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NEUTRINO OSCILLATIONS AND THE EARLY UNIVERSE

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Abstract. The observational and theoretical status of neutrino oscillations in connection with solar and atmospheric neutrino anomalies is presented. The effect of neutrino oscillations on the early Universe evolution is discussed in detail. A brief review is given of the standard Big Bang Nucleosynthesis and the influence of resonant and nonresonant neutrino oscillations on active neutrinos and on BBN. Finally, recent cosmological constraints on neutrino oscillation parameters in case of BBN with neutrino oscillations, are presented.

1. INTRODUCTION

Neutrino - a neutral weakly interacting particle, is of extreme interest for Physics and Astrophysics. It is a key to the investigation of the weak interactions and the physics beyond the standard electroweak model. On the other hand, being a very weakly interacting particle, and hence having an uniquely great penetrating capability, neutrinos carry a precious information for the astrophysical processes in the most dense regions of the star cores and from the very early stages of the Universe evolution (see the recent review of Dolgov, 2002). Therefore, revealing neutrino characteristics is of great importance.

The contemporary particle physics theory neither requires nor forbids a nonzero neutrino mass. In the standard model of particle physics neutrinos are assumed massless. In the more general case of non-zero neutrino masses, the weak neutrino eigenstates may be a linear combination of the massive eigenstates, which means that transitions between neutrinos with different types (flavours), the so called *neutrino oscillations* are possible. Neutrino oscillations and their role in resolving the solar neutrino puzzle were first proposed by B. Pontecorvo (see Pontecorvo, 1958) and already more than 40 years they continue to be the theme of leading experimental and theoretical research.

The basic idea of *neutrino oscillations* is that left-handed mass eigenstates ν_i are distinct from the left-handed flavour eigenstates ν_f:

$$\nu_i = U_{if}\ \nu_f \qquad (f = e, \mu, \tau).$$

Then in the simple two-neutrino oscillation case, the probability to find at a distance l a given neutrino type in an initially homogeneous neutrino beam of the same type is: $P_{ff} = 1 - \sin^2 2\vartheta \sin^2(1.267\, \delta m^2 l/E)$, where δm^2 - the neutrino mass difference in eV^2

and ϑ - the oscillations mixing angle are the oscillation parameters, E is the neutrino energy in GeV, l is in km. Oscillation efficiency is proportional to the oscillation parameters $\sim \sin^2 2\vartheta\ \delta m^2/E$.

The medium distinguishes between different neutrino types due to different interactions (see Wolfenstein, 1978; Mikheyev & Smirnov, 1985). This leads to different average potentials for different neutrino types. The matter mixing angle in the adiabatic case is expressed through the vacuum oscillation parameters and the characteristics of the medium, like its density and temperature. Namely, for the early Universe:

$$\sin^2 \vartheta_m = \sin^2 \vartheta / [\sin^2 \vartheta + (Q \mp L - \cos 2\vartheta)^2],$$

where $Q = -bET^4/(\delta m^2 M_W^2)$, $L = -aET^3 L^\alpha/(\delta m^2)$, L^α is given through the fermion asymmetries of the plasma, a and b are positive constants different for the different neutrino types, $-L$ corresponds to the neutrino and $+L$ to the antineutrino case. Although in general the medium suppresses oscillations by decreasing their amplitude, there also exists a possibility of enhanced oscillation transfer in case a resonant condition between the parameters of the medium and the oscillation parameters holds:

$$Q \mp L = \cos 2\vartheta.$$

Then the mixing in matter becomes maximal, independently of the value of the vacuum mixing angle. Both the nonresonant ($\delta m^2 > 0$) and resonant ($\delta m^2 < 0$) oscillation cases are interesting from cosmological point of view and from the viewpoint of the discussed neutrino anomalies, especially for the solar neutrino anomaly.

In recent years positive indications for neutrino oscillations were obtained at the greatest neutrino experiments (evidence for solar oscillations: Homestake, Kamiokande, SuperKamioKa, Gallex, SAGE, SNO; evidence for atmospheric oscillations: Super-KamioKa, Macro, Soudan 2, IMB; evidence for neutrino oscillations at terrestrial experiments: LSND, KamLAND) (see the review e.g.Gonzalez-Garcia & Nir, 2002). Each of these neutrino anomalies, namely the solar neutrino problem, atmospheric neutrino anomaly and the positive results of terrestrial LSND and KamLAND experiments may be resolved by the phenomenon of neutrino oscillations. These results have a great resonance as far as any experimental evidence for neutrino masses or mixing is a signal of new physics (NP) - physics beyond the standard model of electroweak interactions.

On the other hand, neutrino oscillations affect early Universe evolution by affecting expansion rate and active neutrino densities and energy spectrum, thus influencing the neutrino involved processes, as for example cosmological nucleosynthesis, structure formation, etc. Cosmological nucleosynthesis, traditionally called Big Bang Nucleosynthesis (BBN) is traditionally used as a probe of the conditions of the early Universe, due to the high accuracy of the theoretically predicted abundances of light elements D, He-3, He-4, Li-7 and to the good accuracy of their inferred from observations primordial values. Hence, the requirements for a concordance between theoretically predicted and extracted from observations abundances of the light elements, is used to constrain physics beyond the standard model, like neutrino oscillations.

In the following we will present a brief pedestrial review of the solar and atmospheric neutrino anomalies and then discuss in more detail the role of neutrino oscillations in the early Universe and the cosmological constraints on oscillation parameters, following from BBN.

2. NEUTRINO ANOMALIES AND NEUTRINO OSCILLATION EXPERIMENTS

2. 1. SOLAR NEUTRINO DEFICIT

According to the contemporary astrophysical understanding the Sun is a Main Sequence star at the stage of hydrogen burning. It produces an intense flux of electron neutrinos as a result of its nuclear reactions generating the solar energy. Due to its weak interaction with matter, the solar neutrino reaching the Earth comes from the very deep solar core and carries valuable information about stellar structure and its evolution. Hence, the detection of the neutrino form the Sun has been recognized as a task of great importance as early as the 50 - when Davis started a radiochemical experiment, aiming to detect neutrinos from the Sun, in the golden mine of Homestake. The solar neutrinos also present the unique possibility for investigation of the neutrino properties like neutrino mass and mixing, because the Sun is at very large distance from the Earth, and also because the solar density varies strongly from the center to the surface and thus offers interesting conditions for the penetration of neutrino through layers with different density and thickness.

Since the first attempts to measure solar neutrinos, there has been 3 types of solar neutrino experiments, using Cl, Ga and H_2O as target for measuring electron neutrino from the Sun. The detected fluxes of solar neutrinos in these solar experiments (using different detection methods [1] and sensitive to different energy ranges) are in qualitative agreement with the assumption that Sun burns due to nuclear reactions in its core. However, *all the data of the solar neutrino experiments point to a considerably lower neutrino flux than the expected one in the standard Solar Model. Furthermore, the suppression is different in various experiments, sensitive to different energy range.* This problem is called *solar neutrino anomaly.* Despite the continuous improvements of the Solar Model and the predicted neutrino flux in the last 40 years, the discrepancies between the observations and the predictions of the model persist. Depending on the energy the measured fluxes consist about 0.3 to 0.6 from the predicted value. On the other hand there remains smaller and smaller doubt about the Solar Model prediction capability.[2]

Thus, in case we exclude the possibility that most of the leading solar neutrino experiments are wrong, the experimental data point more and more convincingly to the necessity of new neutrino physics.

Very attractive for explanation of the solar neutrino problem is the idea of neutrino oscillations, capable to explain the observational data and its discrepancies with the predictions of the Solar Model. According to it the produced in the solar core electron neutrino undergoes transformations into other flavours while penetrating through the Sun or the cosmic space till the Earth detectors of electron neutrinos. Hence, the registered electron neutrino flux will be reduced in comparison with the produced in the Sun core.

There exist different types of solar neutrino oscillations solutions - Small Mixing Angle (SMA) and Large Mixing Angle (LMA), depending on the mixing angles at

[1]There exist radiochemical experiments like GALLEX, SAGE and Homestake and electron experiments like Kamiokande and SuperKamioka.

[2]The recent measurement of neutral currents and charged currents fluxes at SNO experiment provide 5.3σ signal for neutrino flavour transitions that is independent of the solar model.

around $\delta m^2 \sim 10^{-5}$ eV^2 and LOW and vacuum oscillation solutions corresponding to very small $\delta m^2 \leq 10^{-7}$ eV^2 mass differences. The present solar neutrino data do not allow to choose definitely among the different possibilities. It only definitely prefers flavour oscillation solutions to active-sterile ones (as was pointed first from cosmology considerations - see section 3). However, in the light of the recent results of the terrestrial experiment KamLAND, there is an indication that LMA solution is the preferred one.

2. 2. ATMOSPHERIC NEUTRINO ANOMALY

A continuous isotropic flux of cosmic rays, consisting of protons and heavy nuclei, is bombarding the Earth's atmosphere. As a result of its interactions with the atmospheric particles muon and electron neutrinos are produced with a wide energy range. The theoretical prediction for the ratio of the muon to the electron flux is $r = \nu_\mu/\nu_e = 2$ for energies less than 1 GeV. Besides, identical up-coming and down-coming fluxes are expected due to the isotropy of the cosmic rays flux and due to the spherical symmetry of the Earth's atmosphere. Any deviation from these theoretical predictions is an indication for new neutrino physics.

The underground neutrino experiments SuperKamioka, Soudan 2 and Macro, as well as the earlier experiments IMB and Kamiokande, have *measured ratio r considerably lower than the expected one* (see for example Fukuda Y., 1998). This discrepancy, the so called *atmospheric neutrino anomaly* is known already for more than 10 years. Besides a dependence of the muon neutrino deficit on the neutrino energy and zenith angle dependence is observed.

The experimental data can be explained in terms of neutrino oscillations, namely by the transition of the muon neutrino into another type. The latest data analysis prefer the $\nu_\mu \leftrightarrow \nu_\tau$ channel as the dominant one. The oscillations into sterile neutrino are disfavoured, because of the absence of suppression of oscillations by the medium, expected in the sterile case at high energies. The best fit oscillation parameters for the available data are nearly maximal mixing and $\delta m^2 = 3 \times 10^{-3}$ eV^2.

2. 3. LABORATORY EXPERIMENTS

Besides these two astrophysical indications for neutrino oscillations and non-zero neutrino mass, there exist also laboratory experiments, the so called terrestrial experiments LSND and KamLAND, whose data have given an indication for oscillations, too.

The short baseline Los Alamos Liquid Scintillation Neutrino Detector (LSND) experiment has registered appearance of electron antineutrino in a flux of muon antineutrino. This anomaly might be interpreted as $\nu_\mu \leftrightarrow \nu_e$ oscillations with $\delta m^2 = O(1$ eV$^2)$ and $sin^2 2\theta = O(0.003)$.

In case LSND result is confirmed[3] an addition of a light singlet neutrino (sterile neutrino ν_s) is required, because three different mass differences, needed for the explanation of the solar, atmospheric and LSND anomaly require 4 different neutrino masses. This simplest extension already has difficulties, because oscillations into purely sterile neutrinos fit neither the atmospheric nor solar neutrino data, and

[3]The LSND result was not confirmed by KARMEN. It will be tested in future by MiniBoom experiment at Fermilab.

besides, as will be discussed further on, are strongly restricted by cosmological considerations.

KamLAND (Kamioka Liquid Scintilator Anti-Neutrino Detector experiment has measured anti electron neutrino deficit in the flux of antineutrinos coming from reactors at $\sim$ 180 km distance. In the context of two-flavour neutrino oscillations KamLAND results exclude all solar oscillation solutions but 'Large Mixing Angle' solution, which is the only remaining oscillation solution to the solar neutrino problem compatible with the KamLAND results and CPT-invariance. The allowed LMA region is further reduced by these results (see Eguchi et al., 2002). So, KamLAND result appears to confirm in totally independent and completely terrestrial way that solar neutrino deficit is indeed due to neutrino oscillations, which was suspected in 7 solar neutrino experiments over the last 40 years.

The neutrino experiments results confirm non-zero neutrino mass and mixing. Non-zero neutrino mass is also cosmologically welcome, as it may play the role of the hot dark matter component essential for successful structure formation (see the next section). The standard model of particle physics (SM) $SU_c(3) \times SU_W(2) \times U_Y(1)$ does not contain non-zero neutrino mass and mixing, hence NP beyond SM is required, while SM is its low energy effective theory. Neutrino data gathered at neutrino experiments and the cosmological considerations concerning neutrino mass and mixing, discussed below, point the way towards this NP - hopefully the true unified theory of elementary particles.

3. NEUTRINOS IN THE EARLY UNIVERSE

After the photons of the microwave background radiation, neutrinos are the most abundant particles in the Universe. Hence, in case they have non-zero mass they may contribute considerably to the total energy density of the Universe. From the requirement that the neutrino density should not exceed the total energy density, an upper limit on the neutrino mass was deduced (the so called Gerdshtein -Zeldovich limit), according to which the neutrino mass should be less than about 10 eV. For more details on neutrino role in cosmology see the recent review paper (Dolgov, 2002) and the references there in.

Much stronger limits on the neutrino mass may be obtained accounting for the considerable role of neutrinos in other important cosmological processes, like primordial nucleosynthesis and the formation of large scale structure of the Universe.

3. 1. LARGE SCALE STRUCTURE AND NEUTRINO

The mass of the visible (radiating) matter in the Universe is at most 0.01 of the total mass deduced from its gravitational effect. The rest 0.99 consists the so called *Dark Matter* of the Universe (DM). Only 0.1 of this DM may be in the form of invisible baryons. The rest should be non-baryonic. I.e. neutrinos, if massive, are natural candidate for DM component.

On the other hand, according to the accepted contemporary theory, structures in the Universe are a result of gravitational instabilities of overdensity perturbations. The latter result from the initial microscopical perturbations generated at the inflationary stage, which have been inflated during the exponential expansion. In order to be in agreement with the sizes of the observed today structures it was found necessary to speed the growth of the perturbations, which is naturally achieved by the presence of non-relativistic DM at the epoch of perturbations growth. However, the precise analysis of the microwave background anisotropy data and structures data points to the necessity of some 20 % admixture of hot DM, which can be naturally provided by light neutrino with mass ∼eV. The best fit are two degenerate neutrino flavours with $m \sim 2.4$ eV, playing the role of the hot DM component.

It is remarkable that such mass value is in accordance with the picture of oscillation models, which predict oscillations between nearly degenerate neutrinos, with negligibly different masses (in case of solar neutrino anomaly with mass difference $\sim 10^{-5}$ eV and in case of the atmospheric anomaly - ~ 0.001 eV). Each of these degenerate neutrino types, in case they have masses of the order of ∼ eV, can successfully play the role of the hot DM.

3. 2. BBN AND NEUTRINO

One of the most exciting events in the early Universe is the primordial nucleosynthesis of the light elements. The idea for the production of elements through nuclear reactions in the hot plasma during the early stage of the Universe evolution belongs to George Gamov and was proposed in the 30s. In the following 70 years this idea has grown to an elegant and famous theory - theory of the cosmological nucleosynthesis (Big Bang Nucleosynthesis), explaining the data on the primordial abundances of the light elements D, He-3, He-4 and Li-7.

Based on the excellent agreement between BBN predictions and the observational data, today we believe that we know with a great precision the physical processes typical for the BBN epoch. Hence, BBN is the most powerful probe for new physics, like the physics predicting neutrino oscillations and non-zero neutrino mass.

STANDARD BBN: The cosmological nucleosynthesis proceeds when the temperature of the plasma falls down to 1 MeV, when the weak processes, governing the neutron-proton transitions become comparable with the expansion rate. As a result the neutron-to-proton ratio freezes out at temperature around 0.7 MeV. This ratio enters in the following rapid nuclear reactions leading to the synthesis of D and the rest light elements formed in the first hundred seconds next to the Big Bang. The production of heavier elements is hindered by the rapid decrease of the Universe density with the cooling of the Universe. And the latter are formed much later in stars.

For analysis of the oscillations effect on BBN, He-4 is the traditionally used element, because the most reliable and abundant data now available are for that element. The contemporary helium values, inferred from observational data, are 0.238–0.245 (the systematic errors are supposed to be around 0.007) (see Izotov & Thuan, 1998). The uncertainty of the observational Y_p is a few percent.

According to the standard cosmological nucleosynthesis (SBBN) He-4 primordial production essentially depends on the freezing of the reactions interconverting neutrons and protons : $\nu_e+n \leftrightarrow p+e^-$, $e^++n \leftrightarrow p+\tilde{\nu_e}$, which maintained the equilibrium of nucleons at high temperature ($T > 1MeV$). Their freeze-out occurred when in the process of expansion the rates of these weak processes $\Gamma_w \sim G_F^2 E_\nu^2 N_\nu$ become comparable and less than the expansion rate $H(t) \sim \sqrt{g_{eff}}\, T^2$. Further evolution is due to the neutron decays that proceed until the effective synthesis of D begins. Almost all available neutrons are sucked into He-4. So, the primordially produced mass fraction of He-4, to a good approximation, is $Y_p(\text{He-4}) \sim 2(n/p)_f/(1+n/p)_f$. Hence, the produced He-4 is a strong function of the effective number of relativistic degrees of freedom at BBN epoch, g_{eff}, and neutron mean lifetime τ_n, which parametrizes the weak interactions strength. It depends on the electron neutrino number density and spectrum, which enter through Γ_w. SBBN assumes equilibrium neutrino distribution.

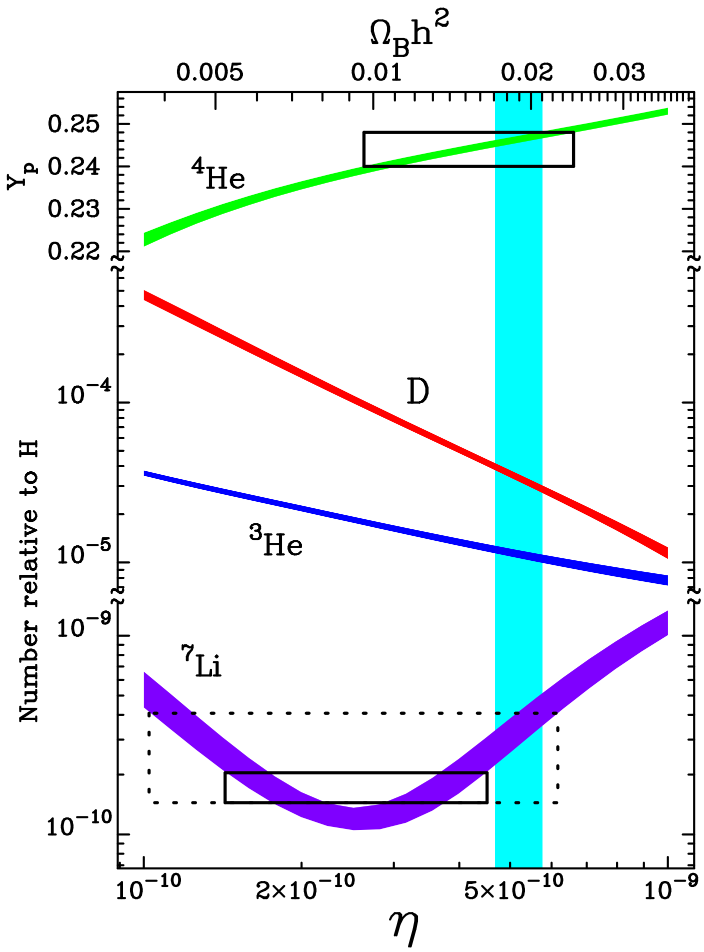

Figure 1: The theoretically calculated primordial abundances of the light elements as a function of the baryon-to-photon ratio η. The inferred from observational data values are presented by the boxes. The vertical band gives D observations towards quasars.

Y_p, predicted by BBN, is calculated with great precision (see Lopez R. E., and Turner M. S., 1999). The theoretical uncertainty is less than 0.1% ($|\delta Y_p| < 0.0002$) within a wide range of the baryon-to-photon ratio η [4]. The predicted He-4 value is in accordance with the observational data for He-4 and is consistent with other light

[4]The preferred today η value is the one obtained on the basis of observations of D towards quasars at high redshifts.

elements abundances (see Fig.1 in Lopez and Turner, 1999). Given this accuracy new physics is not excluded, however it is constrained by cosmology.

BBN WITH NEUTRINO OSCILLATIONS: The influence of neutrino oscillations depends on the type of oscillation channels and the way they proceed (for more details see the review Kirilova & Chizhov, 2001 and references therein). Flavour oscillations do not influence considerably BBN because different neutrino flavours have almost the same temperature and equilibrium distributions. However, active-sterile oscillations may have considerable effect. The presence of such neutrino oscillations changes the main assumptions of SBBN about three neutrino flavours, zero lepton asymmetry and equilibrium neutrino number densities and energy distribution. *Neutrino oscillations affect the neutrino involved processes in the Universe by*

(a) bringing additional degrees of freedom into equilibrium: This leads to faster Universe expansion $H(t) \sim g$, and to earlier n/p-freezing, at times when neutrons were more abundant (see Dolgov, 1981).

(b) depleting the neutrino number densities: Electron neutrino depletion slows down the weak rates, $\Gamma_w \sim N_\nu E_\nu^2$, and leads to an earlier n/p-freezing and a corresponding increase of He-4 yield (see Kirilova, 1988; Barbieri & Dolgov, 1991, Enqvist et al., 1992, Kirilova and Chizhov, 1998).

(c) distorting the neutrino spectrum: 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 energy spectrum of the neutrinos may become strongly distorted (see Fig.2). This effect is considerable both for the vacuum oscillations (see Kirilova, 1988) and oscillations in a medium (Kirilova and Chizhov, 1996). The main effect of this distortion on He-4 is the following: An average decrease of the energy of electron neutrinos decreases Γ_w, and subsequently increases the freezing temperature and He-4.[5]

(d) producing neutrino-antineutrino asymmetry: Dynamically produced asymmetry influences the evolution of neutrino and its oscillation pattern (Kirilova and Chizhov, 1996, Foot et al., 1996). Dynamically produced asymmetry suppresses oscillations at small mixing angles, leading to less overproduction of He-4. In the resonant case the asymmetry effect on BBN is considerable.

The nonequilibrium picture of neutrino oscillation effects (a)-(d) is hard to describe analytically. Hence, exact kinetic equations for neutrino density matrix in momentum space were used to describe oscillating neutrinos in the high temperature Universe. We have explored a modification of BBN with electron-sterile neutrino oscillations $\nu_e \leftrightarrow \nu_s$ and studied the influence of neutrino oscillations on the weak neutron-proton transitions and on the subsequent synthesis of He-4 for the case when neutrino oscillations become effective after the electron neutrino decoupling from the plasma (i.e for $\sin^2 2\vartheta \delta m^2 \leq 10^{-7} eV^2$). Thus, we explored *non-equilibrium oscillations with low mass differences* – by several orders of magnitude beyond the reach of present experimental constraints.

Accounting for all neutrino oscillation effects on electron neutrino and correspondingly on neutron-proton kinetics during neutrons freeze-out, we have calculated the

[5]When due to oscillations the energy of the greater part of the neutrinos becomes smaller than that threshold for the reaction $\tilde{\nu}_e + p \to n + e^+$, the n/p_f-ratio decreases leading to a decrease of He-4. However this effect is a minor one. Hence, the total effect is overproduction of He-4.

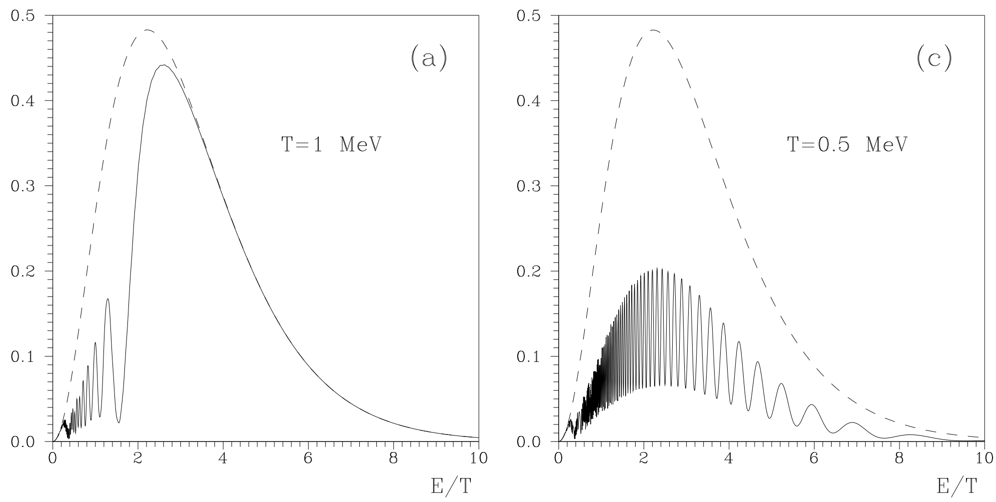

Figure 2: The energy spectrum for certain oscillation parameters is presented at different moments (a) corresponding to 1 MeV and (c) later on - 0.5 MeV. The dashed curves present the equilibrium spectrum. It is obvious that the distortion of the spectrum is considerable and with time involves the whole neutrino ensemble.

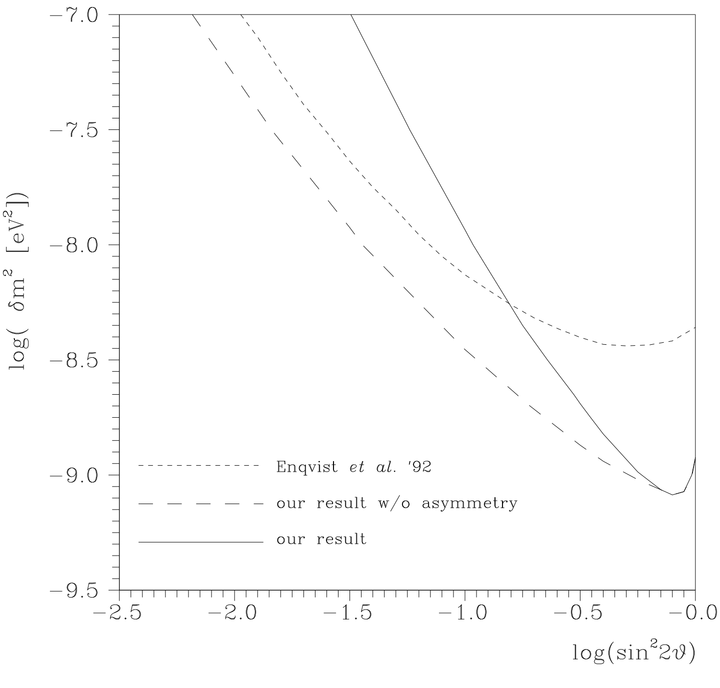

Figure 3: On the $\delta m^2 - \vartheta$ plane isohelium contour $Y_p = 0.24$ is plotted. The long dashed curve presents the same Y_p without the account of the asymmetry growth, while the small dashed curve presents the results of older study, where both the spectrum distortion and the asymmetry growth were ignored.

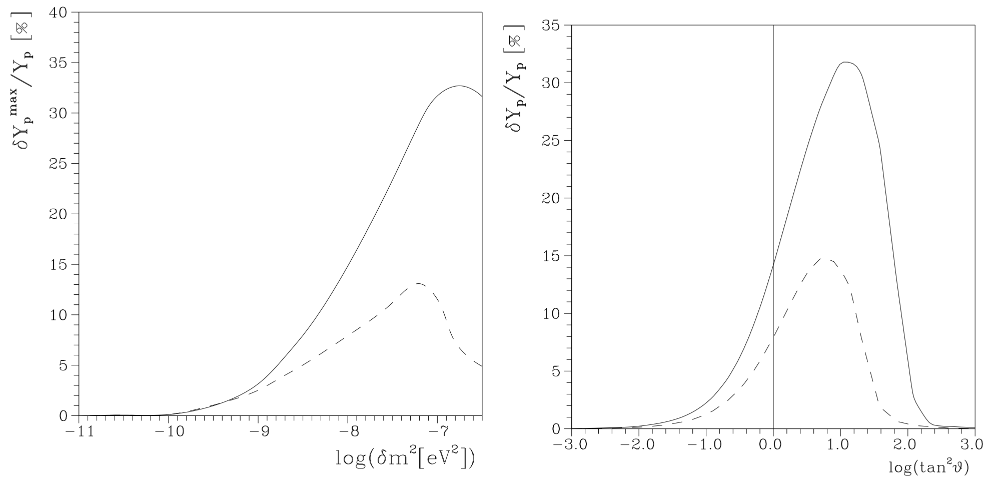

Figure 4: The dependence of the maximal relative overproduction of He-4 on mass differences for the resonant and nonresonant (dashed curve) oscillation cases (l.h.s.). The dependence of the maximal overproduction of He-4 on the mixing angle is given for $\delta m^2 = 10^{-7}$ eV^2 and 10^{-8} eV^2.

primordial production of He-4 both in the nonresonant and the resonant oscillation cases. A selfconsistent numerical analysis of the kinetics of the oscillating neutrinos, the nucleons freeze-out and the asymmetry evolution was provided. The primordial production of He-4 in the presence of electron-sterile neutrino oscillations was calculated for the complete set of oscillation parameters: for all mixing angles ϑ and for the mass differences corresponding to the oscillations model. Both nonresonant (see Kirilova & Chizhov, 1998) and resonant (see Kirilova and Chizhov, 2000) oscillation cases were considered.

In the *nonresonance case* oscillations effect becomes very small (less than 1%) for small mixings: as small as $\sin^2 2\theta = 0.1$ for $\delta m^2 = 10^{-7} eV^2$, and for small mass differences: $\delta m^2 < 10^{-10} eV^2$ at maximal mixing. The effect of oscillations is maximal at maximal mixing and greatest mass differences. In the *resonant oscillation case*, however, for a given δm^2 there exists some resonant mixing angle, at which the oscillations effects are enhanced by the medium, and hence, the overproduction of He-4 is greater than that corresponding to the vacuum maximal mixing angle.

He-4 production may be considerably influenced by effects (a)-(d) due to active-sterile oscillations. The kinetic effect of neutrino oscillations comprises a major portion of the total effect, i.e. it can be larger than the one corresponding to an additional degree of freedom. It plays a considerable role in the overproduction of He-4 (see Fig.3). The rough calculations underestimate oscillations effect by several orders of magnitude of δm^2. He-4 overproduction in the resonant case can be up to 32%, while in the nonresonant one - up to 14% (see Fig.4 in Kirilova, 2002).

COSMOLOGICAL CONSTRAINTS ON OSCILLATION PARAMETERS: The relative increase of He-4 in comparison with the standard one, corresponding to more than 3% overproduction of helium, is unacceptably large for observations of He-4. So, observational BBN data on primordial He-4 put stringent limits on the allowed active-

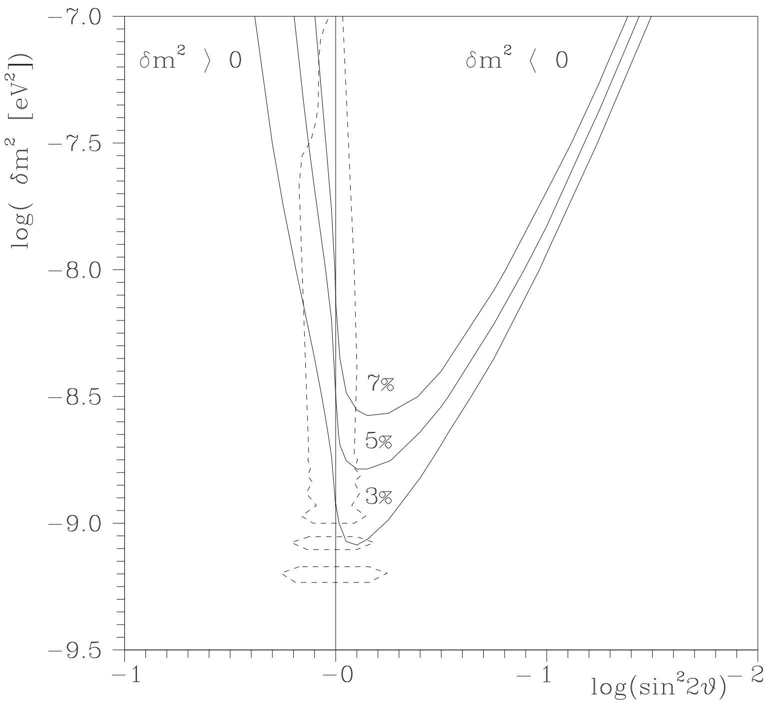

Figure 5: Isohelium contours corresponding to 3%, 5% and 7% overproduction of He-4. The dashed curves present LOW sterile solution.

sterile oscillation parameters. Assuming the conventional observational bound on $\delta Y_p/Y_p^s < 3\%$, based mainly on its systematic uncertainty, the cosmologically excluded region is situated above the 3% contour at Fig.5 (in Kirilova and Chizhov, 2001).

The analytical fits to the exact constraints are:

$$\delta m^2(\sin^2 2\vartheta)^4 \leq 1.5\times10^{-9}\mathrm{eV}^2 \quad \delta m^2>0$$
$$|\delta m^2| < 8.2\times10^{-10}\mathrm{eV}^2 \quad \delta m^2<0,\ \ large\ \ \vartheta,$$

LMA and LOW sterile solutions to the solar neutrino problem are almost completely excluded by BBN considerations.[6] This result is consistent with the last analysis of the global data from SNO, SuperKamiokande, GALLEX+GNO, SAGE and Chlorine experiments, which does not favour $\nu_e \leftrightarrow \nu_s$ LMA and LOW solution[7].

4. CONCLUSIONS

During the last quarter of the 20th century strong evidence for non-zero neutrino masses and mixings has been provided from various neutrino oscillations experiments

[6] Moreover, cosmology is capable to exclude mass differences by several orders of magnitude smaller than the experimentally reached ones.

[7] The possibility to relax cosmological constraints in the presence of initial lepton asymmetry is discussed in Kirilova & Chizhov, 2001

(astrophysical: solar neutrino experiments and atmospheric neutrino experiments and terrestrial: LSND and KamLAND). The essential role of neutrino oscillations for processes in the early Universe was realized. Stringent cosmological constraints on the oscillation parameters were obtained on the basis of BBN considerations.

Non-zero neutrino masses and mixings, required by the experimental data and cosmology, require new physics beyond the standard electroweak model. The scale of this NP is inversely proportional to the neutrino masses and appears to be of the order of the Grand Unification scale. Hence, the neutrino oscillation experiments and the neutrino cosmology, by studying neutrino properties point the way towards the Grand Unified Theory of elementary particles - the holy dream of physics.

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