Several BBN Constraints on Beyond Standard Model Physics

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Abstract

We present several Big Bang Nucleosynthesis constraints on nonequilibrium processes in the Early Universe, representing Beyond Standard Model Physics, including neutrino oscillations, processes with considerable lepton asymmetry, with sterile neutrinos, chiral tensor particles (CTP) interactions, etc.

Keywords: Big Bang Nucleosynthesis constraints, Beyond SM physics, neutrino, chiral tensor particles, lepton asymmetry

1. Introduction

Big Bang Nucleosynthesis is the only reliable probe of the physical conditions of the Universe since its first seconds until the first 20 minutes of its evolution and, hence, BBN provides also a unique test of physics beyond the SM during this period of the radiation dominated (RD) epoch. During BBN the following light elements D, He-3, He-4 and Li-7, are produced in considerable abundances and some tiny traces of heavier nuclei Be-9, B-10, B-11 up to CNO isotopes. Recent reviews on BBN contemporary status can be found in Coc et al. (2015), Cyburt et al. (2016), Partignani (2017), Pitrou et al. (2018) [1-4].

The BBN production of the light elements depends on the baryon density, the expansion rate of the Universe and the interactions strength, usually parameterized correspondingly by baryon-to-photon ratio \( \eta = n_b / n_\gamma \), the relativistic energy density (effective number of relativistic neutrino types) and neutron life time \( \tau_n \). Hence, BBN is a precise Universe baryometer, an exact speedometer at RD stage and the most exact Universe lepton meter (as will be discussed in the next sections). Moreover, contemporary BBN is a parameter free, because all its parameters have already been measured independently. Namely, \( \eta \) has been determined with high precision from CMB anisotropy data (Ade et al., 2016) [5]:

\[ \eta_{\text{CMB}} = 6.10 \pm 0.04 \]

LEP experiments at CERN provided independent measurement of the number of weakly interacting neutrino :

\[ N_v = 2.984 \pm 0.008 \]

and CMB provided independent measurements of \( N_{\text{eff}} \) (the effective number of relativistic species), to be discussed in the next section.

\( \tau_n \) has been recently updated. The average \( \tau_n \) value according to Particle Data Group is [6]:

\[ \tau_n = 879.4 \pm 0.6 \text{ s} \]
BBN predicted abundances depend on the well measured cross sections of nuclear processes, which have been continuously updated. Over 400 nuclear reactions are considered. Modern analyses of nuclear rates for BBN have been provided (NACRE compilation of Angulo et al. 1999 [7]; NACRE-II, Xu et al. 2013[8]) and modern BBN codes are used. Like PArthENoPE (Pisanti et al., 2008; Consiglio et al., 2017), AlterBBN (Arbey, 2012), PRIMAT (Pitrou et al., 2018) [9-12]. BBN predicted yields of light elements are compared with their observationally determined abundances.

The primordially produced light elements abundances are obtained from observational data from regions least contaminated by stellar evolution and following account for galactic chemical evolution is provided. D is measured in high redshift low-metallicity H clouds which absorb light from background QSO. He-4 is determined from analysis of emission lines in extragalactic H II regions in blue compact galaxies, and the following regression to zero metalicity. Li is measured in Population II stars in the spheroid of the Galaxy, with extremely low metalicity, compared to the metalicity of the Sun: Z<1/100 ZSun. The contemporary observational determination of the primordial abundance of D reads (Cooke et al., 2017)[13]:
\[ D/H = (2.527\pm 0.03) \times 10^{-5}. \]

Recent He-4 primordial mass fraction determined with high accuracy is (Particle Data group 2019)[6]:
\[ Y_p = 0.245\pm 0.003. \]

The primordial Li is (Sbordone et al. 2010)[14]:
\[ \text{Li}/\text{H} = (1.58\pm 0.31) \times 10^{-10}. \]

It is by a factor of 3 less than the BBN predicted value. This Li-7 problem is considered as an indication for BSM physics. A recent review on Li problem is presented in ref. (Vinay Singh et al. 2017; see also A. Coc, 2016)[15,16].

The remarkable concordance between the predicted by BBN theory abundances and the determined from observational data allows to use BBN as the earliest test for BSM physics, corresponding to energy range (1 MeV- 10 KeV). BBN is sensitive to the expansion rate H(t), which at the RD stage is parametrized by \( N_{\text{eff}} \), where H(t) = (8/3\pi G)\rho^1/2.

\[ \rho \approx \rho_\gamma + \rho_\nu, \]

and to the lepton asymmetry \( L \) parameterized by the degeneracy parameter \( \xi \).

In standard BBN it is assumed that \( N_{\text{eff}} = 3.046 \) and \( \xi = 0 \). Both D and He-4 produced primordially depend on H(t), and are used to constrain \( N_{\text{eff}} \) (Steigman, 2012; Mangano et al. 2012)[18,17]. CMB provides complimentary bounds, which recently have become comparable in accuracy with the BBN ones.

A recent stringent BBN constraint reads (Pitrou et al. 2018)[4]:
\[ N_{\text{eff}} = 2.88^{+0.27}_{-0.27} \quad (68\%). \]

It is in good agreement with the CMB constraint (Planck Collaboration 2018+ lensing + BAO):
\[ N_{\text{eff}} = 2.99^{+0.34}_{-0.34} \quad (95\%). \]

A considerable reduction of the error was reached by using the updated Planck results plus D plus He-4 data (Pitrou et al. 2018)[4]:
\[ N_{\text{eff}} = 3.01^{+0.15}_{-0.15} \quad (95\% \text{ Planck} + \text{D} + \text{He-4}). \]

Additional relativistic during BBN sterile neutrino \( \nu_s \) is strongly constrained. The BBN cosmological bounds on \( N_{\text{eff}} \) are used also to constrain different models of beyond SM physics which introduce additional light species during the BBN epoch. Just to mention some of them: supersymmetric models, which introduce the lightest particle (neutralino or gravitino), string theory, extradimensions theories, GUT models with right handed neutrinos, etc.

BBN is sensitive to lepton asymmetry (Wagoner et al. 1967)). \( L \) increases the radiation energy density by
\[ \Delta N_{\text{eff}} = 15/7((\xi/\pi)^4 + 2(\xi/\pi)^2) \]

and speeds the Universe expansion, delays of matter/radiation equality epoch, thus influences BBN, CMB, evolution of perturbations i.e. LSS (Lesgourgues&Pastor 1999)[13].
L in the electron neutrino sector effects also neutron-proton kinetics in pre-BBN epoch, implying more stringent constraints on L in the electron neutrino sector. However, due to neutrino oscillations degeneracies in different sectors equilibrate before BBN (Dolgov et al. 2002; Mangano et al. 2011,2013)[20,21]. BBN constraints, based on its dynamical and kinetic effect, accounting for flavor neutrino oscillations and ν decoupling, and based on recent D and He-4 measurement, read:

$$|\xi_\nu| < 0.016(68\%CL) \quad L < 0.01$$

Neutrino active-sterile oscillations may change this bound. In case of electron-sterile oscillations BBN may feel L as small as 10^{-8} (Kirilova 2012)[35] (to be discussed in the third section).

In the next section we discuss BBN with non-equilibrium electron-sterile neutrino oscillations and BBN constraints on neutrino oscillation parameters in case of initially empty sterile neutrino state and case of non-empty sterile state. The third section discusses BBN with tiny L, L<<0.01, and the change of BBN constraints in the presence of such L. The forth section presents BBN constraints on additional chiral tensor particles interactions. The last section presents a summary of the results.

2. BBN Constraints on Non-equilibrium Electron-Sterile Neutrino Oscillations

Fast active-sterile neutrino oscillations proceeding before electron neutrino decoupling bring into equilibrium the sterile neutrino state, thus increasing H(t) and influencing BBN Dolgov (1981)[23]. Besides this dynamical effect these oscillations lead to depletion of the electron neutrinos, which was first estimated in refs. Barbieri&Dolgov (1990, 1991)[24,25]. First BBN constraints on neutrino oscillations in medium were obtained in these pioneer works, see also (Enqvist et al, 1992)[26].

Nonequilibrium electron-sterile neutrino oscillations proceeding after decoupling, $\delta m^2 \sin^2 2\theta < 10^{-7}eV^2$ may distort neutrino energy spectrum and change νe number densities (Kirilova 1988, Kirilova&Chizhov M., 1997, 1998, 1998b) [27,22,28,29], and suppress or enhance neutrino–antineutrino asymmetry (Kirilova&Chizhov M., 1996, 2000)[30,31]. These neutrino oscillations do not have dynamical effect on BBN, they influence it by their effects on pre-BBN nucleons kinetics.

We have studied numerically the evolution of neutron ensembles, evolution of L, and the evolution of nucleons during pre-BBN epoch for the full parameter range of parameters of the oscillations model, and for different population of the sterile neutrino state $0 \leq \delta N_s < 1$ and different values of the relic lepton asymmetry $10^{-11} < L < 0.01$.

We have followed the evolution of the oscillating ν and νe, and the nucleons accounting simultaneously for Universe expansion, neutrino oscillations and neutrino forward scattering.

The evolution of BBN produced He-4 and its dependence on the parameters of the model and its initial conditions, $Y_p$ ($\delta m^2, \theta, L, \delta N_s$) was numerically analyzed. An enormous overproduction of primordially produced He-4 - up to 32% - was found possible mainly due to spectrum distortion of electron neutrino from its equilibrium Fermi-Dirac form caused by neutrino oscillations. This allowed to strengthen previous constraints on neutrino oscillation parameters.

BBN constraints, corresponding to $\delta Y_p/Y_p = 3\%$, $5\%$, $7\%$ were calculated. The analytical fit corresponding to $\delta Y_p/Y_p = 3\%$, for initially zero sterile neutrino population and L of the order of the baryon asymmetry is

$$\delta m^2 \left( \sin^2 2\theta \right)^4 \leq 1.5 \times 10^{-3} eV^2 \quad \delta m^2 > 0$$
$$\delta m^2 < 8.2 \times 10^{-10} eV^2 \quad \text{large } \theta, \delta m^2 < 0$$

The presence of initially non-zero $\nu_s$ state changes BBN constraints on ν oscillations. BBN with neutrino oscillations and non-zero $\nu_s$ population were considered in refs (Kirilova 2004, 2007 ; Kirilova&Panayotov 2006)[32-34]. Additional $\nu_s$ increases H(t) by their contribution to the relativistic energy density during BBN, thus increasing the overproduction of He-4, however they also influence the kinetic effect of electron-sterile oscillations $\delta N_{\nu_s}(\theta ; \delta m^2)$ – they decrease it, thus decreasing the overproduction of He-4 due to neutrino oscillations.

The following empirical relation, derived in refs. (Kirilova, 2004,2007) describes the interplay between these effects:

$$\delta N_{\nu_s}(\theta ; \delta m^2) = \delta N_{\nu_s} (\theta ; \delta m^2) + \delta N_s$$

where $\delta N_{\nu_s}(\theta ; \delta m^2) = \delta N_{\nu_s,nu} (\theta ; \delta m^2)(1-\delta N_s)$
and $\delta N^{max}_{kin}$ is the maximal kinetic effect corresponding to $\delta N_\nu = 0$.

Thus, due to the interplay between the dynamical and kinetic effects non-zero initial population of $\nu_s$ (partially filled) exert non-trivial dependence of BBN and on BBN constraints. Namely, in case the dynamical effect dominates, additional $\nu_s$ population leads to enhancement of He-4 overproduction and strengthens the BBN constraints in comparison with the case of initially zero $\delta N_\nu$. In case the kinetic effect dominates He-4 overproduction decreases with $\delta N_\nu$ increase and BBN constraints relax.

Recently primordial He-4 and D were determined with high accuracy:

$$Y_p = 0.24709 \pm 0.00017 \quad (\text{Pitrou et al. } 2018),$$

$$D/H=(2.527\pm0.03) \times 10^{-5} \quad (\text{Cooke et al.}, 2017).$$

BBN constraints on neutrino oscillations corresponding to $\delta Y_p/Y_p = 1\%$, in accord with the present accuracy of He-4 determination, are to be presented in our study (D.Kirilova, E.Chizhov, 2019).

3. Lepton Asymmetry Effect on Neutrino Oscillations and BBN Constraints

The lepton asymmetry of the Universe $L$ may be non-negligible, i.e. much bigger than the baryon asymmetry, and hidden in the neutrino sector. Standard BBN constrains the value of $L$: $L< 0.01$. However, BBN with electron-sterile neutrino oscillations, discussed above, was shown to be extremely sensitive leptometer, able to detect tiny $L$, $10^{-8} < L < 0.01$ (Kirilova, 2012)[35]. The dynamical and direct kinetic effect of such $L$ are negligible. However, such small $L$ both relic or oscillations generated, influences indirectly BBN via $L$ effect on neutrino oscillations.

Namely, $L$ effects oscillations by changing neutrino number densities; neutrino distribution and neutrino oscillations pattern (depending on its value it can suppress them or lead to their resonant enhancement). On the other hand, oscillations also are capable of suppressing the asymmetry or amplifying it.

Neutrino active-sterile oscillations can suppress pre-existing asymmetry (Barbieri & Dolgov 1991; Enqvist et al. 1992)[25,26] or enhance $L$ in MSW resonant active-sterile oscillations for $\delta m^2 \sin^4 2\theta < 10^{-7} eV^2$ in the collisionless case (Kirilova & Chizhov 1996)[30] and $\delta m^2 > 10^{-5} eV^2$ in oscillations dominated by collisions (Foot et al. 1996)[37].

For non-equilibrium neutrino oscillations between $\nu_e$ and $\nu_s$, effective after $\nu_e$ decoupling, large generation of $L$ was shown possible for (Kirilova, 2012)[35]:

$$|\delta m^2| \sin^4 2\theta \leq 10^{-9.5} eV^2$$

This neutrino oscillations generated asymmetry exerts back reaction on the production of the primordial He-4, namely it suppresses neutrino oscillations and reduces the overproduction of He-4 due to them. Hence, it relaxes BBN constraints on neutrino oscillations parameters (Kirilova, 2000, 2012, 2018)[31,35,36].

Relic asymmetry $L$ may suppress oscillations (Foot & Volkas 1995; Kirilova & Chizhov 1998)[38,28] or enhance oscillations (Kirilova & Chizhov 1999, Kirilova 2012)[29,35]. We have numerically studied that interplay and determined the parameter range for which lepton asymmetry is able to enhance, suppress or inhibit oscillations.

The numerical analysis has proved that for non-equilibrium electron-sterile oscillations discussed here $L < 10^{-8}$ does not effect oscillations and such tiny $L$ may be safely neglected. $L > 10^{-7}$ enhances oscillations, leading to strengthening the BBN bounds on them; while larger $L$ suppress oscillations. $L$ necessary to inhibit neutrino oscillations and hence, to eliminate the BBN bounds on oscillation parameters, is given by (Kirilova 2018)[36]:

$$L > (0.01 \delta m^2 / eV^2)^{1/3}$$

In that case instead this relation can be used as an approximate bound on neutrino mass differences at maximal mixing.

We proposed the ability of L to suppresses and inhibit $\nu_s \leftrightarrow \nu_e$ oscillations, thus preventing $\nu_e$ thermalization, and avoiding cosmological constraints on eV sterile neutrinos as a solution of the dark radiation problem (Kirilova 2012,2013)[35,39]. See also the works by Mirizzi et al. (2012)[40], Hannestad et al. (2012)[41], dedicated to this type of solution.

We calculated also the change of BBN constraints due to dynamical (oscillations generated) or initially present L. In the presence of L BBN constraints on oscillation parameters of neutrino change. We have found that:

a) the asymmetry growth caused by oscillations relaxes BBN constraints at small mixings and strengthens them at large mixings;
b) initial L may relax BBN bounds at large mixings and strengthens them at small mixing;
c) BBN with electron-sterile oscillations feels tiny L and for given neutrino mass difference and it provides the constraint on L:
\[ L < (0.01 \Delta m^2)^{1/5} \]

4. BBN Constraints on CTP Interaction Strength

Chiral tensor particles (CTP) were introduced as an extension of Standard Model for completeness of the representation of the Lorentz group (M. Chizhov, 1993) [42]. These bosons are carriers of new interaction and have only chiral interactions with the known fermions, through tensor anomalous coupling. Experimental search for CTP is conducted at ATLAS experiment of the Large Hadron Collider, which provided experimental constraints on CTP characteristics (Aad et al., 2014) [43].

The cosmological influence of CTP has been considered in Kirilova, Chizhov, 1998; M. Chizhov & Kirilova, 2009; Kirilo-va & V. Chizhov, 2017; Kirilova & E. Chizhov, 2018) [44-48].
CTP contribute to the matter tensor in the right-hand side of the Einstein–Hilbert equation and change the dynamical evolution of the Universe. Namely, the energy density increase caused by the additional degrees of freedom \( g_{CTP} \) BSM physics model with CTP leads to speeding up of the expansion of the Universe during the period of CTP presence:

\[ H = \sqrt{\frac{8\pi^2 G_N g_{eff}(T)}{90} T^2} \]

where \( g_{eff} = g_{SM} + g_{CTP} \).

Besides, CTP directly interact with the particles present at the early high energy stage of the Universe. Using experimental constraints on CTP from ATLAS (Aad et al. (ATLAS Coll.) 2014) [43] the processes of CTP with the constituents of the early Universe plasma, their creation, decay, annihilation and scattering were considered (Kirilo-va, V. Chizhov, 2017) [46]. The period of CTP effectiveness was determined to be:

\[ 6 \times 10^{-42} \text{s} < t < 5 \times 10^{-14} \text{s} \]

This period is at a too early stage of Universe evolution, so they did not directly effect BBN, CMB, LSS or other processes which have left observable relics in todays Universe.

Here we present cosmological constraints on the CTP coupling constant based on the possible interactions of CTP with right-handed neutrinos and their influence on the Big Bang Nucleosynthesis, Kirilova, E. Chizhov, 2019 [48].

If right-handed neutrinos interact with the CTP, they may be produced through CTP exchange during BBN. The term of the effective Lagrangian corresponding to the right-handed neutrino coupling reads:

\[ L = 4 \sqrt{2} G_T \bar{e}_L^c \sigma_{\alpha \beta} \nu_R^\alpha \cdot \bar{\nu}_L^\beta \sigma_{\alpha \beta} d_R + h.c. \]

where \( G_T \) is CTP interaction strength,

\[ \sigma_{\alpha \beta} = \frac{1}{2} \left( \gamma_a \gamma_{\alpha} - \gamma_{\beta} \gamma_a \right) \]

If we impose conservative BBN constraint \( \delta N_e < 1 \) at BBN epoch and entropy conservation: \( g_T^{1+} \), we can calculate \( T_f \) decoupling temperature of right-handed neutrino, assuming dilution of the energy density of 3 neutrino species by factor

\[ \left( \frac{g_\ast(T_R)}{g_\ast(T_i)} \right)^{3/2} > 3; \quad g_\ast(T_R) > 2.28 \times 10.75 = 24.5, \]

which corresponds to \( T_f > 131 \text{ MeV} \).
$T_f$ depends on $G_f$:

$$\frac{\Gamma_R}{H} = \left( \frac{T_R}{T_L} \right)^3 \left( \frac{G_T}{G_F} \right)^2 \sim 1; \quad G_f \leq 1.7 \times 10^{-2} G_F$$

If we impose recent BBN constraint, Pitrou et al. 2018 [4], $\delta N_e < 0.3$ at BBN epoch the following constraints follow, D. Kirilova, E. Chizhov, 2019 [48]

for 3 light right handed neutrinos $T_f > 354$ MeV and

$$G_f \leq 4.2 \times 10^{-6} G_F$$

for 2 light right handed neutrinos

$$G_f \leq 8.4 \times 10^{-4} G_F$$

for 1 light right handed neutrinos

$$G_f \leq 1.4 \times 10^{-3} G_F$$

CTP interactions are expected to be by three orders of magnitude weaker than the weak interactions (milliweak) or less from contemporary precise BBN data (alternatives: no interactions with fermions, or no light right handed neutrino,…). The eventual detection of the chiral tensor particles at LHC will be of great interest because it will provide a TeV window on the Universe and reveal the realm of milli weak interactions.

5. Results and Conclusions

BBN is a powerful probe of the early Universe physics. It severely constrains additional radiation density, lepton asymmetry, neutrino oscillations, additional interactions, etc.

BBN with nonequilibrium $\nu_i \leftrightarrow \nu_\ell$ oscillations allows to put stringent constraints on $\nu$ oscillation parameters in resonant and non-resonant neutrino oscillations case.

BBN constraints on neutrino oscillations parameters depend nontrivially on the population of sterile neutrino and $L$ in the Universe. Additional initial population of the sterile state not always leads to strengthening of constraints - it may relax them. Dynamically generated asymmetry relaxes BBN constraints at small mixing angles.

Relic $L$ may provide relaxation or enhancement of BBN constraints on oscillations. $L=10^4$ relaxes BBN bounds at large mixing and strengthens them at small mixing. Larger $L$ provide relaxation of BBN constraints on oscillations, by suppressing oscillations and causing incomplete thermalization of the sterile neutrino. Large enough $L$ alleviates BBN constraints on oscillation parameters. In that case new stringent cosmological constraints on $L$ are derived in the model of BBN with neutrino oscillations.

In case CTP interact with light right handed neutrinos stringent BBN constraints have been obtained on CTP interaction strength.

CTP could be present at energies typical for inflation, Universe reheating and leptogenesis and baryogenesis. Hence, it is interesting to explore the role of CTP in these processes.

Future astrophysical observations and experiments at accelerators and colliders are necessary to improve our knowledge about the early Universe and detect BSM physics.

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