

Lepton Asymmetry and Neutrino Oscillations Interplay

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Abstract We discuss the interplay between lepton asymmetry L and ν oscillations in the early Universe. Neutrino oscillations may suppress or enhance previously existing L . On the other hand L is capable to suppress or enhance neutrino oscillations. The mechanism of L enhancement in MSW resonant ν oscillations in the early Universe is numerically analyzed. L cosmological effects through ν oscillations are discussed. We discuss how L may change the cosmological BBN constraints on neutrino and show that BBN model with $\nu_e \leftrightarrow \nu_s$ oscillations is extremely sensitive to L - it allows to obtain the most stringent constraints on L value. We discuss also the cosmological role of active-sterile ν mixing and L in connection with the indications about additional relativistic density in the early Universe, pointed out by BBN, CMB and LSS data and the analysis of global ν data.

Keywords Lepton Asymmetry · Neutrino Oscillations · BBN

1 Introduction

Lepton asymmetry (L) of the Universe is not measured yet and may be orders of magnitude bigger than the baryon asymmetry $\beta \sim 6 \cdot 10^{-10}$, which was measured with great precision from Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) data. L is usually defined as $L = (N_l - N_{\bar{l}})/N_\gamma$, where N_l is the number density of leptons, $N_{\bar{l}}$ of antileptons, while N_γ is the number density of photons. Considerable L might be contained only in ν sector. Thus, the detection of the Cosmic Neutrino Background would provide L direct measurement. Till then L is measured indirectly by its influence on observable relics of the Universe. The abundances of the primordially produced light elements during BBN provide such a sensitive test of L .

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Main cosmological effects of L on BBN are its dynamical and kinetic effect. *The dynamical effect of L* consists in the increase of the radiation energy density of the Universe due to non-zero L : $\delta\rho_r = [1 + 7/8(4/11)^{4/3}\delta N_{eff}]\rho_\gamma$, where $\Delta N_{eff} = 15/7[(\xi/\pi)^4 + 2(\xi/\pi)^2]$, where $\xi = \mu/T$ is the ν degeneracy parameter. This effect leads to faster Universe expansion $H = (8/3\pi G\rho)^{1/2}$, which leads to earlier freezing of nucleons and hence influences BBN produced elements. *The kinetic effect* is noticeable for big enough $|L| > 0.01$ in the ν_e sector and is due to different number densities of ν_e and $\bar{\nu}_e$, which participates in neutron-proton transfers: $\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$ in the pre-BBN epoch and, correspondingly, BBN yields (see ref. [1] and refs there in).

Besides these well known effects L may influence BBN through its interplay with neutrino oscillations. Unlike previous effects, this L effect on BBN, called further *indirect kinetic effect*, may be noticeable for much smaller L values, $L \ll 0.01$. Hence BBN with oscillations provides the possibility to measure and/or constrain tiny L with values close to β .

In the next section the interplay between L and ν oscillations is described. In the third section the indirect kinetic effect of L on BBN is studied and the possibility to constrain L via BBN with ν oscillations is discussed. L role as a solution of the problem of the excess radiation density in the Universe is provided in the fourth section.

2 Interplay between L and neutrino oscillations in the early Universe

Small $L \ll 0.01$ has negligible dynamic and direct kinetic effect. Nevertheless, due to its interplay with ν oscillations such L is capable of changing ν number densities, ν distribution and spectrum distortion and changing ν oscillations pattern (suppressing or enhancing oscillations), by which it influences nucleons kinetics and finally BBN production of light elements [2]. This effect was proven to persist down to $L \sim 10^{-8}$ [2–4].

We studied numerically the interplay between tiny L , $10^{-4} > L > 10^{-10}$, and electron-sterile $\nu_e \leftrightarrow \nu_s$ oscillations, effective after active ν decoupling $\delta m^2 \sin^4 2\theta \leq 10^{-7} \text{ eV}^2$.

It is known that active-sterile oscillations may change neutrino-antineutrino asymmetry of the medium, suppress or enhance it [8, 9, 11, 2, 12, 13, 15, 16, 3, 4].

¹ On the other hand L influences ν propagation. Qualitatively this influence may be described as follows: The average potentials V_f for ν depend on the particle asymmetries of different constituents of the medium and they differ for different neutrino types due to different interactions with the particles of the plasma [17]:

$$V_f = \sqrt{2}G_F Q N_\gamma / M_W^2 \pm L N_\gamma \quad (1)$$

¹ There are other cosmological effects of active-sterile neutrino oscillations, like excitation of additional light particles into equilibrium [5, 6] and distortion ν energy distribution [7, 8].

where $f = e, \mu, \tau$, "minus" corresponds to ν and "plus" to $\bar{\nu}$, $Q \sim -ET$, $L \sim -L_\alpha$, L^α is given through the fermion asymmetries of the plasma (in the discussed case $L \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}$).

In the adiabatic case the effect of the medium can be hidden in the oscillation parameters δm^2 and ϑ by introducing matter oscillation parameters:

$$\sin^2 \vartheta_m = \sin^2 \vartheta / [\sin^2 \vartheta + 2G_F((Q/M_W^2 \mp L)N_\gamma/\delta m^2 - \cos 2\vartheta)^2]. \quad (2)$$

L , as a characteristic of the medium, may suppress oscillations by decreasing their amplitude, or enhance oscillation transfer in case resonant condition between the parameters of the medium and the oscillation parameters holds:

$$2G_F(Q/M_W^2 \mp L)N_\gamma = \cos 2\vartheta \times \delta m^2 \quad (3)$$

In the early Universe at high temperature $Q/M_W^2 > L$ resonant oscillations both for ν and $\bar{\nu}$ are possible if $\delta m^2 < 0$. With the cooling of the Universe when L begins to dominate, $Q/M_W^2 < L$, resonant transfer for antineutrinos in case $\delta m^2 < 0$, or for neutrinos if $\delta m^2 > 0$ is possible.² Thus neutrino propagation and resonance in the neutrino sector differs from that of antineutrino for non-zero L . Due to L influence of the ν propagation L may change n_ν , its spectrum distribution and oscillation pattern.

This simplified description of the medium influence is applicable in the equilibrium situation, when working in terms of average ν momentum and particle densities is reasonable. In the nonequilibrium situation, when spectrum distribution of ν is considerable, as is the case of late electron-sterile oscillations discussed here, it strongly effects both ν propagation and L evolution. Hence, for the correct description of the neutrino - asymmetry interplay it is essential to provide an accurate account of the neutrino spectrum distortion due to L and oscillations.³

2.1 Exact description of the propagation of neutrinos and L evolution

The equations governing ν evolution, in terms of neutrino density matrix in momentum space, are given below. They account simultaneously for neutrino- L interplay, Universe expansion, ν oscillations and ν forward scattering and describe precisely ν energy distribution [8]. Our numerical analysis of L and ν propagation was based on these equations:

$$\begin{aligned} \partial\rho(t)/\partial t &= Hp_\nu (\partial\rho(t)/\partial p_\nu) + \\ &+ i[\mathcal{H}_o, \rho(t)] + i\sqrt{2}G_F(\mathcal{L} - Q/M_W^2)N_\gamma[\alpha, \rho(t)] + O(G_F^2) \\ \partial\bar{\rho}(t)/\partial t &= Hp_\nu (\partial\bar{\rho}(t)/\partial p_\nu) + \end{aligned}$$

² The resonant condition for $Q = 0$ was first studied and is known as Mikheev-Smirnov-Wolfenstein effect [18].

³ For example, in the nonequilibrium situation, when spectrum distribution of ν was properly described, simultaneous resonance transfer was found possible also in the $\delta m^2 < 0$ case due to the "resonant wave" passing through the neutrino distribution [2].

$$+i[\mathcal{H}_o, \bar{\rho}(t)] + i\sqrt{2}G_F(-\mathcal{L} - Q/M_W^2)N_\gamma[\alpha, \bar{\rho}(t)] + O(G_F^2).$$

$$L_{\nu_e} \sim \int d^3p(\rho_{LL} - \bar{\rho}_{LL})/N_\gamma$$

where $\alpha_{ij} = U_{ie}^*U_{je}$, $\nu_i = U_{il}\nu_l$ ($l = e, s$). \mathcal{H}_o is the free ν Hamiltonian. Q arises as an W/Z propagator effect, $Q \sim E_\nu T$. $\mathcal{L} \sim 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}$, $L_{\mu,\tau} \sim (N_{\mu,\tau} - N_{\bar{\mu},\bar{\tau}})/N_\gamma$. At decoupling of ν_e ν_s was assumed empty.⁴

Due to L the equations are coupled integro-differential. L leads to different evolution of ν from $\bar{\nu}$ due to the different sign of L in the equations. Numerical analysis of the evolution of ν ensembles, evolution of L , and also the evolution of nucleons for the entire range of oscillation parameters and for the temperature range [2 MeV, 0.3 MeV] and for $10^{-10} < L < 0.01$ was provided in non-resonant ν oscillations. In case of resonant oscillations L initial value was taken to be $L_i \sim \beta$. We have described precisely ν momenta distribution: 5000 bins were used in the non-resonant oscillations case, and up to 10 000 in the resonant case.

In case of *nonresonant oscillations and relic L* the following relations describe with good accuracy the exact behavior of L and L -oscillations interplay: $L \geq 10^{-7}$ enhances oscillations, $L > 0.1(\delta m^2/eV^2)^{2/3}$ suppresses oscillations, and asymmetries $L > (\delta m^2/eV^2)^{2/3}$ inhibit oscillations. For illustration of the exact dependences see figures in ref. [4].

In case of *resonant $\nu_e \leftrightarrow \nu_s$ oscillations* the evolution of L has a rapid oscillatory behavior. The region of parameter space for which a generation of L is possible was found $|\delta m^2| \sin^4 2\theta \leq 10^{-9.5} eV^2$.⁵ A maximum possible growth of L by 5 orders of magnitude was determined.

L role in BBN with ν oscillations was numerically studied as well. The change in BBN constraints on oscillation parameters due to L and BBN constraints on L in case of $\nu_e \leftrightarrow \nu_s$ are presented in the next section.

3 BBN with active-sterile neutrino oscillations and lepton asymmetry

Big Bang Nucleosynthesis is theoretically well established due to the precise data on nuclear processes rates, known from laboratory experiments at the energies relevant to BBN epoch, and the precise data on the light elements abundances D, He and Li. Besides, the baryon-to-photon ratio, which is the only parameter in the standard BBN, has been independently measured with good accuracy by CMB precision data. Therefore, BBN is used as the most early and precision probe for physical conditions in early Universe and, hence, presents the best astrophysical and cosmological probe for new physics and microphysics, relevant at BBN energies.

⁴ The case of non-zero population of ν_s was considered in refs. [15,19,20].

⁵ The instability region is slightly more stringent than the existing in literature for other oscillation models ref. [22].

Being the best speedometer at radiation dominated stage BBN was used to probe ν properties, the number of light species, ν oscillations, distortion in ν distribution, etc. Due to its sensitivity to the expansion rate and to the nucleons kinetics in the pre-BBN epoch it has been shown that BBN presents also the most exact leptometer (see ref. [4] and references there in). Thus BBN studies allow to put stringent limits on oscillation parameters [5, 7, 6, 8, 21, 12, 13, 15, 19, 20, 23] and on L in the presence of electron-sterile oscillations [2–4].

3.1 BBN constraints on L

Eventual ν degeneracies of flavor neutrinos will equilibrate before BBN due to flavor ν oscillations, having in mind recently measured value θ_{13} . Then BBN constraints on L read [24–29]:

$$|L| < 0.1. \quad (4)$$

For such small L the dynamical effect of L is negligible. These constraints allow the possibility of L orders of magnitude larger than β .

That small L in the flavor ν sector cannot mimic the extra relativistic degrees of freedom during BBN, which seem to be required by recent analysis of cosmological and neutrino oscillations data (to be discussed in more detail in the fourth section).

3.2 L and BBN with late electron sterile ν oscillations

In case of $L \sim \beta$ stringent BBN constraints on active-sterile oscillation parameters exist. *The presence of bigger L may change considerably BBN constraints on oscillations parameters* due to L indirect kinetic effect.

In BBN with electron-sterile ν oscillations Y_p decreases at small mixing parameters values due to L growth caused by resonant ν transfer, thus at these mixing angles *oscillations generated L relaxes the BBN constraints on oscillations* [8, 12, 4].

In case of relic $L > \beta$ the presence of such L relaxes the BBN bounds at maximal mixing and strengthens them at small mixing angles. In this case depending on the asymmetry-oscillations interplay the asymmetry may enhance, suppress or stop ν oscillations, reflecting correspondingly to strengthening, relaxation or elimination of the BBN constraints. In the last case the approximate BBN constraint reads:

$$\delta m^2 (eV^2) < L^{3/2}. \quad (5)$$

Thus, L generated in the electron-sterile sector may (partially) suppress the oscillations in other sectors, hindering equalization of chemical potentials, thus relaxing the stringent BBN bound. The presence of L (no matter how

generated), capable to suppress oscillations, may lead to only partial population of the sterile neutrino. Vice versa L values capable to enhance oscillations will bring faster the sterile state into equilibrium.

The model of BBN with $\nu_e \leftrightarrow \nu_s$, effective after electron ν decoupling presents the possibility to feel extremely small asymmetries $L > 10^{-8}$ due to the indirect kinetic effect of L (see ref. [4]). This sensitivity allows to derive stronger constraints on L . *Equation (5) can be considered also as BBN constraint on L in case of presence of electron-sterile oscillations.* Thus for example, having the indications for such oscillations with $\delta m^2 \sim 10^{-5}$ [30] and replacing this value in the eq.(5), a much stronger upper limit on L may be obtained than the one presented in eq.(4).

4 L and excess radiation density in the Universe

In recent years an increasing number of *cosmological indications* suggesting excess relativistic density, corresponding to different epochs, appeared [31–36]. Besides, ν *oscillations data* require 1 or 2 additional sub-eV sterile neutrino, participating into oscillations with flavor neutrinos with higher mass differences values, than the ones required by solar and atmospheric ν oscillations experiments [37, 39–42]. It is interesting if cosmology allows 2 light additional sterile neutrinos and if they can explain the excess relativistic density.

Additional light sterile neutrinos with the mixing and mass differences estimated by ν oscillations data will be brought into equilibrium in the early Universe. BBN favors the presence of one such ν_s but He and D data excludes 3 fully thermalized ν_s . Besides, neutrinos in sub-eV range produce too much hot dark matter [43, 44]. Thus, two additional ν_s are in tension both with BBN and with LSS requirements [45, 46, 36].

L , namely its dynamical and direct kinetic effects, has been considered as an explanation of the excess radiation. It was shown that excess radiation cannot be explained by degenerate BBN [29]. However, the presence of L may be the solution in case its value is enough to suppress active-sterile oscillations so that ν_s are not fully thermalized [6, 9, 2, 38]. Our estimation of the value of L necessary to suppress oscillations and achieve the suppression of ν_s production is $L \geq 0.08$. This is higher than the values discussed by refs.[38, 48], that found $|L| > 10^{-2}$. The difference might be due to the fact that these studies do not account for the ν energy distribution or due to different approximations used.

Thus, in modified BBN with ν oscillations and high enough L the models with 2 additional light sterile neutrinos may be allowed. To obtain the exact L value a precise numerical analysis, solving the exact kinetic equations, including all ν species and accounting for all L effects, discussed above, should be provided.

The excess relativistic density might point to additional sterile neutrinos and the presence of L , however there exist other possibilities: ν active-sterile oscillations, MeV decaying particles during BBN [50] or other modifications of the standard cosmological model. Future experimental and observational

data will choose among different possibilities. In particular, it is expected that Planck data will be able to check the status of extra radiation.

5 Conclusions

There exists interesting interplay between small L , relic or produced by active-sterile ν oscillations, and late active-sterile ν oscillations. A detail numerical analysis of this interplay between lepton asymmetry $L \ll 0.01$, and ν oscillations was carried out. The evolution of ν and L was studied using exact kinetic equations for ν density matrix in momentum space and describing the ν energy distribution with very high accuracy - up to 10 000 bins.

A considerable enhancement of L - by 5 orders of magnitude - was found possible in late electron-sterile Mikheyev-Smirnov-Wolfenstein oscillations, effective after the decoupling of active neutrino. The region in the oscillation parameter space of considerable L growth was determined.

The parameter range for which relic L is able to enhance, suppress or inhibit oscillations was determined.

Cosmological influence of small L , which do not have direct effect on nucleons kinetics during BBN, was discussed. Such small asymmetries are invisible by CMB, but may be felt by BBN. It was shown that L as small as 10^{-8} may be felt by BBN via oscillations. Also BBN constraints on ν oscillations parameters depend nontrivially on L .

L generated by oscillations at small mixing angles suppresses ν oscillations and reduces the overproduction of Y_p and relaxes BBN constraints.

Relic L present during BBN, depending on its value, can strengthen, relax or wave out BBN constraints on oscillations. The value of L , capable to stop ν oscillations is determined for different sets of oscillations parameters of the model, a good approximation to the exact value is $L > (\delta m^2 / (eV^2))^{2/3}$. On the other hand this can be considered the first obtained constrained on L in BBN with electron-sterile neutrino oscillations.

Due to its interplay with neutrino oscillations L may play important role for resolving the problem of additional radiation density suggested by cosmological observational data and by ν oscillations data. In principal BBN with L may allow 2+3 oscillations models, in case L value is high enough to suppress active-sterile oscillations, thus providing incomplete thermalization of ν_s and relaxing BBN constraints on additional light sterile species.

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