Cosmological Constraints on Chiral Tensor Particles

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We discuss an extended model with chiral tensor particles in the Universe. Their direct influence on the Universe dynamics and their characteristic interactions in the hot Universe plasma, considered in previous publications, are briefly reviewed. A short discussion on the contemporary cosmological bounds on effective number of the relativistic degrees of freedom is provided. Cosmological constraints on the tensor particles interactions strength are obtained, corresponding to different cosmological bounds on the relativistic degrees of freedom and for different assumptions about right handed neutrinos.

Keywords: chiral tensor particles; early Universe; BBN constraint

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1. Introduction

The extended model with chiral tensor (ChT) particles, new type of spin-1 particles, was first discussed by Chizhov.\textsuperscript{1} The ChT particles were introduced as an extension of the Standard Model for completeness of the representation of the Lorentz group. These particles are predicted to be the carriers of new interaction and they have only chiral interactions with the known fermions, through tensor anomalous coupling. This model and its predictions, as well as the signatures for the experimental detection of ChT particles have been discussed in numerous publications.\textsuperscript{2–6} Experimental constraints on ChT particles masses and couplings provided by the ATLAS collaboration at the Large Hadron Collider at CERN, that carries on an experimental search of ChT particles.

The cosmological influence of ChT particles has been analyzed, as well (see refs.\textsuperscript{10–14}) in these works ChT particles influence on the Universe dynamics and their characteristic interactions with the early Universe plasma were considered.

The ChT particles and the corresponding extension of the Higgs sector contribute to the matter tensor in the right-hand side of the Einstein–Hilbert equation,
increasing the Universe density and changing the dynamical evolution of the Universe. Namely, at the early epoch while ChT particles are relativistic, their additional degrees of freedom and the ones introduced by the corresponding Higgs sector extension in the model increase the total effective degrees of freedom by \( g_{\text{ChT}} = 28 \), corresponding to two additional tensor doublets, a triplet and singlet gauge vector particles and an extra Higgs doublet. This results into a slight increase of the expansion rate during the period of effective interactions of ChT particles in comparison with the Standard Cosmological Model.

The characteristic interactions of ChT particles with the early Universe plasma, their creation, scattering, annihilation and decay processes were updated recently\textsuperscript{13} using the latest experimental constraints on their characteristics, that have been obtained at ATLAS (Aad et al., 2014, 2014a)\textsuperscript{8, 9} at LHC. The constraints on the tensor particle masses, provided by the ATLAS Collaboration read \( M_0^T > 2.85 \) TeV and \( M_+^T > 3.21 \) TeV.

The time interval of effective interactions of ChT particles in the early Universe history and, hence, of their abundant presence was determined to be\textsuperscript{13}

\[ t_c = 6 \times 10^{-42} \, s < t < t_d = 5 \times 10^{-14} \, s. \]

The corresponding energy range is from \( T_c = 1.8 \times 10^{17} \) GeV down to \( T_d = 6 \times 10^3 \) GeV. ChT creation processes unfreeze at \( t > t_c \), when the Universe temperature falls below \( T_c \), where \( T_c \) has been estimated by comparing the tensor particle creation rate with the universe expansion rate at the radiation dominated (RD) epoch \( H = \sqrt{8\pi^3G_N g_* / 90 T^2} \), where \( g_* \) is the total number of the effective degrees of freedom\textsuperscript{13}.

In most inflationary scenarios, however, the temperature at the reheating epoch after inflation is much lower. Thus, actually tensor particles creation processes proceed effectively since the reheating epoch of the concrete inflationary model till ChT decay at around \( T_d = 6 \times 10^3 \) GeV.

Chiral tensor particles are present during a period much earlier than the Big Bang Nucleosynthesis (BBN) epoch and Cosmic Microwave Background (CMB) formation epoch, and, therefore, ChT particles cannot directly influence the observable relics from BBN and CMB - the light element abundances and the observed characteristics of CMB.

However, in case ChT particles interact with the right-handed neutrinos (or other representatives of dark radiation)\textit{indirect constraints} on ChT interactions can be obtained from the requirement that the introduced into equilibrium additional relativistic right-handed neutrinos should not exceed the cosmological (BBN, CMB, etc.) limits.

In the next section we discuss different recent cosmological constraints on the effective number of relativistic particles. In the third section we discuss the possible ChT particles interactions with right-handed neutrinos and obtain a cosmological constraint on the ChT particle interactions strength for different number of light right handed neutrino species and for different cosmological bounds on the effective number of relativistic particle species during BBN.
2. BBN and cosmological constraints on additional radiation

Big Bang Nucleosynthesis is a reliable probe of the physical conditions of the early universe and provides a unique test of Physics Beyond the SM during the radiation dominated epoch. See for example refs. [16–19].

Contemporary BBN is theoretically well established - based on well-understood physics. The primordially produced abundances are usually parameterized by the baryon-to-photon ratio, relativistic energy density (effective number of relativistic neutrino types $N_{\text{eff}}$) and neutron life time. The predicted abundances depend also on the well measured cross sections of nuclear processes, which have been continuously updated [20, 21]. More and more precise BBN codes have been invented [22–25].

Precision Planck CMB measurements also probe the baryon density, helium content, and $N_{\text{eff}}$, thus allowing for an independent precise cosmological test using CMB data alone [16].

The precision of observational data on primordial abundances has been drastically improved, as well, during the last decade. New observations of high redshift low metallicity QSO help to improve considerably the determination of $D$ and its uncertainty [20]. During recent years more precise determination of He-4 abundance was provided, as well, thanks to its updated emissivity and the observed new infra-red line [27].

BBN predicted abundances (except Li-7) are in a good overall agreement with the ones inferred from observations. This good concordance between BBN theory and observational data allows to use it as a precision probe of Beyond SM Physics during the BBN epoch (1 MeV-10 KeV).

2.1. Cosmological constraints on the effective number of relativistic particles

In particular, BBN is used as a precise speedometer at RD stage. He-4 is very sensitive element to the expansion rate of the universe at the BBN epoch $H(t)$, which is usually parameterized by the effective number of relativistic neutrino types $N_{\text{eff}}$ (Shvartsman 1969) [23]. At RD stage of the universe relativistic neutrinos (or any additional relativistic particles) contribute to the total energy density $\rho$ by:

$$\rho_\nu = \frac{7}{8}(T_\nu/T)^4 N_{\text{eff}}\rho_\gamma(T).$$

Hence, they influence the expansion rate of the universe $H \sim \sqrt{8\pi G N_{\text{eff}}\rho/3}$, and the primordial production of light elements.

Hence, the cosmological bounds on $\delta N_{\text{eff}}$ are used to constrain Beyond SM physics which introduce additional light species, as for example supersymmetric scenarios (constraining lightest particle neutralino or gravitino), string theory, extra dimensions theories, theories with right-handed (sterile) neutrinos, neutrino oscillations, lepton asymmetry, the discussed here chiral tensor particles, etc.

We list below some of the recently obtained cosmological bounds on $N_{\text{eff}}$. 
A maximum likelihood analysis by Cyburt et al. (2016) provides the following BBN constraints: $N_{\text{eff}} < 3.4$.

Recently He-4 primordial mass fraction was determined with even higher accuracy (Pitrou et al. (2018)):

$$Y_p = 0.24709 \pm 0.00017.$$ 

This allowed to put the following stringent constraints on $N_{\text{eff}}$ by cosmological considerations of the BBN produced He-4:

$$N_{\text{eff}} = 2.88 \pm 0.27 \text{ (95%).}$$

For comparison the CMB constraint (Planck Collaboration 2015) reads:

$$N_{\text{eff}} = 3.13 \pm 0.31 \text{ (95%).}$$

Besides, constraints on $N_{\text{eff}}$ have also been obtained on the basis of Lyman Alpha forest BOSS data, CMB data from Planck, ACT, SPT, WMAP polarization (Rossi Yeche et al. 2015):

$$N_{\text{eff}} = 2.911 \pm 0.22 \text{ (95%).}$$

for neutrino mass $m_\nu < 0.15$ eV. Similar stringent constraints from baryon acoustic oscillations data are discussed by Sasankan et al. 2017.

The improved determination of $D$ provides even more stringent constraints. $D/H$ provides a tight measurement of $N_{\text{eff}}$ when combined with the CMB baryon density and provides a $2\sigma$ upper limit $N_{\text{eff}} < 3.2$.

Using CMB plus $D$ plus He-4 data allows a considerable reduction of the error:

$$N_{\text{eff}} = 2.88 \pm 0.16 \text{ (95% Planck + D + He - 4)}$$

Similar stringent constraint is provided by CMB plus BBN analysis:

$$N_{\text{eff}} = 3.01 \pm 0.15 \text{ (95% Planck + BBN)}$$

In particular, cosmology constraints severely the thermalized during BBN light sterile neutrinos. In the next section these cosmological limits are used to constrain the decoupling temperature of right handed neutrinos and ChT particles interaction strength.

### 3. BBN Constraints on the ChT Particles Interactions Strength

If right-handed neutrinos interact with the chiral tensor particles they may be produced through ChT particles exchange during BBN epoch. The term of the effective Lagrangian corresponding to the right handed neutrino coupling reads:
\[ L = \frac{4}{\sqrt{2}} G_T \bar{e}_L \sigma_{\alpha \beta} \nu_R \cdot \bar{u}_L \sigma_{\alpha \beta} d_R + h.c. \]

where \( G_T \) measures the effective ChT interaction strength, \( \sigma_{\alpha \beta} = \frac{i}{2} (\gamma_\alpha \gamma_\beta - \gamma_\beta \gamma_\alpha) \).

It is straightforward to obtain cosmological bound on the coupling constant of new particles on the basis of BBN considerations. Cosmological constraint on \( G_T \) was first discussed in ref.\(^{12}\)

In what follows we obtain cosmological constraints on ChT interaction strength \( G_T \) for different number of light right handed neutrinos and using different cosmological constraints on the effective number of relativistic particle species \( \delta N_{\text{eff}} \).

Assuming that ChT particles interact with right handed neutrinos, we determine also the decoupling temperature of right-handed neutrinos in different cases.

### 3.1. \( \delta N_{\text{eff}} < 0.4 \).

At present the most conservative BBN bound on the additional relativistic (light) neutrinos is:

\[ \delta N_{\text{eff}} = g_R (T_{\nu_R}/T_{\nu_L})^4 < 0.4. \]  

(2)

Then in case of three light right-handed neutrinos \( \nu_R \), it follows

\[ 3 (T_{\nu_R}/T_{\nu_L})^4 < 0.4, \]  

(3)

which puts a constraint on the decoupling/freezing temperature of the right-handed neutrinos \( T_f \) using the BBN constraint on \( \delta N_{\text{eff}} \) and entropy conservation relation

\[ g T^3 = \text{const}, \]

namely

\[ T_{\nu_R}/T_{\nu_L} = \left( \frac{43}{4}/g_*(T_f) \right)^{1/3} < 0.604. \]

(4)

The following constraint on the decoupling temperature is obtained:

\[ T_f > 251 \text{ MeV}. \]  

(5)

The decoupling temperature of a given species is connected with its interactions coupling strength:

\[ (G_T/G_F)^2 \sim (T_f/2 \text{ MeV})^{-3}, \]  

(6)

where 2 MeV is the decoupling temperature of the active neutrino species, \( G_F \) is the Fermi constant. Hence, the constraint on the ChT particles coupling is derived:

\[ G_T < 7.1 \times 10^{-4} G_F. \]

(7)

In case of 2 light sterile neutrinos the decoupling temperature is \( T_f > 177 \text{ MeV} \) and the corresponding constraint on ChT particles coupling reads: \( G_T < 1.19 \times 10^{-3} G_F. \). For only 1 light sterile neutrino the constraints are, correspondingly: \( T_f > 125 \text{ MeV} \) and \( G_T < 2.0 \times 10^{-3} G_F. \).
3.2. $\delta N_{\text{eff}} < 0.3$.

Using the bound:

$$\delta N_{\text{eff}} = g_R (T_{\nu_R}/T_{\nu_L})^4 < 0.3,$$

which is close to the recently obtained refined BBN bound on the additional light neutrinos\(^{25}\) we determined the cosmological constraint on ChT interaction strength in case of 3, 2 and 1 light sterile neutrino. Following the described above considerations, in case of tree light $\nu_R$ the decoupling temperature of $\nu_R$ is found to be $T_f > 354$ MeV and the BBN constraint on ChT particles strength is

$$G_T < 4.2 \times 10^{-4} G_F. \tag{9}$$

In case of 2 light $\nu_R$, we have found $T_f > 224$ MeV and $G_T < 8.4 \times 10^{-4} G_F$, correspondingly.

In case of 1 light $\nu_R$, $T_f > 158$ MeV and $G_T < 1.4 \times 10^{-3} G_F$.

3.3. $\delta N_{\text{eff}} < 0.2$.

For the more stringent BBN constraint

$$\delta N_{\text{eff}} = g_R (T_{\nu_R}/T_{\nu_L})^4 < 0.2,$$

obtained when D data is also included\(^{16}\) the cosmological constraints on $G_T$ for 3, 2 and 1 $\nu_R$ are correspondingly:

In case of tree light $\nu_R$, $T_f > 1585$ MeV

$$G_T < 4.5 \times 10^{-5} G_F. \tag{11}$$

In case of 2 light $\nu_R$, $T_f > 354$ MeV and $G_T < 4.2 \times 10^{-4} G_F$.

In case of one light $\nu_R$, $T_f > 178$ MeV and $G_T < 1.2 \times 10^{-3} G_F$.

Thus, contemporary precise cosmological data, and in particular the improved bounds on $\delta N_{\text{eff}}$, leads to more stringent constraints on ChT particles interactions - they should be milli-weak or weaker (depending on the assumed number of light right-handed neutrino species). Therefore, for all analyzed cases the derived cosmological constraints require tensor particles masses higher than several TeV, while in many cases they should be higher than tens of TeV. Thus, the obtained here cosmological constraints are stronger than the experimental constraints on the tensor particle masses, provided by the ATLAS Collaboration at LHC.

4. Conclusion and Discussion

We discuss an extended Beyond Standard Model of Particle Physics and Cosmology with new ChT particles. The presence of these particles during the very early universe leads to slight speed up of the universe expansion and ChT particles direct interactions in the early universe plasma: creation, scattering, annihilation and decay. However, it was found that ChT particles have been abundant at such an
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early stage of universe evolution, that they or their decay products have not effected BBN, CMB or other processes which have left observable relics in today’s universe. Thus, ChT particles are allowed from cosmological considerations, however, direct cosmological constraints cannot be obtained.

However, indirect cosmological constraints on ChT interactions can be derived in case ChT particles interact with right handed neutrinos. In this work we discuss this possibility. We have derived stringent cosmological constraints on ChT interactions strength - it should be milli weak or weaker, depending on the number of the light right-handed neutrino types. For all analyzed cases tensor particles masses should be higher than several TeV, while for many cases they should be higher than tens of TeV. Thus, the obtained here cosmological constraints are in accord or stronger than the experimental constraints on the tensor particle masses, provided by the ATLAS Collaboration at LHC. The eventual experimental detection of the chiral tensor particles will be of great interest because it will reveal the realm of milli weak interactions.

These cosmological constraints can be interpreted also as an indication for absence of ChT interactions with sterile neutrinos. On the contrary, eventual future detection of the ChT particles and determination of their interaction strength may be used as an indicator for the number of the light right-handed neutrino species.

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