Impact of lepton asymmetry and sterile neutrinos on Primordial Nucleosynthesis

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The ratio is defined between the number of additional relativistic degrees of freedom, ΔN_{eff}, and parameter of lepton asymmetry of neutrino, ξ, in the epoch of the Primordial Nucleosynthesis (PN), when the theoretically predicted value of abundance of the primordial ^{4}He, Y_{p}, agrees with the value defined from the observations. It is shown that the presence of the light fully or partially thermalized sterile neutrinos does not contradict the observational data on PN at value $\xi \approx 0.05$, which might be generated in the early Universe within the existing models of leptogenesis and resonant neutrino oscillations.

Keywords: early Universe, Primordial Nucleosynthesis, sterile neutrinos, lepton asymmetry.

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Introduction

The phenomenon of neutrino oscillations provides evidence of their non-zero mass. Besides, the standard model of elementary particles (SM) leaves the mechanism of mass generation for neutrinos unclear. One of the opportunities for SM expansion providing for the generation of neutrino masses is the introduction of sterile neutrinos — fermions, which do not take part in any standard interactions. Expansion of the SM with its minimal changes, including the sterile neutrinos, was called the neutrino minimal standard model (νMSM), which may also solve the two fundamental cosmological problems: nature of the dark matter and baryon asymmetry of the Universe [1].

Cosmological manifestations of the sterile neutrinos depend substantially on the scales of their masses. One may identify the following mass range (see, for example, [2]): light sterile neutrinos ($1\,\text{eV}-1\,\text{keV}$), heavy sterile neutrinos ($1\,\text{keV}-100\,\text{GeV}$) and super-heavy sterile neutrinos ($\geq 100\,\text{GeV}$). Super-heavy sterile neutrinos, as the Universe expands, become nonrelativistic for the time $\lesssim 10^{-3}$ s from the moment of the Big Bang, and being the unstable particles, decay within $\lesssim 10^{-7}$ s, generating the baryon asymmetry [2]. The heavy sterile neutrino may have the lifetime comparable with the Universe age or exceed it, which makes such neutrino a good candidate for the role of the dark matter particles [2]. The light sterile neutrino may also be the candidate for the role of the dark matter particles and contribute significantly thereto (see, for instance, [3]). On the other hand, such neutrino is relativistic in the early Universe, therefore it contributes to the full energy density, and therefore increase the rate of the Universe expansion, and, accordingly, impact its primordial chemical composition [4]. The primordial element that is most sensitive to this effect is ^{4}He [5].

According to the theory of the Primordial Nucleosynthesis (PN), the abundance of the primordial ^{4}He, Y_{p}, is the function of two variables — baryon-to-photon ratio, $\eta_{\text{b}} = n_{\text{b}}/n_\gamma$, and effective number of relativistic degrees of freedom related to the neutrino, N_{eff}. In ΛCDM-cosmological model these variables have the following values: $\eta_{\text{b}}^{(0)} = (6.14 \pm 0.19) \cdot 10^{-10}$, $N_{\text{eff}}^{(0)} = 2.99 \pm 0.17$ [6]. These values defined by analysis of the cosmic microwave background anisotropy agree well with the independent estimates of these parameters obtained using the observed abundances of the primordial elements (D, ^{3}He, ^{4}He, ^{7}Li) [5]. Additional relativistic degrees of freedom related to the sterile neutrinos are defined by parameter $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{(0)}$, which depends on the thermalization degree of these particles in the early Universe ($0 \leq N_{\text{eff}} \leq 1$). Recent papers show that such neutrinos are fully thermalized, i.e. $\Delta N_{\text{eff}} = 1$ [7,8]. Introduction of a complete relativistic degree of freedom results in the fact that at the fixed value of η_{b} the theoretical value Y_{p} is substantially higher than the one observed [5].

On the other hand, the PN theory may include lepton asymmetry $L_\nu = (n_\nu - n_{\bar{\nu}})/(n_\nu + n_{\bar{\nu}})$ — relative inequality of neutrino and antineutrino concentrations, which is conveniently parameterized using value $\xi = \mu/T_\nu$, where μ — chemical potential of the neutrino. Lepton asymmetry may be generated within νMSM to $L_\nu \sim 10^{-4}$ [9] and then increased via resonant oscillations to the values $L_\nu = 0.2-0.3$ [10]. Lepton asymmetry impacts both the velocity of the Universe expansion, changing the densities of neutrino and antineutrino, and the velocities of low interaction reactions, changing the ratio of neutron and proton concentration and, accordingly, the final value Y_{p}. The presence of the additional relativistic degrees of freedom causes increase in abundance of ^{4}He, however, the positive lepton asymmetry ξ, in turn, reduces Y_{p} (see, for example, [11]). This makes it possible for these two effects to mutually compensate each other and therefore allow for the existence of the light sterile neutrino within PN, not contradicting the observations.

1. Dynamics of the Universe evolution with sterile neutrinos and lepton asymmetry

At the radiation-dominated stage of the Universe evolution its expansion rate was determined by the energy density in the relativistic degrees of freedom [4], which at PN temperatures ($1\,\mathrm{MeV} \gtrsim T \gtrsim 0.1\,\mathrm{MeV}$) are presented by photons, electrons, positrons, neutrinos and antineutrinos:

$$\rho = \rho_\gamma + \rho_{e^\pm} + \rho_{\nu\tilde{\nu}}. \quad (1)$$

Dependence on ξ and ΔN_{eff} is included only in $\rho_{\nu\tilde{\nu}}$ as follows [11]:

$$\rho_{\nu\tilde{\nu}} \propto N_{\mathrm{eff}} \int_0^\infty y^3 dy \left(\frac{1}{\exp(y-\xi)+1} + \frac{1}{\exp(y+\xi)+1} \right)$$
$$\approx \left(N_{\mathrm{eff}}^{(0)} + \Delta N_{\mathrm{eff}} \right) \left(\frac{7\pi^4}{60} + \frac{\pi^2}{2}\xi^2 \right). \quad (2)$$

Formula (2) demonstrates the increase in the energy density $\nu\tilde{\nu}$ at the presence of the positive values ΔN_{eff} and ξ compared to the standard case, ($\xi = 0$, $\Delta N_{\mathrm{eff}} = 0$). This, in its turn, increases the Universe expansion rate, which leads to the increase of value Y_{p} due to higher neutron-to-proton ratio till the end of PN, which is described in detail in section 2.

2. Impact of lepton asymmetry at the rate of weak interaction reactions in the early Universe

At $T \gtrsim 2\,\mathrm{MeV}$ the weak interaction reactions were intense, including the ones determining the neutron-to-proton ratio [4]:

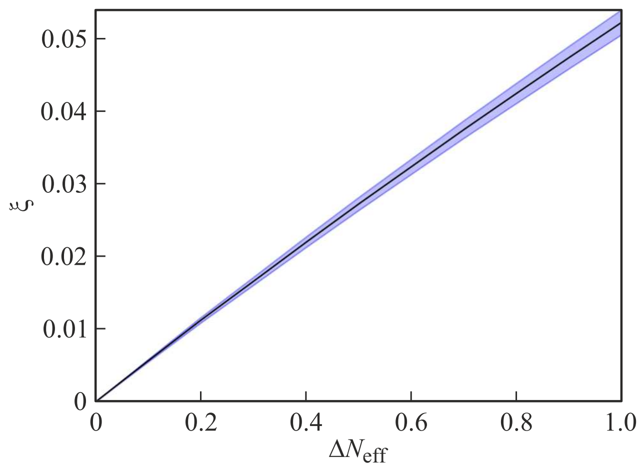
$$n + e^+ \leftrightarrow p + \tilde{\nu}_e, \quad (3)$$

$$n + \nu_e \leftrightarrow p + e^-, \quad (4)$$

$$n \leftrightarrow p + e^- + \tilde{\nu}_e. \quad (5)$$

As a result, the neutrons and protons were in equilibrium concentrations. Further at $T < 2\,\mathrm{MeV}$ the rate of Universe expansion becomes significantly higher than rates of the reactions (3), (4) and the reverse reaction (5), which causes their termination (so called neutron freeze-out) [4]. Starting from this moment and to the beginning of PN, the neutron-to-proton ratio varies only due to the free decay of neutrons (forward reaction (5)). The evolution of the mass fraction of neutrons $X_{\mathrm{n}} = n_{\mathrm{n}}/(n_{\mathrm{n}} + n_{\mathrm{p}})$ is defined by the equation

$$\frac{dX_{\mathrm{n}}}{dt} = -\lambda_{\mathrm{np}} X_{\mathrm{n}} + \lambda_{\mathrm{pn}}(1 - X_{\mathrm{n}}). \quad (6)$$



The ratio between ξ and ΔN_{eff}, corresponding to the equality $Y_{\mathrm{p}}(\xi, \Delta N_{\mathrm{eff}}) = Y_{\mathrm{p}}^{(\mathrm{obs})}$. The blue region is the interval 3σ related to the error of value $Y_{\mathrm{p}}^{(\mathrm{obs})}$.

Characteristic velocities of the specified reactions λ_{np} and λ_{pn} depend on the asymmetry of neutrinos ξ [12]. Increasing ξ causes higher velocities in the forward direction ($n \to p$) and reduction in reciprocal rates ($p \to n$). Since the elements heavier than ^{4}He are generated in much smaller amount, one may approximately define Y_{p} as $Y_{\mathrm{p}} \approx 2X_{\mathrm{n}}$. Therefore, the lepton asymmetry in the early Universe plays a double role. Increase in ξ, on the one hand, increases Y_{p} due to the increase of $\rho_{\nu\tilde{\nu}}$ and change in the dynamics of the Universe expansion, and on the other hand, it decreases Y_{p} due to the change in the rate of weak reactions. At the same time the total action of the lepton asymmetry reduces to the decrease of Y_{p}. Therefore, the lepton asymmetry can compensate the effect of increased primordial ^{4}He abundance, caused by the potential presence of light sterile neutrinos.

3. Results

The necessary correlation between ξ and ΔN_{eff} obtained from the numerical solution to equation (6), is presented in the figure. The function $Y_{\mathrm{p}}(\xi, \Delta N_{\mathrm{eff}})$ obtained from the solution to equation (6) may be approximated with the following expression:

$$Y_{\mathrm{p}} = 0.2462 \times \left(1 + \frac{\Delta N_{\mathrm{eff}}}{3}\right)^{0.178\pm0.002} (1-\xi)^{0.9537\pm0.0002}, \quad (7)$$

where the errors of the powers correspond to the uncertainty of value $Y_{\mathrm{p}}^{(\mathrm{obs})}$. From equation $Y_{\mathrm{p}}(\xi, \Delta N_{\mathrm{eff}}) = Y_{\mathrm{p}}^{(\mathrm{obs})}$ one may produce the following approximation formula of interconnection between ξ and ΔN_{eff}:

$$\xi = 1 - \left(1 + \frac{\Delta N_{\mathrm{eff}}}{3}\right)^{-(0.187\pm0.002)}. \quad (8)$$

For complete compensation of the additional degree of freedom $\Delta N_{\mathrm{eff}} = 1$ we obtain from expression (8) the necessary value of the asymmetry parameter $\xi = 0.052 \pm 0.001$. This value is slightly different from value $\xi = 0.04$ from paper [13], which shows the best compliance with the observational data, where the results of paper [14] have not been taken into account yet.

Conclusion

The paper showed that the presence of light fully or partially thermalized sterile neutrino does not contradict the observational data on PN by value $\xi \approx 0.05$. Such value of lepton asymmetry may be generated in the epoch of PN within the existing leptogenesys models (including within νMSM) and resonant neutrino oscillations.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] T. Asaka, M. Shaposhnikov. Phys. Lett. B, **631**, 151 (2005). DOI: 10.1016/j.physletb.2005.09.070
[2] D.S. Gorbunov. Physics Uspekhi, **57** (5), 503 (2014). DOI: 10.3367/UFNr.0184.201405i.0545
[3] P.A. Chernikov, A.V. Ivanchik. Astron. Lett., **48** (12), 689 (2022). DOI: 10.1134/S1063773722110056
[4] D.S. Gorbunov, V.A. Rubakov. *Vvedenie v teoriyu ranney Vselennoy. Teoriya goryachego Bolshogo Vzryva* (LENAND, M., 2016), ed. 3-rd, Vol. 1. ISBN: 978-5-9710-1679-3
[5] B.D. Fields. JCAP, **03**, 010 (2020). DOI: 10.1088/1475-7516/2020/03/010.
[6] Planck Collaboration, A&A, **641**, A6 (2020). DOI: 10.1051/0004-6361/201833910
[7] S. Gariazzo et al., JCAP, **07**, 014 (2019). DOI: 10.1088/1475-7516/2019/07/014
[8] A.P. Serebrov, R.M. Samoilov, M.E. Chaikovskii, O.M. Zherebtsov. JETP Lett., **116** (10), 669 (2022). DOI: 10.1134/S002136402260224X
[9] L. Canetti, M. Drewes, T. Frossard, M. Shaposhnikov. Phys. Rev. D, **87**, 093006 (2013). DOI: 10.1103/PhysRevD.87.093006
[10] A.D. Dolgov. Nucl. Phys. B, **610**, 411 (2001). DOI: 10.1016/S0550-3213(01)00323-6
[11] S. Weinberg. *Cosmology* (Oxford University Press, 2008), ISBN: 978-0-19-852682-7
[12] R.V. Wagoner, W.A. Fowler, F. Hoyle. ApJ, **148**, 3 (1967). DOI: 10.1086/149126
[13] O. Seto, Y. Toda. Phys. Rev. D, **104**, 063019 (2021). DOI: 10.1103/PhysRevD.104.063019
[14] O.A. Kurichin, P.A. Kislitsyn, V.V. Klimenko, S.A. Balashev, A.V. Ivanchik. MNRAS, **502** (2), 3045 (2021). DOI: 10.1093/mnras/stab215

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