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Article

# FRW Cosmology with Chiral Tensor Particles

Daniela Kirilova <sup>1,\*</sup>, Emanuil Chizhov <sup>1</sup> and Mihail Chizhov <sup>2</sup>

<sup>1</sup> Institute of Astronomy and NAO, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria; echizhov@astro.bas.bg

<sup>2</sup> Faculty of Physics, Sofia University "St. Kliment Ohridski", 1164 Sofia, Bulgaria; mih@phys.uni-sofia.bg

\* Correspondence: dani@astro.bas.bg

**Abstract:** We discuss an extended model of FRW cosmology with additional chiral tensor particles. We discuss the influence of these particles on the expansion rate of the Universe, their direct interactions with the constituents of the early Universe plasma, we determine their cosmological place and derive updated cosmological constraints on their interaction strength.

**Keywords:** chiral tensor particles; beyond standard model; Big Bang nucleosynthesis; right handed neutrino

## 1. Introduction

We discuss an electroweak model with a new type of boson particles, chiral tensor particles (CTP), and CTP effects in the primeval plasma of the early Universe. CTP are chiral particles with spin-1 and carry only chiral interactions with the known fermions [1].

The cosmological influence of the CTP, specifically the *CTP dynamical effect* and *CTP direct and indirect interactions*, discussed in previous publications [2–4,4] are reviewed. It was found that CTP have *dynamical effect* due to their contribution to the matter tensor in the Einstein-Hilbert equation, leading to a change in the dynamical evolution of the Universe. CTP also have *direct interactions* with particles present at the early stages of the Universe.

Non-direct effects of the CTP particles on the early evolution of the Universe were considered as well [2,5–7]. Cosmological constraint on the CTP coupling constant, based on possible interactions of CTP with right-handed neutrinos and their influence on the Big Bang Nucleosynthesis (BBN) were obtained. CTP interaction strength was constrained to be centi-weak or weaker.

In this publication we consider CTP indirect effects during the BBN, and use them to obtain updated cosmological constraints on CTP interaction strength. The constraints are based on the most recent precise data on the light element abundances of  $D$  and  ${}^4He$ . As will be shown in this work, we obtain by order of magnitude stronger constraints.

Next section presents a short review on the extended electroweak model with additional chiral tensor particles. In Section 3 the influence of the CTP in the early Universe is discussed, in Section 4 we derive updated constraints on *right handed neutrino freezing temperature* and on *CTP coupling strength*, obtained on the basis of the indirect CTP effect on BBN.

## 2. Extended Electroweak Model with Additional Chiral Tensor Particles

An electroweak model with additional chiral tensor particles was proposed on the basis of theoretical considerations, namely the completeness of the representation of the Lorentz group, in the pioneer publication by M. Chizhov [1]. It has also been shown that such particles can help to solve hierarchy problem [8]. These chiral tensor particles resemble the Higgs doublet and transform under the fundamental representation of  $SU(2)_L$  group of the Standard Model. However, contrary to the scalar Higgs field CTP are spin-1 chiral particles and are carriers of new interaction and have chiral interactions with the known fermions, through tensor Pauli anomalous coupling. More detail about the extended model



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with CTP can be found in the review [9]. (We would like to note that both the Avdeev-Chizhov CTP model and its CP generalization inspired by the SU(2/1) superalgebraic chiral structure of the electroweak interactions are both conformal invariant in any even dimension [10].)

CTP are represented by an *antisymmetric* tensor fields of a rank two. Therefore, CTP are introduced as doublets  $T_{\mu\nu} = (T_{\mu\nu}^+, T_{\mu\nu}^0)$ . An additional doublet  $U_{\mu\nu} = (U_{\mu\nu}^0, U_{\mu\nu}^-)$  with an opposite chiral- and hypercharge and also the extended Higgs sector  $(H_1^+, H_1^0), (H_2^0, H_2^-)$  with second doublet are introduced to avoid chiral anomalies, connected with CTP. As in the Standard Model, a Higgs-like mechanism is used to provide mass to the massless tensor particles, which have just longitudinal degrees of freedom. However, contrary to the Standard Model, the role of the Higgs field is played by gauge vector particles: four  $SU(2)_L$  singlets  $P_\mu^i (i = 1, \dots, 4)$  or by a triplet, denoted by  $C_\mu$ , and singlet,  $P_\mu^5$  (depending on the chiralities of the CTP). These vector fields have triple interactions with CTP and the Higgs fields, which enable CTP to acquire transverse physical degrees of freedom. To avoid flavor violation of neutral currents due to the doubling of doublets it is assumed that the doublets  $H_1$  and  $T_{\mu\nu}$  interact only with down-type fermions, while the doublets  $H_2$  and  $U_{\mu\nu}$  — with up-type ones.

CTP have chiral Yukawa interactions with the known fermions. Their Lagrangian reads [9]:

$$\mathcal{L}_T = \frac{y_U}{2\sqrt{2}} \bar{Q} \sigma^{\mu\nu} u_R U_{\mu\nu} + \frac{y_T}{2\sqrt{2}} (\bar{Q} \sigma^{\mu\nu} d_R + \bar{L} \sigma^{\mu\nu} e_R) T_{\mu\nu} + h.c., \quad (1)$$

where  $Q = (u_L d_L)$  and  $L = (v_L e_L)$  are quarks and leptons doublets. It is obvious that this Lagrangian is invariant with respect to all internal symmetries.

The introduction of additional particles, namely two additional tensor doublets, the triplet and singlets gauge vector particles and the extra Higgs doublet increases the total effective number of the degrees of freedom by

$$g_{CTP} = g_T + g_U + g_C + g_P + g_H = 4 + 4 + 6 + 10 + 4 = 28. \quad (2)$$

Due to CTP unique properties it is possible to disentangle them from other hypothetical particles at hadron colliders [11–13]. The possibility of production of new chiral tensor particles at the hadron colliders the Tevatron and LHC was first considered [14]. Their coupling constants to ordinary fermions can be fixed using the hypothesis about a dynamical generation of kinetic terms for the bosons and assuming an universality of interactions of these particles. Quantitative estimations of the production cross-sections of the chiral particles were made. It is noteworthy that, due to their non-gauge interactions with fermions, their decays to light fermions do not lead to Jacobian peak in the transverse momentum and mass distribution.

Moreover, the lightest chiral particles  $U_{\mu\nu}$  show leptophobic character, which makes their detection at hadron colliders challenging.

Search for CTP has been conducted by the international collaboration ATLAS at CERN. There exists experimental constraints on CTP masses [15,16]. Namely: experimental constraints on the masses of the tensor particles interacting with down type fermions at 95% CL are:  $M_{T^0} > 2.85$  TeV and  $M_{T^+} > 3.21$  TeV. The masses of tensor particles interacting with up-type fermions are not yet experimentally constrained.

### 3. Chiral Tensor Particles in the Early Universe

An extended cosmological model with CTP was studied in a cycle of publications, where cosmological influence of CTP has been considered [3–5,7,17–19].

#### 3.1. CTP Dynamical Effect

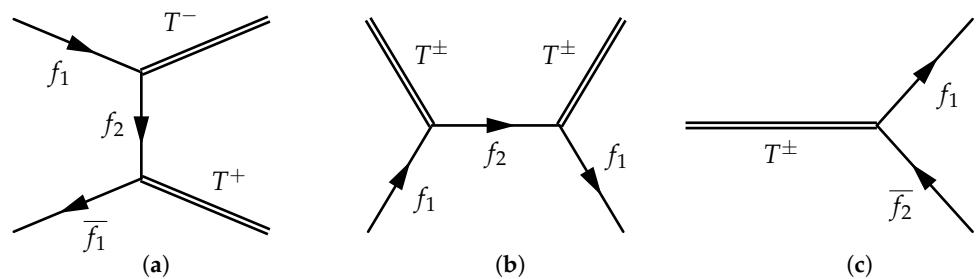
CTP contribute to the matter tensor in the right-hand side of the Einstein–Hilbert equation. In the extended cosmological model with CTP the total effective number of the degrees of freedom is increased  $g_* = g_{SM} + g_{CTP}$ , hence the energy density  $\rho = \frac{\pi^2}{30} g_* T^4$

and the expansion rate of the Universe is increased compared to the Standard Cosmological Model:  $H = \sqrt{8\pi^3 G_N g_* / 90} T^2$ . It has been shown that CTP presence slightly change the Universe expansion rate at a very early stage of the Universe's evolution, while CTP are abundantly present (the period is defined below, in the next subsection).

### 3.2. CTP Direct Interactions

CTP characteristic direct interactions with the particles present at the high energy stage of the Universe have been calculated [4]. Using experimental constraints on CTP [15,16].

The processes involving CTP in the early Universe, namely their interactions with the constituents of the early Universe plasma, their creation (Figure 1a), annihilation (Figure 1a with reversed time), scattering (Figure 1b) and decay (Figure 1c) were considered [4].



**Figure 1.** (a) Chiral tensor particles creation from fermion-antifermion collisions; (b) Fermions scattering on CTP particles; (c) Decay of CTP  $T^\pm$ .

Process efficiency vs expansion were analyzed. At early epoch while CTP particles were relativistic their cross-sections decrease with energy increase,  $\sigma \sim E^{-2}$ , and therefore CTP particles have been frozen. With the cooling of the Universe due to expansion, the mean energy of particles  $E$  decreases and CTP interactions unfroze. The characteristic temperatures and the corresponding cosmic times have been calculated for the CTP direct interactions.

$$\Gamma_{int} = \sigma(T) \times n(T) \geq H(T) = \frac{1}{2t}, \text{ where } n(T) = \frac{3\zeta(3)}{4\pi} T^3 \quad (3)$$

It has been found that CTP creation becomes effective when  $T$  falls below  $\approx 1.83 \times 10^{17}$  GeV, corresponding to cosmic time  $t_c \approx 6 \times 10^{-42}$  s.

CTP annihilations proceed till  $t_a \approx 2.42 / \sqrt{g_*} T_a^2$  [MeV] s where  $T_a = 2M_T$ . Then for  $M_T = 3$  TeV we calculated the annihilation time  $t_a = 5 \times 10^{-14}$  s. However if we take the estimation about the masses following from BBN cosmological constraint discussed in Section 4, namely  $M_T \sim 8$  TeV the corresponding annihilation epoch will end earlier,  $t_a = 7 \times 10^{-15}$  s.

With the decrease of the Universe temperature during its expansion, the CTP become non-relativistic. Then the inverse decay processes can be neglected. CTP decay width is estimated to be:

$$\Gamma \approx y_T^2 M_T / 4\pi. \quad (4)$$

The cosmic time corresponding to the decay at  $T_d \approx M_T$ , assuming  $M_T = 3$  TeV  $t_d = 2 \times 10^{-13}$  s. Assuming  $M_T \leq 8$  TeV the corresponding decay time will be  $t_d = 2.8 \times 10^{-14}$  s.

The provided analysis of the cosmological place of the CTP shows, that the decay time is later than the annihilation time, so CTP mainly disappear from the cosmic plasma due to annihilations and the rest decay rapidly soon after that at  $t_d$ . The period of efficiency of CTP direct interactions, defined in case  $M_T = 3$  TeV, is:  $6 \times 10^{-42} \text{ s} < t < 5 \times 10^{-14} \text{ s}$  corresponding to  $T$  interval  $1.8 \times 10^{17} - 6.0 \times 10^3$  GeV. Otherwise, in case  $M_T \sim 8$  TeV the period of efficiency is slightly shortened  $6 \times 10^{-42} \text{ s} < t < 7 \times 10^{-15} \text{ s}$ . Thus, the analysis showed that CTP direct interaction were effective for a very short period at a very early stage of Universe evolution and during this period CTP have been abundant. So they

could not directly effect BBN or Cosmic Microwave Background, which proceed at much later epochs. Therefore, the cosmological observational data from BBN and CMB do not constrain CTP on the basis of their direct interactions.

However, it is still possible to obtain cosmological bounds on the CTP interaction strength  $G_T$  [2] on the basis of BBN considerations in case right handed neutrinos  $\nu_R$  interact with the chiral tensor particles. Then  $\nu_R$  can be produced during BBN epoch through CTP exchange and they may effect the primordial production of elements and hence, BBN constraints may be derived. We discuss these BBN constraints on CTP and the temperature of freezing of r.-h. neutrino below.

#### 4. BBN Constraints on the Freezing Temperature of Right Handed Neutrino and on Its Interactions with CTP

Big Bang Nucleosynthesis is among the most reliable tests of Beyond Standard Model (BSM) physics, thanks to the remarkable agreement between the theoretically predicted and derived from observations abundances of light elements produced during BBN. Cosmological constraint on the CTP coupling constant  $G_T$  based on possible interactions of CTP with right-handed neutrinos and their influence on the Big Bang Nucleosynthesis were first discussed in [2]. In case right-handed neutrinos interact with CTP they may be produced via CTP exchange during BBN epoch. The term of the effective Lagrangian corresponding to the right handed neutrino coupling to the Standard Model fermions reads:

$$L = \frac{4}{\sqrt{2}} G_T \bar{e}_L \sigma_{\alpha\beta} \nu_R \cdot \bar{u}_L \sigma_{\alpha\beta} d_R + h.c., \quad (5)$$

where  $G_T$  measures the effective CTP interaction strength,  $G_T \sim (y_T/M_T)^2$ ,  $\sigma_{\alpha\beta} = \frac{i}{2}(\gamma_\alpha \gamma_\beta - \gamma_\beta \gamma_\alpha)$ .

In following papers BBN constraints have been derived corresponding to different BBN bounds on  $\delta N_{eff}$  [5,7]. In the last decade primordial  ${}^4\text{He}$  was known with 3–5% precision and the BBN constraints on BSM physics used this precision. Here we present the obtained constraints on  $T_f$  and  $G_T$  corresponding to the recently obtained stringent BBN constraint on the additional relativistic degrees of freedom  $\delta N_{eff} < 0.2$  and for different assumptions about the number of light right handed neutrinos.

Besides, during the last decade the primordial abundances of the light elements D and  ${}^4\text{He}$  were determined with higher and higher accuracy [20–22]. The higher precision of  ${}^4\text{He}$  determination is mainly due to the inclusion of  $\text{HeI} \lambda 10830\text{He}$  infrared emission line measured in the extremely metal poor galaxy Leo P. These observations together with previous ones lead to the primordial helium abundance  $Y_p$  [22–24]:

$$Y_p = 0.2453 \pm 0.0034. \quad (6)$$

The higher precision of helium measurements allows to update and strengthen the cosmological BBN constraints on BSM physics. In this section we revise the cosmological constraints and present their more stringent values corresponding to around 1% uncertainty of  ${}^4\text{He}$ .

We discuss first the new cosmological constraints on the number of the effective degrees of freedom of relativistic particles during the BBN epoch and apply it to update the BBN constraints on the freezing temperature of the light r.-h. neutrinos. Then we derive updated BBN constraints on the interaction strength of BSM interactions of right handed neutrino with CTP.

##### 4.1. Recent Constraints on Light Neutrino Types

BBN constrains the effective number of relativistic species  $N_{eff}$  or light neutrino types because additional light particles into equilibrium increase the expansion rate of the Universe  $H \sim (G_N \rho)^{1/2}$ , where  $\rho = \rho_\gamma + \rho_\nu$  is the relativistic density. The effective number of relativistic species  $N_{eff}$  is defined by  $\rho_\nu = 7/8T/T_\nu)^4 N_{eff} \rho_\gamma(T)$ . Non-zero

$\delta N_{eff} = N_{eff} - 3.045$  indicates any extra relativistic component. BBN, and in particular  $^4\text{He}$ , is a sensitive probe to additional species.  $^4\text{He}$  is the best speedometer among the light elements produced during BBN. It is a strong function of the effective number of light stable particles at BBN epoch. BBN and the recent precise determination of primordially produced helium-4 provide the following stringent constraints on the number of light neutrino types during BBN epoch:  $N_{eff} < 3.18$  at 95% C.L. [25].

Thus, although this BBN constraint is consistent with the standard model value  $N_{eff} = 3.045$ , the deviations from it may indicate extra relativistic component like right handed neutrinos. In what follows we use  $\delta N_{eff} < 0.2$  for obtaining BBN constraints on right handed neutrino decoupling and on new CTP physics.

#### 4.2. BBN Constraint on Right Handed Neutrino Decoupling

In the expanding Universe particles are kept in thermal equilibrium while their interaction rates  $\Gamma(T)$  are higher than the expansion rate  $H(T)$ . Freeze-out occurs when they become comparable  $\Gamma(T_f) \sim H(T_f)$ . We updated the cosmological constraint on the freezing temperature of r.-h. neutrino  $T_f$  using recent BBN constraint  $\delta N_{eff} = g_R(T_R/T_L)^4 < 0.2$ , and using the entropy conservation

$$gT^3 = const \quad (7)$$

valid in case of adiabatic expansion of the Universe. Here  $T_R$  and  $T_L$  denote the temperatures of the right handed neutrino and left handed neutrino, correspondingly.

In refs. [5,6] we have updated the analysis of previous studies. Namely, for the relation between the effective degrees of freedom in the early Universe and the freezing temperature we used the data provided in ref. [26].

Assuming the existence of 3 light right-handed neutrinos types  $\nu_R$ , from the BBN constraint it follows:

$$\delta N_{eff} = 3(T_R/T_L)^4 < 0.2 \quad (8)$$

This leads to a constraint on the freezing temperature of the right-handed neutrinos  $T_f$  using the BBN constraint on  $\delta N_{eff}$  and entropy conservation relation  $gT^3 = const$ , namely

$$T_R/T_L = (\frac{43}{4}/g_*(T_f))^{1/3} < 0.508. \quad (9)$$

The derived constraint on the decoupling temperature is  $T_f > 1600$  MeV.

The constraint in case of 2 light r.-h. neutrino is correspondingly  $T_f > 200$  MeV. In case of only 1 light r.-h. neutrino  $T_f > 170$  MeV. These values are slightly lower than the determined in previous publications.

#### 4.3. BBN Constraint on CTP Interactions

The freezing temperature of a given species depends on its interaction coupling strength:

$$\Gamma_R/\Gamma_L = (T_f/2)^3(G_{new}/G_F)^2 \sim 1 \quad (10)$$

Comparing this freezing temperature with the electron neutrino decoupling temperature 2 MeV, one can get an insight of the coupling constant of new interactions of the right handed neutrinos [27]. For example constraints can be obtained on right handed neutrino coupling to  $Z'$  gauge bosons in models of superstrings, extended technicolor, etc.

In particular, in the case when right handed neutrinos interact with the chiral tensor particles, they may be produced through chiral tensor particles exchange during BBN (see Figure 2) and the corresponding Lagrangian of Equation (5). Then, it is possible to obtain BBN constraint on CTP interaction strength.



**Figure 2.** Feynman diagrams corresponding to Lagrangian (5): (a) presents the explicitly given first term of the Lagrangian; (b) presents the hermitian conjugated term.

Namely, the constraints on  $T_f$  can be interpreted as constraints on CTP interactions with right-handed neutrinos because

$$(G_F/G_T)^2 \sim (T_f/2 \text{ MeV})^3, \quad (11)$$

where 2 MeV is the freezing temperature of the electron neutrino,  $G_F$  is the weak interaction strength and  $G_T$  is the interaction strength of CTP interactions right handed neutrino may participate in. Then the following constraints follow: in case of 3 light right handed neutrinos

$$G_T/G_F < 4.5 \times 10^{-5}. \quad (12)$$

This BBN constraint points to the possibility of a smaller than milli-weak tensor interactions.

For 2 light right handed neutrinos similar analysis leads to the constraint:  $G_T/G_F < 4.2 \times 10^{-4}$ , for 1 light right handed neutrinos, correspondingly, the constraint reads:  $G_T/G_F < 1.2 \times 10^{-3}$ .

These constraints on  $G_T$  are much stronger than estimated in previous works. Such interactions should be at least thousands times weaker than the weak interactions, i.e., milli-weak interactions or weaker. Alternatives are that CTP have no interactions with fermions, or no light right handed neutrinos exist.

Here it is interesting to note that such a possibility about a lepto-phobic character of CTP interactions has been proposed [28] similar to the Higgs properties. Hence, CTP detection at hadron colliders may be even more challenging.

The analysis provides also a hint to the CTP masses. Namely, since  $G_F \sim (g/M_W)^2$  and  $G_T \sim (y_T/M_T)^2$  assuming  $G_T \sim 10^{-4}G_F$  and  $y_T \sim g$ , it follows:  $M_T \sim 100M_W$ . This prediction points to particle masses  $M_T \sim 8 \text{ TeV}$ , i.e., considerably higher than the available experimental constraints.

## 5. Conclusions

We provided a short review of the cosmological influence of new chiral tensor particles on the early Universe. CTP particles characteristic processes: creation, annihilation, scattering and decay have been calculated. It was shown that their direct interactions, assuming  $M_T \sim 8 \text{ TeV}$ , are effective for a short period  $6 \times 10^{-42} \text{ s} < t < 7 \times 10^{-15} \text{ s}$  during the Universe evolution, which corresponds to the energy window  $1.8 \times 10^{17} \text{ GeV} < T < 1.6 \times 10^4 \text{ GeV}$ . Thus, CTP have been in equilibrium, i.e., abundantly present at a very early stage of Universe evolution, so that they could not directly effect BBN, CMB or other processes at much later epoch, which have left observable relics in today's Universe. Hence, CTP cannot be constrained on the bases of their direct interactions and their influence on these relics.

CTP also lead to an increase of the effective degrees of freedom and hence slightly speed up the expansion of the Universe and change its temperature-time dependence while CTP are in thermodynamical equilibrium in the early Universe plasma. However this effect again has negligible influence on the later epochs of BBN and CMB.

It was shown that, assuming that CTP interact with right handed neutrino, it will be possible to constrain CTP interactions from cosmology. Here, we provide an update of

the BBN constraints on the freezing temperature of the light right handed neutrinos and the CTP interaction strength in case these neutrinos are produced via CTP exchange. This BBN constraint corresponds to the recent more precise measurements of the primordial abundances of the light elements and the corresponding cosmological constraint on the effective number of relativistic during BBN species. It was found that CTP interactions should be at least thousands times weaker than the weak interactions, i.e., CTP interactions are milli-weak or weaker depending on the number of light right-handed neutrino species. These results are important for studies of new physics in general.

The eventual future detection of the chiral tensor particles will provide a TeV window on the Universe, revealing the realm of milli weak interactions.

Besides, CTP may be present at energies typical for inflation, Universe reheating and leptogenesis and baryogenesis, therefore it is interesting to explore further the role of CTP in the very early Universe. Moreover, the extended model with CTP proposes new source for CP-violation and may present a natural mechanism for leptogenesis and baryogenesis scenarios.

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**Data Availability Statement:** All data both the original raw data and resultant from our study is available in the article itself.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

CTP	Chiral Tensor Particles
BBN	Big Bang Nucleosynthesis
BSM	Beyond Standard Model

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