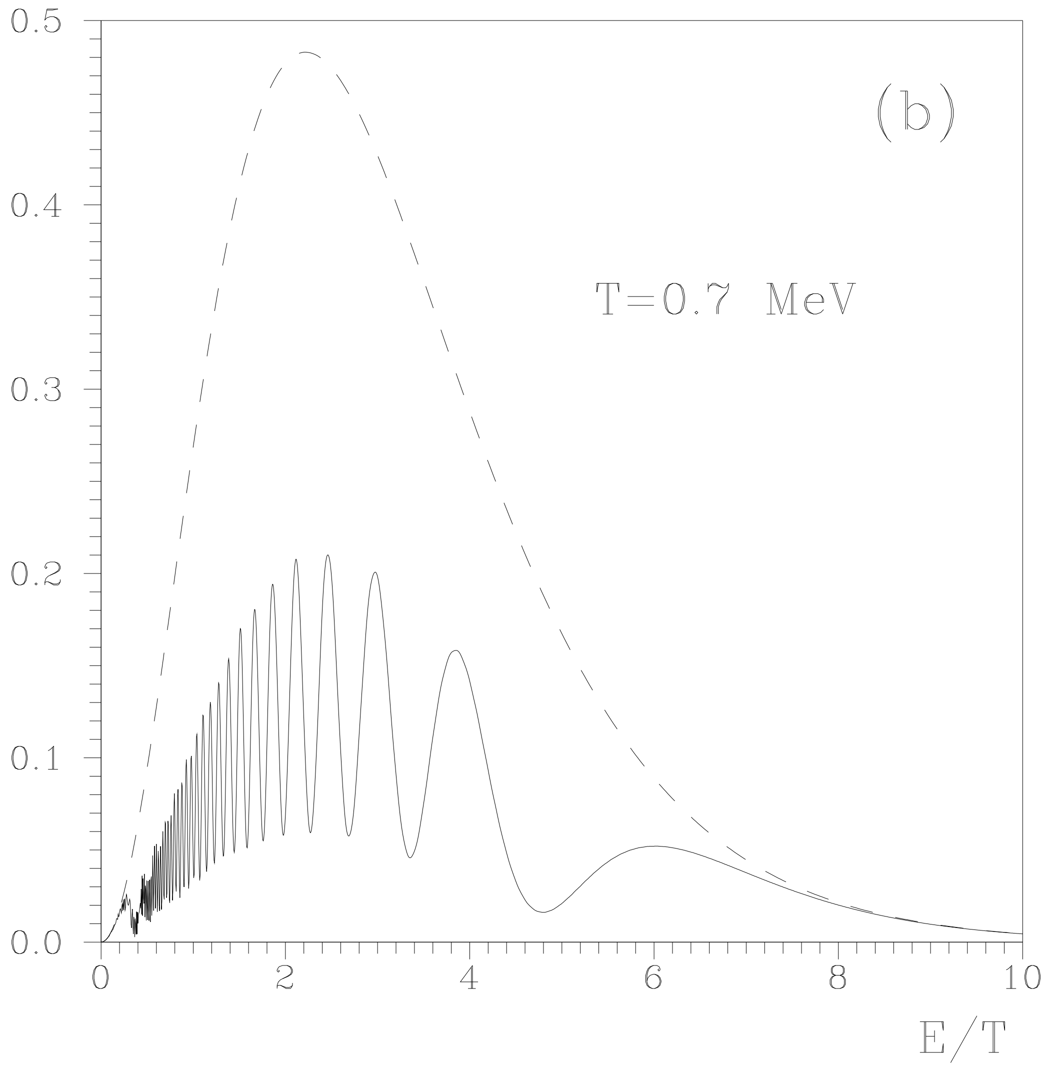

Figure 1b: The figure illustrates the degree of distortion of the electron neutrino energy spectrum $x^2\rho_{LL}(x)$, where $x = E/T$, caused by oscillations with mass difference $|\delta m^2| = 10^{-7}$ eV^2 and $\sin^2 2\vartheta = 0.1$ at a characteristic temperature 0.7 MeV.

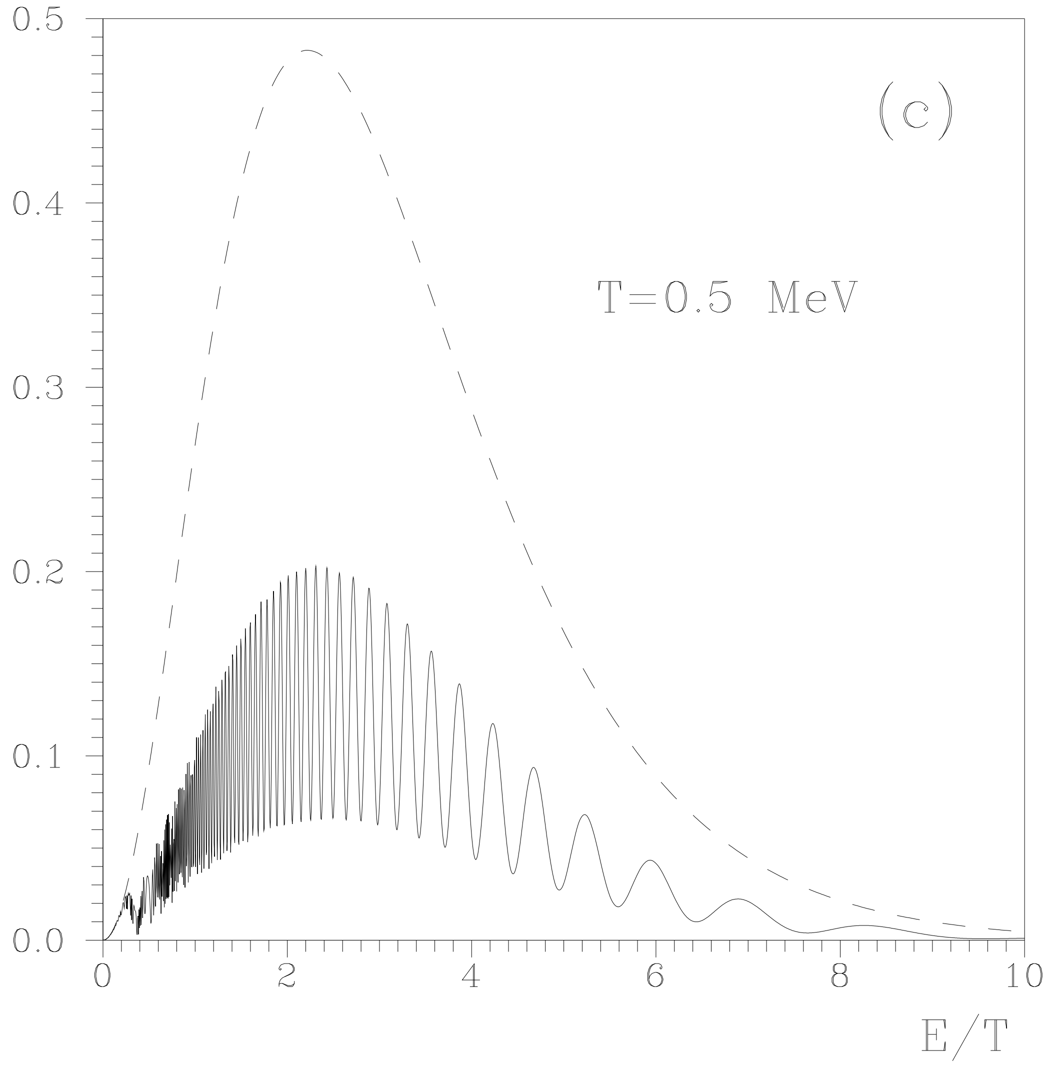

Figure 1c: The figure illustrates the degree of spectrum distortion of the electron neutrino caused by oscillations with mass difference $\delta m^2 = 10^{-7}$ eV^2 and $\sin^2 2\vartheta = 0.1$ at a characteristic temperature 0.5 MeV.

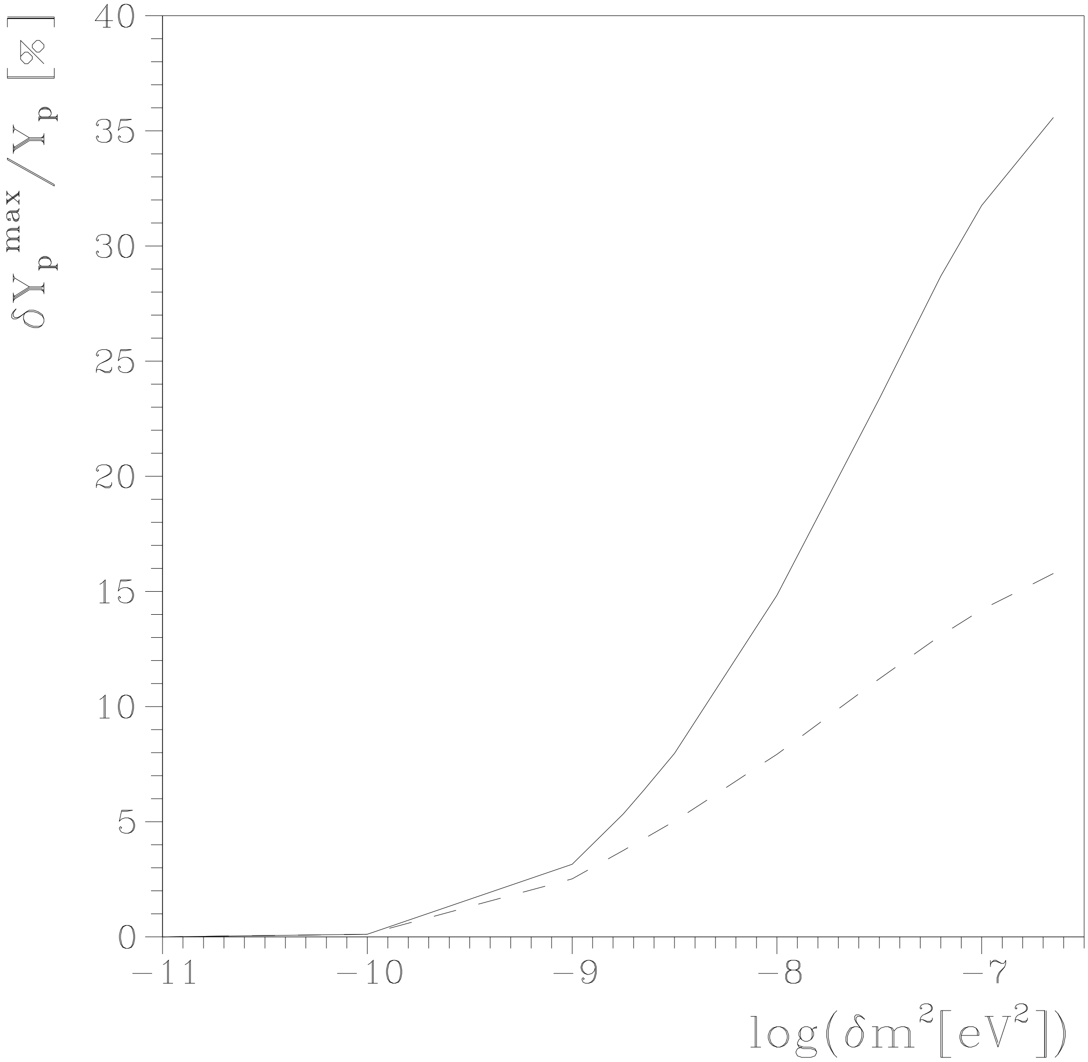

Figure 2: Maximum primordial ^{4}He abundance for the resonant (upper curve) and the non-resonant oscillation case (lower curve), as a function of the neutrino mass differences. The non-resonant case is calculated at maximum mixing, while in the resonant case the helium abundance is calculated at the resonant mixing angle for the corresponding mass difference.

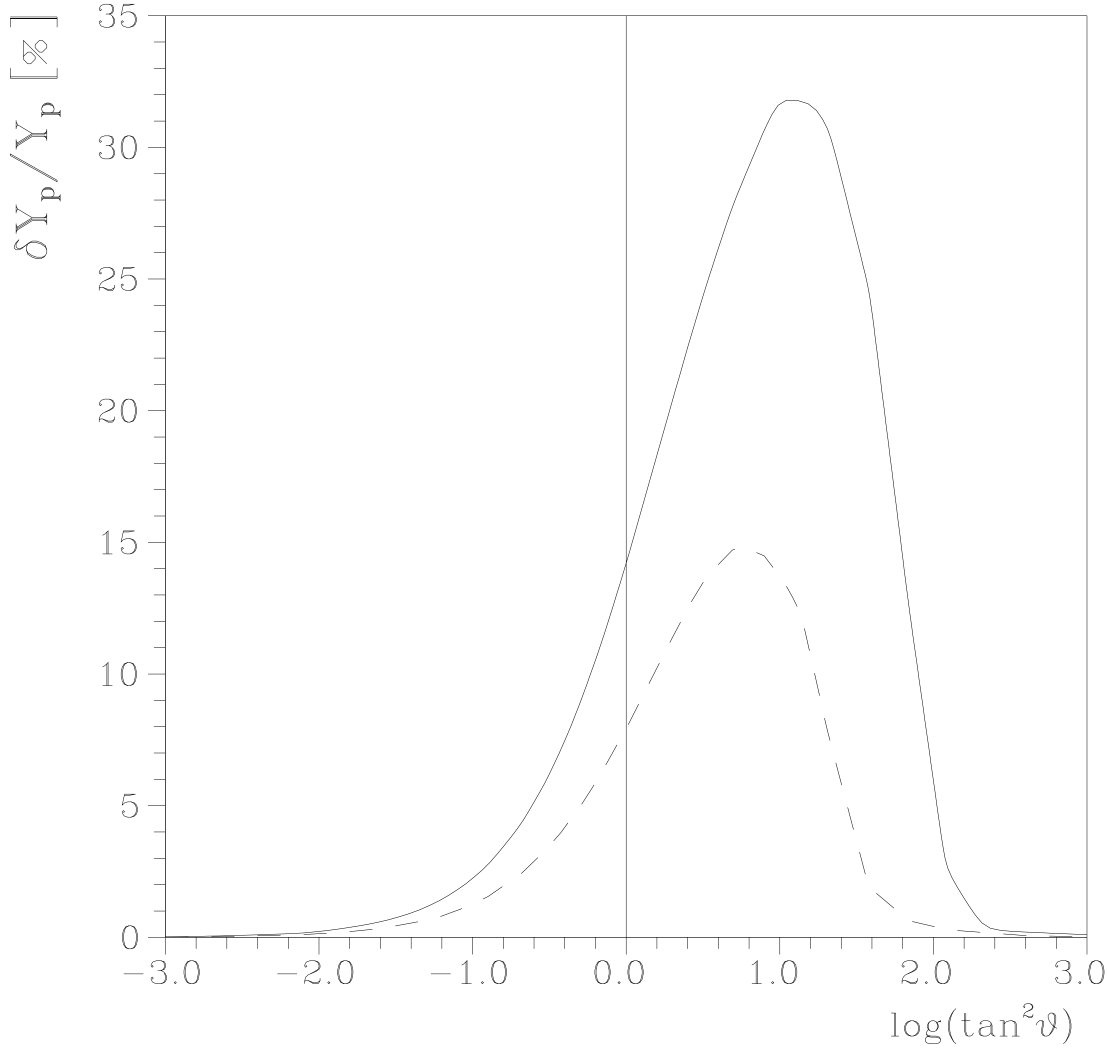

Figure 3: The dependence of the relative increase of primordial helium on the mixing angle for the resonant (r.h.s.) and non-resonant (l.h.s.) oscillation case. The upper curve corresponds to $\delta m^2 = 10^{-7}$ eV^2, the lower one to $\delta m^2 = 10^{-8}$ eV^2.