Chiral tensor particles in the early Universe

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The status of the chiral tensor particles in the extended electroweak model, their experimental constraints, signatures and the possibilities for their detection at the new colliders are reviewed. The characteristic interactions of the chiral tensor particles in the early Universe plasma and the corresponding period of their cosmological influence is determined. The dynamical cosmological effect, namely the speeding of the Friedmann expansion due to the density increase caused by the introduction of the new particles, is evaluated.

It is shown that the existence of the chiral tensor particles is allowed from cosmological considerations and welcomed by the particle physics phenomenology.

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1. Introduction

In this work we will discuss the presence of a new type of spin-1 particles in the primeval plasma and their effects on the Friedmann expansion and on the processes in the early Universe.

Neither a supersymmetry, nor extra-dimensions have been observed or detected up till now and they remain just a theoretical construction. Nevertheless, they are considered as natural extensions of the standard model of elementary particles and their search continues in most of the particle physics experiments dedicated to physics beyond the standard model.

Physics beyond the standard model, discussed here, namely the introduction of new chiral tensor (ChT) particles into the standard electroweak model, is based on the experimental fact that such type of particles exist in Nature at the QCD scale as the hadron resonances. An extension of the standard model by ChT particles
at the electroweak scale is similar to the technicolor idea, which considers hadron resonances like prototypes of the electroweak bosons.

On the other hand, from theoretical point of view, the ChT particles are inserted into the standard model of elementary particles to complete the set of Yukawa interactions and realize all possible irreducible representations of the Lorentz group. Such model was first presented in Ref. 2 and was discussed in more detail in the review in Ref. 3.

The new ChT particles, present in the early Universe, 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. Besides they have direct interactions with the particles present at the early stage of the Universe evolution.

In the next section we briefly review the current status of the ChT particles. In the third section we estimate the characteristic scale of their typical processes and their effect on the expansion rate of the Universe and discuss the BBN constraint on their effective coupling constant. The last section presents our conclusions and vision about future exploration of the ChT particles.

2. Today’s status of chiral tensor particles

According to the extended model2,3 with ChT particles, the latter are described by an antisymmetric tensor fields of a rank two, like the stress tensor of the electromagnetic field. An antisymmetric tensor field describes two fields with spin one, which are represented by a polar and an axial vectors with respect to spatial transformations. (Unlike the common association of the word tensor with particles with spin two, which are described by a second rank symmetric tensor, like the graviton.)

**Chirality.** The new particles have a chiral charge and change the fermion chirality in contrast to the gauge bosons with spin one, which have minimal interactions with fermions and do not change their chirality. They have an anomalous (Pauli) interaction with matter, which provides a distinguishing signature for their detection.

**Introduction of the chiral tensor particles into the SM.** The ChT particles are introduced as doublets \( (T_{\mu\nu}^+ T_{\mu\nu}^0) \), like Higgs particles, due to the same as Higgs chirality property. As a result of their richer interaction possibilities new chiral anomalies appear. The latter are avoided by introducing an additional doublet \( (U_{\mu\nu}^0 U_{\mu\nu}^-) \) with an opposite chiral- and hypercharge. This doubling of doublets concerns also the Higgs sector, thus, similar to the SUSY case, it becomes \( (H_1^+ H_1^0) \), \( (H_2^0 H_2^-) \).

Massless tensor particles have just longitudinal degrees of freedom. In order for them to acquire mass a Higgs-like mechanism should be applied. However, in this case the role of the Higgs field will be played by a triplet and a singlet gauge vector particles or by four \( SU(2)_L \) singlets (depending on the chiralities of the ChT particles), which supply them with the transverse physical degrees of freedom. Thus,
in addition to the discussed Higgs doublets an extra triplet and five singlets, denoted further on by $C_\mu$ and $P^i_\mu$ ($i = 1, \ldots, 5$), correspondingly, should be introduced as well for the two tensor doublets.

However, the doublets doubling may cause a flavor violation in the neutral sector. This can be easily avoided if 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.

**Chiral tensor particles degrees of freedom.** The antisymmetric tensor particles while massless, have only longitudinal physical degrees of freedom opposite to the case of gauge fields. Therefore, the presence of the two additional tensor doublets, the triplet and singlets gauge vector particles and the extra Higgs doublet leads to an increase of the total effective number of the degrees of freedom while the additional particles are relativistic by $g_{\text{ChT}} = g_T + g_U + g_C + g_P + g_H = 4 + 4 + 6 + 10 + 4 = 28$, namely: $g^* = g_{\text{SM}} + g_{\text{ChT}} = 106.75 + 28 = 134.75$.

**Chiral tensor particles masses.** As in the SM the particle masses are induced through the Higgs mechanism. The presence of the vacuum expectation values of the two different Higgs doublets leads to different masses for the tensor particles interacting with up- and down-type fermions, correspondingly $M_U \sim 700 \text{ GeV}$ and $M_T \sim 1 \text{ TeV}$. The spectrum of the ChT particle masses in the extended model is considered more precisely in Ref. 5.

**Experimental signatures and constraints.** A. The presence of the ChT particles do not contradict the present experimental data and moreover can explain successfully a number of anomalies in the precise low energy physics, namely:

- **weak radiative pion decay anomaly:** The Dalitz plot of the weak radiative pion decay cannot be interpreted in the framework of the standard V-A interactions. The anomaly consists in the fact that the predicted decay probability is higher than the measured one. In the standard model the theoretically calculated probability is defined by the sum of the squares of two matrix elements. In the extended electroweak model with the ChT particles there exists an additional matrix element in the probability, which leads to a distinctive destructive interference. Hence, the predicted probability matches the measured one, provided the effective coupling constant of the tensor interactions is $G_T \sim 10^{-2} G_F$, where $G_F$ is the Fermi coupling constant, i.e. the new interactions are centi-weak. A cosmological constraint of the same order can be obtained from BBN considerations as discussed in section 3.

- **CVC anomaly in tau decays:** There exists $4.6 \sigma$ difference between the predicted from $e^+e^-$ annihilation and the measured branching ratio of tau decay into two pions. This anomaly can be explained using the lepton universality of the tensor interactions and the same strength $G_T \sim 10^{-2} G_F$, as found above.

- **muon g-2 anomaly:** There exists a $3.3 \sigma$ discrepancy between the measured and theoretically predicted value of the muon anomalous magnetic moment. The presence of the massive neutral tensor particles can naturally explain this anomaly: Thanks to the mixing of the neutral tensor particle with the photon, the
photon shows an anomalous interactions with the fermions, which actually reflects the anomalous interaction of the tensor particles with the fermions. Moreover, unlike other existing in literature models explaining this anomaly, this mechanism predicts a systematic shift in the fine structure constant value determined from the electron anomalous magnetic moment.  

B. Besides the successful explanation of the listed above anomalies, the tensor interactions do not contradict the precise low energy experiments like: super-allowed beta decay, muon decay, neutron decay, etc. The results of DELPHI, TWIST and $\mu_P$ experiments do not exclude the presence of these particles with the parameters discussed above.

The chiral tensor particles may be produced and detected at powerful high energy colliders. For example, some feature indicative for the ChT particles was already observed at the Tevatron. The chiral tensor particles, if they exist, should be certainly discovered at the ongoing Large Hadron Collider by CMS and ATLAS experiments at CERN, in case they have the mentioned above masses and coupling constants.

3. Cosmological Effects of Chiral Tensor Particles

Cosmological influence of antisymmetric tensor particles was first discussed in Ref. Here we use the currently updated characteristics of the ChT particles to discuss their effect on the early Universe. We will consider two types of cosmologically important effects of ChT particles: first, the additional particles influence on Universe dynamics, and second, ChT particles direct interactions with the other constituents of the early Universe plasma.

**ChT particles effect on the Universe expansion.** The presence of two doublets of antisymmetric tensor particles and the corresponding additional Higgs doublet, triplet and singlets of gauge vector particles leads to a considerable increase of the energy density of the Universe in comparison with the Standard Cosmological Model case $\rho = \rho_{SCM} + \rho_{CNT}$. This results in speeding up the Friedmann expansion $H = \sqrt{\frac{8\pi}{3} G_N \rho}$, where $H$ is the rate of the expansion, $G_N$ is the gravitational constant. At the early stage, while the additional particles are relativistic, their contribution can be expressed through the effective degrees of freedom, namely: $\rho_{CNT} = \frac{8\pi}{30} g_{CNT} T^4$, where $T$ is the photon temperature. Hence, for cosmic times $t$ later than ChT particles creation time $t_c$ and before ChT particles became non-relativistic or decay, i.e. $t_c < t < t_d$, the Friedmann expansion is speeded up $H = \sqrt{\frac{8\pi}{3} G_N g_*/90} T^2$, where $g_*$ is the total number of the effective degrees of freedom $g_* = 134.75$, as discussed in the previous section. The temperature-time dependence is also shifted, namely the cosmic time, corresponding to a given temperature, slightly decreases compared to the standard cosmological model case, since $t \sim 1/(\sqrt{g_*} T^2)$ and $g_* > g_{SM}$.

**ChT particles interactions in the early Universe.** Through their interactions with the fermions the tensor particles directly influence the early Universe
plasma. Analyzing the interactions of the tensor particles, we have estimated the characteristic temperatures and cosmic times for these particles, namely their creation, scattering, annihilation and decay.

Tensor particle interactions become effective when the characteristic rates of interactions \( \Gamma_{\text{int}} \sim \sigma n \) become greater than the expansion rate \( H(T) \). At energies greater than the tensor particles mass, the cross sections have the following behavior \( \sigma \sim E^{-2} \). Hence at very high energies tensor particles have been frozen, and with the cooling of the Universe during its expansion, they unfreeze. The temperature of unfreezing \( T_{\text{eff}} \), i.e. the temperature corresponding to the beginning of the epoch of particles effectiveness due to a given interaction \( i \rightarrow f \) is defined from the relation

\[
\sigma_{if}(T) n(T) = H(T)
\]

and the corresponding cosmic time is estimated as

\[
t_{\text{eff}} \approx \frac{2.42}{\sqrt{g^*} T_{\text{eff}}^2 \text{[MeV]}} \text{ s}.
\]

The cross-section for the creation of pairs of longitudinal tensor particles from fermion-antifermion collisions is calculated to be:

\[
\sigma_{c} \approx \frac{\pi \alpha^2 \ln(E/v)}{64 \sin^4 \theta_W E^2},
\]

where the fine-structure constant \( \alpha(M_Z) \approx 1/127.9 \), the weak-mixing angle \( \sin^2 \theta_W \approx 0.23136 \) and the Higgs vacuum expectation \( v \approx 250 \text{ GeV} \). Thus the tensor particle creation becomes effective at \( T < T_c \approx 3.3 \times 10^{16} \text{ GeV} \), which corresponds to cosmic times \( t > t_c \approx 1.9 \times 10^{-40} \text{ s} \).

The fermions scattering on tensor particles has a cross-section

\[
\sigma_{s} \approx \frac{\pi \alpha^2}{192 \sin^2 \theta_W E^2}.
\]

It becomes effective at \( T < T_s \approx 3.4 \times 10^{14} \text{ GeV} \) and \( t > t_s \approx 1.8 \times 10^{-36} \text{ s} \).

Tensor particles annihilations proceed till \( t_a \approx 2.42/(\sqrt{g^*} T_a^2 \text{[MeV]}) \text{ s} \approx 2.1 \times 10^{-13} \text{ s} \), where \( T_a = 2MT \).

The decay width of the tensor particles is \( \Gamma \approx \alpha M_T / \sin^2 \theta_W \approx 34 \text{ GeV} \). The lifetime and the corresponding cosmological temperature are \( t_d = 1.9 \times 10^{-26} \text{ s} \) and \( T_d = 3.3 \times 10^9 \text{ GeV} \). The decay time is much earlier than the annihilation, hence the tensor particles disappear from the cosmic plasma mainly by decaying. The period of their effectiveness is the period from the time of their creation to the moment of their decay, \( t_c = 1.9 \times 10^{-40} \text{ s} < t < t_d = 1.9 \times 10^{-26} \text{ s} \), i.e. during the very early stage of the Universe evolution. The corresponding energy range spreads from \( 10^{16} \text{ GeV} \) down to \( 10^9 \text{ GeV} \). So, the ChT particles decay safely early so that their decay products do not disturb the CMB. On the other hand they are present at energies typical for inflation, Universe reheating, lepto- and baryogenesis, et cetera. The ChT particles eventual role in these processes is to be explored in future studies.

We would like only to mention here that the extended model with ChT particles proposes new source for CP-violation due to the richer structure of particles and

\[ a \text{The interactions of the transverse components of the tensor fields are similar to the interactions of the transversal gauge W and Z fields, and therefore we are not going to discuss them here.} \]
interactions, and therefore, may present a natural mechanism for leptogenesis and baryogenesis scenarios.

**BBN constraint on the ChT interactions strength.** In the discussed extended model with the ChT particles right-handed neutrinos interact with the chiral tensor particles and in case the neutrinos are light they can be produced through ChT particles exchange. Then it is straightforward to obtain rough cosmological bound on the coupling constant of the ChT particles $G_T$ on the basis of BBN considerations.\(^8\)

Using the BBN bound on the additional light neutrinos $N_{\text{eff}} = g_R(T_{\nu_R}/T_{\nu_L})^4 < 1$ and assuming three light right-handed neutrinos, it follows that $3(T_{\nu_R}/T_{\nu_L})^4 < 1$, which puts a constraint on the decoupling/freezing of the right-handed neutrinos. The temperature of freezing $T_f$ of $\nu_R$ may be determined using the BBN constraint and entropy conservation relation $gT^3 = \text{const}$, namely $T_{\nu_R}/T_{\nu_L} = (43/4g_*(T_f))^{1/3} < 0.76$. Then the rough constraint on the decoupling temperature is $T_f > 140$ MeV.

On the other hand the decoupling temperature of a given species is connected with its interactions coupling strength, hence $(G_T/G_F)^2 \sim (T_f/3 \text{ MeV})^{-3}$, where we assume 3 MeV as the decoupling temperature of the active neutrino species. Then the constraint on the ChT coupling is $G_T < 10^{-2}G_F$.

In case of two light right-handed neutrinos, the corresponding constraints on the decoupling temperature is $T_f > 100$ MeV, which slightly changes the constraint on the coupling. These two cases provide BBN constraints in agreement with the value of the $G_T$ provided from the experimental data discussed in the second section. So BBN cosmological constraint points as well to the possibility of a centi-weak tensor interactions.\(^b\)

4. Conclusion

As has been discussed, the existence of chiral tensor particles does not contradict the experimental data of the precise low energy experiments like: super-allowed beta decay, muon decay, neutron decay, etc. Moreover, chiral tensor particles help to explain some anomalies in the precision low energy physics, namely, the weak radiative pion decay anomaly, the CVC anomaly in tau decays, the muon g-2 anomaly, etc. Besides, chiral tensor particle anomalous interactions with matter provide a distinguishing signature for their detection. The new particles may be produced and detected at powerful high energy colliders. Particularly, if they exist, they should be certainly discovered at the ongoing Large Hadron Collider by CMS and ATLAS experiments at CERN, in case they have the mentioned above masses and coupling constants. At present the search of these particles is included in the ongoing exper-

\(^b\)Considerably looser BBN bound will follow in case of only one light right-handed neutrino species, as seen from the above considerations, namely $G_T \leq G_F$. The eventual future detection of the ChT particles and determination of their coupling constant may point to the number of the light right-handed neutrino species.
imental program of the ATLAS Collaboration at LHC. Some feature indicative for tensor particles was already observed at the Tevatron.\cite{17}

Besides, as demonstrated in this work, these particles are allowed by cosmology, as well. BBN cosmological considerations point to the possibility of a centi-week tensor interactions. ChT particles cause a slight increase of the Friedmann expansion and correspondingly change the temperature-time dependence during the period of effectiveness of their interactions with the other Universe constituents: This period lasts from the time of their creation till their decay, namely $t_c = 1.9 \times 10^{-40} \text{ s} < t < t_d = 1.8 \times 10^{-26} \text{ s}$. The corresponding energy range is from $10^{16} \text{ GeV}$ (typical for the inflationary period) down to $10^9 \text{ GeV}$, which according to us is very promising for theoretical speculations involving the chiral tensor particles concerning inflationary models, reheating scenarios, baryogenesis and leptogenesis scenarios, etc.

Hopefully, in future more particle physics experiments will pay attention to the experimental exploration of the characteristics of the chiral tensor particles and they will be included in the theoretical models of the early Universe evolution as well.

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