Violation of CPT Invariance in the Early Universe and Leptogenesis/Baryogenesis

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Abstract. In this talk, I review some plausible scenarios entailing violation of CPT symmetry in the early Universe, due to space-time backgrounds which do not respect some of the assumptions for the validity of the CPT theorem (here considered will be Lorentz invariance and/or Unitarity). The key point in all these models is that the background induces different populations of fermions as compared to antifermions, and hence CPT Violation (CPTV), already in thermal equilibrium. Such populations may freeze out at various conditions depending on the details of the underlying microscopic model, thereby leading to leptogenesis and baryogenesis. Among the considered scenarios is a stringy one, in which the CPTV is associated with a cosmological background with torsion provided by the Kalb-Ramond antisymmetric tensor field (axion) of the string gravitational multiplet. We also discuss briefly (Lorentz Violating) CPTV models that go beyond the local effective lagrangian framework, such as a stochastic Finsler metric and D-particle foam. In the latter, the CPTV is induced by the interactions of stringy matter with populations of stochastically fluctuating point-like space-time defects (D-particles) that can be encountered in string/brane Cosmologies. The preferential rôle of neutrinos is singled out in this latter scenario as a consequence of gauge symmetry (charge) conservation.

1. Introduction and Summary

The universe is overwhelmingly made up of matter rather than anti-matter. According to the standard Big Bang theory, matter and antimatter have been created in equal amounts in the early universe. However, the observed charge-parity (CP) violation in particle physics [1], prompted A. Sakharov [2] to conjecture that for Baryon Asymmetry in the universe (BAU) we need:

- Baryon number violation to allow for states with $\Delta B \neq 0$ starting from states with $\Delta B = 0$ where $\Delta B$ is the change in baryon number.
- If C or CP conjugate processes to a scattering process were allowed with the same amplitude then baryon asymmetry would disappear. Hence C and CP need to be broken.
- Chemical equilibrium does not permit asymmetries. Hence Sakharov required that chemical equilibrium does not hold during an epoch in the early universe.

Hence non-equilibrium physics in the early universe together with baryon number (B), charge (C) and charge-parity (CP) violating interactions/decays of anti-particles in the early universe, may result in the observed BAU. In fact there are two types of non-equilibrium
processes in the early universe that can produce this asymmetry: the first type concerns processes generating asymmetries between leptons and antileptons (leptogenesis), while the second produces asymmetries between baryons and antibaryons (baryogenesis). The observed asymmetry today, between baryon \( n_B \) and anti-baryon \( n_{\bar{B}} \) number densities is estimated in the Big-Bang theory [3] to imply:

\[
\Delta n(T \sim 1 \text{ GeV}) = \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim \frac{n_B - n_{\bar{B}}}{s} = (8.4 - 8.9) \times 10^{-11}
\]

at the early stages of the expansion, e.g. for times \( t < 10^{-6} \) s and temperatures \( T > 1 \) GeV. In the above formula \( s \) denotes the entropy density. Unfortunately, the observed CP violation within the Standard Model (SM) of particle physics (found to be of order \( \epsilon = O(10^{-3}) \) in the neutral Kaon experiments [1]) induces an asymmetry much less than that in (1) [4]. There are several ideas that go beyond the SM (e.g. grand unified theories, supersymmetry, extra dimensional models etc.) which involve the decays of right handed sterile neutrinos. For relevant important works on this see [5, 6, 7, 8, 9, 10, 11]. These ideas lead to extra sources for CP violation that could generate the observed BAU. Some degree of fine tuning and somewhat ad hoc assumptions are involved in such scenarios and the quest for an understanding of the observed BAU still needs further investigation. An example of fine tuning is provided by the choice of the hierarchy of the right-handed Majorana neutrino masses. For instance, enhanced CP violation, necessary for BAU, can be achieved in models with three Majorana neutrinos, by assuming two of these neutrinos are nearly degenerate in mass.

The requirement of non-equilibrium is on less firm ground [12] than the other two requirements of Sakharov, e.g. if the non-equilibrium epoch occurred prior to inflation then its effects would be hugely diluted by inflation. A basic assumption in the scenario of Sakharov is that CPT symmetry [13] (where \( T \) denotes time reversal operation) holds in the very early universe which leads to the production of matter and antimatter in equal amounts. Such CPT invariance is a cornerstone of all known local effective relativistic field theories without gravity, which current particle-physics phenomenology is based upon. It should be noted that the necessity of non-equilibrium processes in CPT invariant theories can be dropped if the requirement of CPT is relaxed [14]. This violation of CPT (denoted by CPTV) may be the result of a breakdown of Lorentz symmetry (which might happen at ultrahigh energies [15]) or of Unitarity, in the sense of quantum-gravity-induced decoherence in the matter sector, which might be strong in the Early Universe [16, 17]. For many models with CPTV, in the time line of the expanding universe, CPTV generates first lepton asymmetries (leptogenesis); subsequently through sphaleron processes [21] or Baryon-Lepton (B-L) number conserving processes in Grand Unified Theories (GUT), the lepton asymmetry can be communicated to the baryon sector to produce the observed BAU. Thus, CPTV in the early universe may also obviate the need for including extra sources of CP violation, such as sterile neutrinos and/or supersymmetry, in order to obtain the observed BAU.

The structure of the talk, which is based on work appeared in [22], will be as follows: in the next section 2 we shall briefly review some relevant existing models for fermionic asymmetry, which entail CPTV-induced differences in the dispersion relations between particles and antiparticles propagating in curved gravitational backgrounds in the early universe. In section 3, we review a new model for gravitational leptogenesis, proposed in [22], which follows broadly an earlier framework [23, 24], but differs crucially in that the full gravitational multiplet [25] that arises in string theory is used. The leptogenesis in this model is due to CPTV dispersion

1 Locality violations, through non-local mass terms [18], have also been considered in models of CPTV in the neutrino sector but will not be discussed here, due to limitations in space. It must be stressed, though, that such models of CPTV are independent from those due to Lorentz and Unitarity violation [19, 20].
relations between fermions/antifermions, induced by the (constant) torsion associated with the antisymmetric Kalb-Ramond tensor field in the gravitational multiplet of the string. In section 4, we consider another scenario for gravitational leptogenesis that involves a non-Riemannian Finsler metric, with stochastically fluctuating parameters, a variant of which appears in our string/brane ("D-foam") model in the following section 5. In section 5 we present our D-foam model for the stringy universe and the induced CPTV and leptogenesis/baryogenesis. The model is characterised by CPTV and matter dominance over antimatter naturally, without the need for an adjustment of the sign of the lepton/antilepton asymmetry. This is an interesting feature of our model which differentiates it from earlier proposals on gravitational leptogenesis/baryogenesis [26, 27, 28, 29, 24, 23, 30, 31, 32], where the sign of the asymmetry is implicitly chosen. In common with earlier discussions of CPTV in baryogenesis [33], this class of models involves violation of Lorentz symmetry, but only because of a non-zero variance of the stochastic parameter. Moreover, neutrinos are singled out as interacting predominantly with the (Anti)particles will have, by definition, (negative) positive energies. Mass differences between particles and antiparticles, + will denote a fermionic (anti-)particle and − will denote a bosonic (anti-)particle. (Anti)particles will have, by definition, (negative) positive energies. Mass differences between particles and antiparticles, m − m ≠ 0, generate a matter-antimatter asymmetry in the relevant number densities n and τ n − τ m = g.d.o.f. ∫ d⃗p [f(⃗E, µ) − f(⃗E, m)], where g.d.o.f. denotes the number of degrees of freedom of the particle species under study. In the case of spontaneous Lorentz violation [33] there is a vector field Aµ with a non-zero time-like expectation value which couples to a global current Jµ such as baryon number through an interaction lagrangian density

\[ L = \lambda A_\mu J^\mu. \]  

This leads to m ≠ m and µ ≠ m. Alternatively, following [34] we can make the assumption that the dominant contributions to baryon asymmetry come from quark-antiquark mass differences, and that their masses “run” with the temperature i.e. m ∼ gT (with g the QCD coupling constant). One can provide estimates for the induced baryon asymmetry on noting that the maximum quark-antiquark mass difference is bounded by the current experimental bound on the proton-antiproton mass difference, δm_p(= |m_p − m_\bar{p}|), known to be less than 2 × 10^{-9} GeV. Taking n_\gamma ∼ 0.24 T^3 (the photon equilibrium density at temperature T) we have [34]:

\[ \beta_T = \frac{n_B}{n_\gamma} = 8.4 \times 10^{-3} \frac{m_u \delta m_u + 15 m_d \delta m_d}{T^2}, \quad \delta m_q = |m_q - \bar{m}_q|. \]  

\[ \beta_T \] is too small compared to the observed one. To reproduce the observed \[ \beta_T = 6 \times 10^{-10} \] one would need \[ \delta m_q(T = 100 \text{ GeV}) \sim 10^{-5} - 10^{-6} \text{ GeV} \gg \delta m_p, \] which is somewhat unnatural.

2. Models of Background-induced CPT Violation (CPTV) in the Early Universe

In this section we shall review some existing models of CPTV induced asymmetry between matter and antimatter in the early universe, which can be contrasted with our approach in sections 3-5 later in the article. We shall be brief in our exposition, referring the interested reader to the relevant literature for more details.

2.1. CPTV Models with Particle-Antiparticle Mass Difference

The simplest possibility [34] for inducing CPTV in the early universe is through particle-antiparticle mass differences m ≠ \bar{m}. These would affect the particle phase-space distribution function f(E, µ), f(E, µ) = [exp(E − µ)/T ± 1]^{-1}, E^2 = \vec{p}^2 + m^2, and antiparticle phase-space distribution function \[ \bar{f}(\bar{E}, \bar{\mu}) = [\exp(\bar{E} - \bar{\mu})/T ± 1]^{-1}, \quad \bar{E}^2 = \vec{\bar{p}}^2 + \bar{m}^2, \] with \( \bar{p} \) being the 3-momentum. (Our convention will be that an overline over a quantity will refer to an antiparticle, + will denote a fermionic (anti-)particle and − will denote a bosonic (anti-)particle). (Anti)particles will have, by definition, (negative) positive energies. Mass differences between particles and antiparticles, \( \bar{m} - m \neq 0 \), generate a matter-antimatter asymmetry in the relevant number densities n and \[ \bar{n} - n = g_{d.o.f.} \int \frac{d\vec{p}}{(2\pi)^3} [f(\vec{E}, \mu) - f(\vec{E}, \bar{\mu})], \] where g_{d.o.f.} denotes the number of degrees of freedom of the particle species under study. In the case of spontaneous Lorentz violation [33] there is a vector field A_\mu with a non-zero time-like expectation value which couples to a global current J_\mu such as baryon number through an interaction lagrangian density

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However, active (light) neutrino-antineutrino mass differences alone may reproduce BAU; some phenomenological models in this direction have been discussed in [35], considering, for instance, particle-antiparticle mass differences for active neutrinos compatible with current oscillation data. This leads to the result

$$ n_B = n_\nu - n_\bar{\nu} \simeq \frac{\mu_\nu T^2}{6} $$

yielding $n_B/s \sim 10^{-11}$ at $T \sim 100$ GeV, in agreement with the observed BAU. (Here $s$, $n_\nu$, and $\mu_\nu$ are the entropy density, neutrino density and chemical potential respectively.)

### 2.2. CPTV Decoherence Models

Particle-antiparticle mass differences however may not be the only way by which CPT is violated. As discussed in [16, 17], quantum gravity fluctuations in the structure of space-time, may be strong in the early universe; the fluctuations may act as an environment inducing decoherence for the (anti-)neutrinos. However the couplings between the particles and the environment are different for the neutrino and antineutrino sectors. Once there is decoherence for an observer with a low energy (compared to the Planck scale $M_P \sim 10^{19}$ GeV), the effective CPT symmetry generator may be ill-defined as a quantum mechanical operator, according to a theorem by R. Wald [36], leading to an intrinsic violation of CPT symmetry. This type of violation may characterise models of quantum gravity with stochastic space-time fluctuations due, for instance, to gravitational space-time defects, as is the case of certain brane models [37, 38, 39]. In such a case, a slight mismatch in the strength of the stochastic space-time fluctuations between particle and antiparticle sectors, can lead to different decoherence parameters to describe the interaction of the gravitational environment with matter.

In [16, 17], simple models of Lindblad decoherence [40], conjectured to characterise quantum-gravity-induced CPTV decoherent situations [41, 42], have been considered for neutrinos [43]. It was assumed on phenomenological grounds, that non-trivial decoherence parameters were only present in the antiparticle sector: this is consistent with the lack of any experimental evidence to date [44, 45, 46] for vacuum decoherence in the particle sector. The antineutrino decoherence parameters (with dimension of energy) had a mixed energy dependence. The model of [16, 17] assumes a diagonal $\mathcal{L}_{\mu\nu}$. A diagonal Lindblad decoherence matrix for three-generation neutrinos requires eight coefficients $\gamma_i$. Some of the eight coefficients were assumed for simplicity in [16, 17] to be proportional to the antineutrino energy $\gamma_i = \frac{E}{M_P} \nu$, $i = 1, 2, 4, 5$, while the remaining (subdominant) ones were inversely proportional to it $\gamma_j = \frac{10^{-24} \text{(GeV)}}{E^2}$, $j = 3, 6, 7, 8$. The model was proposed without any microscopic justification; its choice was originally motivated by fitting the LSND “anomalous data” in the antineutrino sector [47] with the rest of the neutrino data, and this required $T$ to be $T/M_P \sim 10^{-18}$, i.e. in the temperature range of electroweak symmetry breaking. One can derive [16, 17] an active (light) $\nu - \bar{\nu}$ asymmetry of order

$$ A = \frac{|n_\nu - n_{\bar{\nu}}|}{n_\nu + n_{\bar{\nu}}} \simeq \frac{\gamma_1}{\sqrt{\Delta m^2}} = \frac{T}{M_P} \frac{E}{\sqrt{\Delta m^2}},$$

where $\Delta m^2$ denotes the (atmospheric) neutrino mass squared difference, which plays the role of a characteristic low mass scale in the problem. This lepton number violation is communicated to the baryon sector by means of baryon number ($B$) plus lepton number ($L$) conserving sphaleron processes (in fact, in this case one needs an antilepton excess in order to produce a baryon excess). These processes lead to an estimate [16] for the current value of $B$ to be

$$ B = \frac{n_\nu - n_{\bar{\nu}}}{s} \sim A \frac{n_\nu}{g^* n_\gamma} $$

(6)
with $n_\gamma$ the photon number density, $g^*$ the effective number of degrees of freedom (at the temperature where the asymmetry developed, i.e. the electroweak symmetry breaking temperature in the model of [16]). $g^*$ depends on the matter content of the model (with a typical range $g^* \in [10^2 - 10^3]$). For such parameter values $A \sim 10^{-6}$ and so the observed BAU may be reproduced in this case without the need for extra sources of CP violation e.g. sterile neutrinos. Such models, however, do not provide an underlying microscopic understanding. In particular there is missing an understanding of the preferential role of the neutrino compared to other particles of the Standard Model in the CPT violating decoherence process. Within some microscopic models of space-time foam, involving populations of point-like brane defects (D-particles) puncturing three(or higher)-spatial dimension brane worlds [37, 38, 39], such a preferred role may be justified as we shall discuss in section 5.

### 2.3. CPTV-induced by Curvature effects in Background Geometry

Although the role of gravity was alluded to in the last subsection, associated features of space-time were not discussed. In the literature the role of gravity has been explicitly considered within a local effective action framework which is essentially that of (2) A coupling to scalar curvature $R$ [27, 23, 30, 28] through a CP violating interaction Lagrangian $\mathcal{L}$:

$$\mathcal{L} = \frac{1}{M_*^2} \int d^4x \sqrt{-g} (\partial_\mu R) J^\mu$$

where $M_*$ is a cut-off in the effective field theory and $J^\mu$ could be the current associated with baryon (B) number. There is an implicit choice of sign in front of the interaction (7), which has been fixed so as to ensure matter dominance.

It has been shown that [27] $\frac{n_{e-L}}{s} = \frac{R}{M_*^2 T_d}$, $T_d$ being the freeze-out temperature for $B - L$ interactions. The idea then is that this asymmetry can be converted to baryon number asymmetry provided the $B + L$ electroweak sphaleron interaction has not frozen out. To leading order in $M_*^{-2}$ we have $R = 8\pi G(1 - 3w)\rho$ where $\rho$ is the energy density of matter and the equation of state is $p = w\rho$ where $p$ is pressure. For radiation $w = 1/3$ and so in the radiation dominated era of the Friedmann-Robertson-Walker cosmology $R = 0$. However $w$ is precisely $1/3$ when $T_\mu = 0$. In general $T_\mu \propto \beta(g) F^{\mu\nu} F^{\nu\mu}$ where $\beta(g)$ is the beta function of the running gauge coupling $g$ in a $SU(N_c)$ gauge theory with $N_c$ colours. This allows $w \neq 1/3$. Further issues in this approach can be found in [27, 23, 30, 28].

Another approach involves an axial vector current [24, 29, 31, 32] instead of $J_\mu$. The scenario is based on the well known fact that fermions in curved space-times exhibit a coupling of their spin to the curvature of the background space-time. The Dirac Lagrangian density of a fermion can be re-written as:

$$\mathcal{L} = \sqrt{-g} \bar{\psi} \left( i\gamma^a \partial_a - m + \gamma^a \gamma^5 B_a \right) \psi$$

$$B^d = \epsilon^{abcd} e_{b\lambda} \left( \partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\beta} e^\nu_c e^\mu_a \right)$$

in a standard notation, where $e^\mu_a$ are the vielbeins, $\Gamma^\mu_{\alpha\beta}$ is the Christoffel connection and Latin (Greek) letters denote tangent space (curved space-time) indices. The space-time curvature background has, therefore, the effect of inducing an “axial” background field $B_a$ which can be non-trivial in certain anisotropic space-time geometries, such as Bianchi-type cosmologies or in regions of space-time near rotating (Kerr) primordial black holes [24, 29, 31, 32]. For an application to particle-antiparticle asymmetry it is necessary for this axial field $B_a$ to be a constant in some local frame. The existence of such a frame has not been demonstrated. As before if it can be arranged that $B_a \neq 0$ for $a = 0$ then for constant $B_0$ CPT is broken: the dispersion relation of neutrinos in such backgrounds differs from that of antineutrinos. Explicitly we have

$$E = \sqrt{(\vec{p} - \vec{B})^2 + m^2 + B_0}$$

$$\bar{E} = \sqrt{(\vec{p} + \vec{B})^2 + m^2} - B_0$$

(9)
The relevant neutrino asymmetry emerges on following the same steps used when there was an explicit particle-antiparticle mass difference. As a consequence the following neutrino-antineutrino density difference is found in Bianchi II Cosmologies [24, 29, 31, 32]:

\[ \Delta n_{\nu} \equiv n_{\nu} - n_{\bar{\nu}} \sim g^* T^3 \left( \frac{B_0}{T} \right) \]  

(10)

with \( g^* \) the number of degrees of freedom for the (relativistic) neutrino. An excess of particles over antiparticles is predicted only when \( B_0 > 0 \), which had to be assumed in the analysis of [24, 29, 31, 32]; we should note, however, that the sign of \( B_0 \) and its constancy have not been justified in this phenomenological approach\(^2\).

At temperatures \( T < T_d \), with \( T_d \) the decoupling temperature of the lepton-number violating processes, the ratio of the net Lepton number \( \Delta L \) (neutrino asymmetry) to entropy density (which scales as \( T^3 \)) remains constant,

\[ \Delta L(T < T_d) = \frac{\Delta n_{\nu}}{s} \sim \frac{B_0}{T_d} \]  

(11)

which, for \( T_d \sim 10^{15} \text{ GeV} \) and \( B_0 \sim 10^5 \text{ GeV} \), implies a lepton asymmetry (leptogenesis) of order \( \Delta L \sim 10^{-10} \), in agreement with observations. The latter can then be communicated to the baryon sector to produce the observed BAU (baryogenesis) by a B-L conserving symmetry in the context of either Grand Unified Theories (GUT) [24], or sphaleron processes in the standard model.

Before closing this section we also mention that the splitting (9) of the energy levels between neutrinos and antineutrinos may also lead to neutrino-antineutrino mixing and thus oscillations (in a manner envisaged originally by Pontecorvo) or affect the magnitude of the neutrinoless double-beta decay amplitudes [31, 32]. These effects can lead to additional constraints on \( B^0 \), since, e.g. the neutrino-antineutrino oscillations may affect the relative abundance of different neutrino flavours in the Universe. Indeed, the increased oscillation length, predicted [32] due to the gravitational CPTV effects in early epochs of the Universe, may lead to higher production of muon neutrinos than that estimated without the gravitational effect, with profound consequences for early Universe cosmology, unless \( B^0 \) is appropriately constrained. Moreover, the neutrinoless double-beta decay amplitudes are modified in the presence of \( B^0 \) as: \( A \propto \sqrt{(B^0)^2 + m_{\nu_e}^2} \), where \( m_{\nu_e} \) is the electron-neutrino Majorana mass.

3. CPTV-induced in (String-Inspired) Background Geometry with Torsion

In this section we will discuss the case of a constant \( B^0 \) “axial” field that appears due to the interaction of the fermion spin with a string-theory background geometry with torsion. This is a novel observation, which (as far as we are aware) was discussed for first time in [22]. In the presence of torsion the Christoffel symbol contains a part that is antisymmetric in its lower indices: \( \Gamma^{\lambda}_{\mu\nu} \neq \Gamma^{\lambda}_{\nu\mu} \). Hence the last term of the right-hand side of the Eqn.(8) is not zero. Since the torsion term is of gravitational origin it couples universally to all fermion species. The effect of the coupling to neutrinos will be clarified below.

The massless gravitational multiplet in string theory contains the dilaton (spin 0, scalar, the “trace” of graviton), \( \Phi \), the graviton (spin 2, symmetric tensor), \( g_{\mu\nu} \), and the spin 1 antisymmetric tensor \( B_{\mu\nu} \). The (Kalb-Ramond) field \( B \) appears in the string effective action only through its totally antisymmetric field strength, \( H_{\mu\nu\rho} = \partial_{[\mu} B_{\nu\rho]} \), where \([\ldots] \) denotes antisymmetrization of

\(^2\) The above considerations concern the dispersion relations for any fermion, not only neutrinos. However, when one considers matter excitations from the vacuum, as relevant for leptogenesis, we need chiral fermions to get non trivial CPTV asymmetries in populations of particle and antiparticles, because \( < \psi_\uparrow \gamma^\gamma \psi_\downarrow > = - < \psi_\downarrow \gamma^\gamma \psi_\uparrow > + < \psi_R \gamma^\gamma \psi_R > \).
the indices within the brackets. The calculation of string amplitudes [48] shows that $H_{\mu \nu \rho}$ plays the role of torsion in a generalised connection

$$\Gamma^\lambda_{\mu \nu} = \Gamma^\lambda_{\mu \nu} + e^{-2\Phi} H^\lambda_{\mu \nu} = \Gamma^\lambda_{\mu \nu} + T^\lambda_{\mu \nu}. \quad (12)$$

In ref. [49] exact solutions to the conformal invariance conditions (to all orders in $\alpha'$) of the low energy effective action of strings have been presented. In four “large” (uncompactified) dimensions of the string, the antisymmetric tensor field strength can be written uniquely as

$$H_{\mu \nu \rho} = e^{2\Phi} \epsilon_{\mu \nu \rho \sigma} \partial^\sigma b(x) \quad (13)$$

with $\epsilon_{0123} = \sqrt{g}$ and $e^{\mu \nu \rho \sigma} = |g|^{-1} \epsilon_{\mu \nu \rho \sigma}$, with $g$ the metric determinant. The field $b(x)$ is a “pseudoscalar” axion-like field. The dilaton $\Phi$ and axion $b$ fields are fields that appear as Goldstone bosons of spontaneously broken scale symmetries of the string vacua, and so are exactly massless classically. In the effective string action such fields appear only through their derivatives. In the “physical” Einstein frame, relevant for cosmological observations, the temporal component of the metric is normalised to $g_{00} = +1$ by an appropriate change of the time coordinate. In this setting, the solution of [49] leads to a Friedmann-Robertson-Walker (FRW) metric, with scale factor $a(t) \sim t$, where $t$ is the FRW cosmic time. Moreover, the dilaton field $\Phi$ behaves as $-\ln t + \phi_0$, with $\phi_0$ a constant, and the axion field $b(x)$ is linear in $t$. There is an underlying world-sheet conformal field theory with central charge $c = 4 - 12Q^2 - \frac{6}{n+2} + c_I$ where $Q^2(>0)$ is the central-charge deficit and $c_I$ is the central charge associated with the world-sheet conformal field theory of the compact “internal” dimensions of the string model [49]. The condition of cancellation of the world-sheet ghosts that appear because of the fixing of reparametrisation invariance of world-sheet co-ordinates requires that $c = 26$. The solution for the axion field is

$$b(x) = \sqrt{2} e^{-\phi_0} \sqrt{Q^2} M_s \sqrt{n} t, \quad (14)$$

where $M_s$ is the string mass scale and $n$ is a positive integer, associated with the level of the Kac-Moody algebra of the underlying world-sheet conformal field theory. For non-zero $Q^2$ there is an additional dark energy term in the effective target-space time action of the string [49] of the form $\int d^4x \sqrt{-g} e^{2\Phi} (-4Q^2)/\alpha'$. The linear axion field (14) remains a non-trivial solution even in the static space-time limit with a constant dilaton field [49]. In such a case space time is an Einstein universe with positive cosmological constant and constant positive curvature proportional to $6/(n+2)$. For the solutions of [49], the covariant torsion tensor $e^{-2\Phi} H_{\mu \nu \rho}$ is constant. (This follows from (12) and (13) since the exponential dilaton factors cancel out in the relevant expressions. ) Only the spatial components of the torsion are nonzero in this case, $T_{ijk} \sim \epsilon_{ijk} \dot{b} = \epsilon_{ijk} \sqrt{2Q^2} e^{-\phi_0} \frac{M_s}{\sqrt{n}}$, where the overdot denotes derivative with respect to $t$. As discussed in [22], in the framework of the target-space effective theory, the relevant Lagrangian terms for fermions (to lowest order in $\alpha'$) will be of the form (8), with only the temporal component $B^0$ of the $B^d$ vector being nonzero:

$$B^0 \sim \sqrt{2Q^2} e^{-\phi_0} \frac{M_s}{\sqrt{n}} \text{GeV} > 0. \quad (15)$$

We follow the conventions of string theory for the sign of $B^0$. From phenomenological considerations $M_s$ and $g_s^2/4\pi$ are taken to be larger than $O(10^4)$ GeV and about 1/20 respectively. A stringent constraint on the Kac-Moody level is not imposed from the requirement of CPTV-induced leptogenesis. We observe from (15) that the central charge deficit $Q^2$ of the underlying conformal field theory determines the order of particle-antiparticle asymmetries in this
model. The particle-antiparticle asymmetry occurs already in thermal equilibrium, due to the background-induced [24] difference in the dispersion relations between particles and antiparticles. For CPT-Violating leptogenesis at the GUT scales involving right-handed neutrinos, for instance, decaying to Higgs and active neutrinos and the corresponding antiparticles, one would require [24], \( B^0 \sim 10^6 \) GeV. However, since the coupling of fermions to torsion is universal, the axion background would also couple to quarks and charged leptons. Hence a constant torsion-induced \( B^0 \) could lead directly to baryogenesis at the quark decoupling temperature \( T_q \sim 100 \) MeV, provided \( B^0 \) assumes an appropriate value much lower than \( 10^5 \) GeV. In such a scenario, the observed BAU could be realised directly through the quark-H-torsion interactions; unfortunately, the corresponding neutrino asymmetry would be too high, given that the neutrino decoupling temperatures are at 1 MeV scale. Note that standard model B-L conserving sphaleron processes freeze-out much earlier (at temperatures of order 100 GeV), but such interactions cannot produce sufficient baryon asymmetry in the universe without extra sources for CP violation [4].

A phenomenologically viable alternative scenario is one in which \( B^0 \) is not constant with time. In such a scenario the universe undergoes a phase transition at GUT scales (\( \sim 10^{15} \) GeV). Above the GUT temperature heavy right-handed Majorana neutrinos could decouple or lepton number violating (but B-L conserving) processes could occur. At the phase transition the value of the H-torsion background could change from a large to a smaller value. This approach is based on the possibility that conformal field theories with different central charges characterise different epochs of the early universe [49]. Transitions between such conformal (fixed) points in moduli space correspond to non-conformal (Liouville) time evolution [50] and represent phase transitions in the early universe. Following the idea of Ref.[24], this leptogenesis can be communicated to the baryon sector by means of B-L conserving sphaleron processes. The difference between the fermion and antifermion populations is due to the interaction with a CPTV background torsion and occurs already in thermal equilibrium. Provided the background torsion is constant in time over the appropriate epoch of the evolution of the universe (until the freeze out of the pertinent processes characterising the epoch), such differences cannot be eroded during the expansion of the universe. No enhanced CP violation in the lepton sector is essential for leptogenesis in this approach, in contrast to the case of conventional leptogenesis [51, 52, 53, 5, 54]: it should be stressed, though, that this observation does not completely remove the need for right-handed sterile neutrinos. The latter may be essential, for instance, for explaining the smallness of the active neutrino masses, through seesaw mechanisms, or may play the role of dark matter [5, 54].

4. CPTV in Stochastic Finsler Geometries

Although all the models displaying CPTV that we have considered so far are based on local effective field theories, there is no compelling reason for a restriction to such a framework. In fact a microscopic model involving space-time defects based on string-brane theory suggests the use of a non-Riemannian metric background similar to that which occurs in Finsler geometry [55, 56]. (This model will be discussed in the following section.) Independently there has been much interest in Finsler geometry [57, 58, 59, 60, 61, 62, 63, 64, 65, 66] for characterising the Early universe [67, 68, 69, 70, 71] and for descriptions of modified dispersion relations for particle probes [72, 68, 56, 73]. Finsler geometry has a metric which, in addition to space-time coordinates, depends also on “velocities”. Lorentz symmetry is broken through some fixed vectors in the metric. We explore the consequences of making such vectors having components which are stochastic with possibly zero mean. This is a feature that arises in the defect model of D-foam [72, 38, 37] that we will consider in the next section. The defects stochastically fluctuate, due to both statistical and quantum stringy effects in large populations of such D-particles that can populate eras of the early universe. As we shall discuss below, the result of the

\(^3\) Such processes are allowed due to the Yukawa coupling terms of right-handed Majorana Neutrinos to the lepton sector of the Standard Model, which also yield Majorana mass terms to the active neutrinos via seesaw [5].
interaction of neutrinos with these defects, leads to stochastically fluctuating Finsler-like metrics. However we wish to consider the consequences for CPTV and matter-antimatter asymmetry of this stochasticity in a general context. This underlying model provides our main motivation to study this class of space-times in this section and to contrast our findings on the induced CPTV for such cases with the corresponding ones for the D-foam model.

Below we shall be brief in our description of the stochastic CPTV backgrounds, concentrating only on the main features leading to modified dispersion relations that are different between particles and antiparticles. For the interested reader details can be found in [22].

We focus on on-shell neutrinos (which are now known to have small masses). Again, this is motivated by our desire to discuss leptogenesis in such geometries. Moreover, for reasons that will become clear in section 5, it is neutrinos that play a preferential rôle in interacting non-trivially with the D-particle foam background, which induces stochastically fluctuating Finsler-like space times. As our main motivation is to compare the generic Finsler-like case with the D-foam model, as far as CPTV is concerned, we restrict our attention here on the effects of stochastically fluctuating Finsler geometries on dispersion relations of neutrinos and antineutrinos. We shall consider a particular type of Finsler metric on a manifold $M$ which is known as the Randers metric [55] 4. It was noted in [76] that the geodesics of this metric coincided with the minimum time trajectories of a particle moving on a Riemannian manifold in the presence of a time independent drift given by a vector field. This is similar to Fermat’s principle for propagation in refractive media. We mention in passing that similarities of D-particle foam to a refracting medium have been discussed in the literature [72, 77, 78]. If we were to assume that the result on minimum time trajectories was true for a pseudo-Riemannian situation and the drift was given by collisions due to D-particle scattering, then at a heuristic level a stochastic drift could be a reasonable generic phenomenological model of the back-reaction of low dimensional recoiling branes on matter.

The metric in this models is given by [22] (below, $x^\mu$ denotes space-time coordinates, while the variables $y^\mu$ play the rôle of “velocities” in the Finsler framework)

$$g_{\mu\nu}(x,y) = r_{\mu\nu}(x) + \phi^2(x) l_{\mu} l_{\nu} + \left( \frac{r_{\mu\rho}(x)}{\alpha(x,y)} - \frac{r_{\mu\sigma}(x) y^\rho y^\sigma}{\alpha(x,y)^3} \right) \phi(x) l_{\rho} y^\sigma + \frac{1}{\alpha(x,y)} (r_{\mu\rho}(x) y^\rho \phi(x) l_{\nu} + r_{\nu\rho}(x) y^\rho \phi(x) l_{\mu}), \quad \alpha(x,y) = \sqrt{r_{\mu\nu}(x) y^\mu y^\nu},$$

where $l_{\mu}$ is a constant vector. In our model $\phi(x)$ will be a gaussian stochastic variable. On average the metric will be like a Riemannian metric if the mean of $\phi$ vanishes.

We shall consider a situation with $r_{\mu\nu}(x) = \eta_{\mu\nu}$ where $\eta_{\mu\nu}$ is the diagonal Minkowski matrix with entries $(1, -1, -1, -1)$. (The summation convention of repeated indices will be always understood unless explicitly stated otherwise.) Within the framework of a Robertson-Walker metric we shall ignore effects on the time-scale of the inverse expansion rate. We have assumed a homogeneous $\phi$ with $\phi$ being $x$ independent. The mass shell conditions of generalised plane-wave solutions for particles in this background $h^{\mu\nu} \omega_\mu \omega_\nu = m^2$, where $\omega_\mu = g_{\mu\nu}(x,y)y^\nu$ is a “phase-space” variable, dual to $y^\mu$, and $h^{\mu\nu}(x,\omega)$ is the inverse of the Finsler metric in phase-space [22], lead to the generalised dispersion relations. In the model it is possible to choose $l_{\mu}$. Not all choices will lead to asymmetric population distributions between particles and anti-particles.

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4 We mention, for completeness, that the other popular class of Finsler geometries, that appears in the General Relativistic version [59, 62, 60, 61] of the so-called Very Special Relativity Model [74], and cosmological extensions thereof [67, 69] are not characterised by CPTV in the dispersion relations, nor of the spin-curvature type discussed in section 2.3. In fact such VSR-related models have been proposed in the past as candidates for the generation of Lepton-number conserving neutrino masses [75], and hence our Lepton-number violating considerations in this work do not apply.
space-like choice \( l_0 = 0 \) gives a degenerate spectrum for particle and anti-particle and hence no CPTV in dispersion relations. Therefore this case cannot be used for Leptogenesis in our framework. More generally the dispersion relation is \[ \omega_0 = \pm \frac{\phi}{m} l_0 \left( 2\omega^2 + m^2 \right) + \mathcal{R}(\phi, \omega, m) \] (16)

where \( \mathcal{R}(\phi, \omega, m) = \left( \omega^2 + m^2 + \frac{\phi}{m} \left( 2\omega^2 + m^2 \right) \right) \left( l_1\omega_1 + l_2\omega_2 + l_3\omega_3 \right) \right)^{1/2}. \) The +sign is for the particle and the −sign is for the antiparticle. For the “time-like” case \( l_0 = 1, l_1 = l_2 = l_3 = 0 \) the dispersion relation reduces to \( e^{\omega_0} = \sqrt{\omega^2 + m^2} \pm \frac{\phi}{m} \left( 2\omega^2 + m^2 \right). \) The sign of \( l_0 \) can be reabsorbed in \( \phi. \) For the “null” case \( l_0 = 1 \) and \( l_2 = l_3 = 0 \) the dispersion relation reduces to \( \omega_0 = \sqrt{\omega^2 + m^2} \left( 1 + \frac{\phi}{m} \left( 2 - \frac{m^2}{\omega^2 + m^2} \right) \omega_1 \right) \pm \frac{\phi}{m} \left( 2\omega^2 + m^2 \right). \) The parameters \( \omega \) play the rôle of momenta \( \vec{p} \) in our case of neutrinos of mass \( m = m_\nu \) propagating in these space-times, and the Finsler metric may be seen as sort of back reaction on the space-time of such a propagation (to better appreciate this, the reader is invited to the discussion in the next section 5, where a particular model of D(efect)-foam is considered as a medium for neutrino propagation in the early universe, leading to Finsler-like metric distortions as a consequence of medium/particle interactions). Corresponding to such models involving D-foam, the parameter \( \phi \) is modelled as a stochastic gaussian process with a mean \( a \) and standard deviation \( \sigma. \) The fermion number distribution \( n \) from equilibrium statistical mechanics is given by \( n = g_{d.o.f.} \int \frac{d^4p}{(2\pi)^4} \frac{1}{e^{\beta \left( \frac{\omega}{m_\nu} - \mu \right)} + 1}, \) where we have ignored degeneracy factors. First of all, it immediately follows from the corresponding dispersion relation that for the “time-like” case, when \( a = 0, \) there is no particle/antiparticle asymmetry. This is to be expected, given that \( a \neq 0 \) corresponds in a sense to an averaged Lorentz violation in this stochastic geometry, and hence one of the basic assumptions for CPT Invariance of the effective theory of neutrinos in this “medium” is relaxed. For the “time-like” case, when \( a \neq 0 \) and \( \beta \) small, we obtain to leading order in \( T/m \gg 1 \) \[ \ll \Delta \omega \gg \sim -a g_{d.o.f.} T^3 \frac{m^2}{15} \left( \frac{T}{m} \right)^2. \] We require \( a < 0 \) in order to have a particle-antiparticle asymmetry where the particle distribution dominates the antiparticle distribution. This yields the following Lepton (neutrino) asymmetry, assumed to freeze at the neutrino decoupling temperature \( T_d \)

\[ \Delta L = \frac{\Delta n_\nu}{s} \sim -10 a \frac{T_d}{m_\nu} \] (17)

where, as usual, \( s \) denotes the entropy density, which for relativistic species is assumed to be \( s \sim g_{d.o.f.} \frac{2\pi^2}{45} T^3. \) Thus, from (17) we see that there is no CPTV asymmetry in the Lorentz invariant (on average) case \( a = 0. \)

To obtain the phenomenologically correct value of \( \Delta L(T \sim T_d) \sim 10^{-10}, \) which is then communicated to the baryon sector via B-L conserving sphaleron processes, or B-L conserving grand unified models (assumed appropriately embedded in such space-time geometries), one needs to fix appropriately the value of \( a, \) consider appropriate conditions for freeze-out, that depend on the underlying microscopic model, and take into account that, according to current data, the masses of the active neutrinos that are assumed to participate in (17) must be smaller than \( m_\nu < 0.2 \) eV. For example, in GUT-scale lepton-number violation models, as we discussed before, \( T_d \sim 10^{15} \) GeV, which implies that one needs only an extremely small in magnitude violation of Lorentz symmetry on average in this stochastic Finsler space time, \( a \sim 10^{-36}, \) in order to reproduce the observed Baryon Asymmetry in the universe. The assumption of fixing the sign of \( a \) is considered as fine tuning, and is a feature that is common in the models of gravitational leptogenesis/baryogenesis that exist in the current literature, as discussed briefly above \[ 26, 27, 24, 29, 31, 32, 23, 30, 28. \] One can calculate the asymmetry for the null case with results similar to the time-like case considered above \[ 22. \]
5. Stringy-Defect(D-)foam-induced CPTV and Leptogenesis

In this section we shall consider a population of D0-branes (or lower dimensional compactified D-branes which are effectively point-like from from the point of view of a brane world observer) interacting with neutral fermions such as the neutrino and anti-neutrino. This interaction leads to different dispersion relations for neutrinos and anti-neutrinos which in turn leads to an excess of the population of neutrinos over anti-neutrinos. The freeze-out of neutrinos at the decoupling temperature of neutrinos leads to leptogenesis given by the standard cosmological considerations. The latter results, through standard Baryon (B) and Lepton (L) number violating sphaleron processes or B-L conserving interactions in grand unified models describing matter excitations on the brane, to the observed Baryon Asymmetry in the Universe, with complete dominance of matter over antimatter, in a rather natural way, as we shall discuss below. Moreover, as we shall explain below, in this model of D(efect)-foam, the prevalence of matter over antimatter, i.e. the positive sign of the asymmetry $\Delta n > 0$, follows naturally, as a consequence of loss of energy of neutrinos during their interactions with the space-time defects, due to recoil of the latter. Thus, the sign of the induced asymmetry need not be fixed by hand, unlike the cases of gravitational leptogenesis discussed in previous sections. For instructive purposes, we first discuss the properties of the foam model, in the next subsection, before moving onto issues of CPTV and leptogenesis. D-foam models are stringy models of space-time foamy geometries, which involve brane universes, propagating in higher-dimensional bulk geometries. The bulk contains point-like D-brane defects (“D-particles” or D0 branes) whose population density is constrained by the amount of CPTV that we observe. In many string theories (such as bosonic and type IIA string theories) they are stable zero-dimensional defects. However for our purposes we will consider them to be present in string theories of phenomenological interest since, even when elementary D-particles cannot exist consistently, as is the case of type IIB string models, there can be effective D-particles formed by the compactification of higher dimensional D-branes (e.g. three-branes wrapped around three-cycles, with relatively small radii).

The preferential rôle of neutrinos in feeling the full effects of D-foam, and hence the CPTV, is attributed to electric charge conservation: the representation of SM particles as open strings, with their ends attached to the brane worlds, prevents capture and splitting of open strings carrying electric fluxes by the D-particles. (We should recall that in string theory the electric charge is at the end point of an open string.) D-particles are electrically neutral and thus electric charge would not have been conserved if such processes had taken place. This is also consistent with the effective D-particles which may have formed as a result of nucleation. Hence, the D-particle foam is transparent to charged excitations of the SM, leaving neutral particles, in particular neutrinos, susceptible to the foam effects. This different behaviour of neutrinos from charged leptons implies a background-induced breaking of the SU(2) gauge symmetry of the standard model. In type IIB string theories, effective D-particles can interact, but in a suppressed manner, with the entire SU(2) lepton doublet, so the SU(2) symmetry is not broken. However, in such scenarios these interactions are suppressed compared to photons, as discussed in [78]. The D-foam interactions with sterile right-handed Majorana neutrinos, though, remain unsuppressed, since the sterile neutrinos do not have any standard model charges. Such heavy states can participate in lepton-number violating processes freezing out at GUT scales. For our purposes in this work we may consider that statistically significant populations of D-particles existed in the early eras of the brane universe. As the time elapses, the brane universe, which propagates in the higher-dimensional bulk, enters regions characterised by D-particle depletion, in such as way that the late eras cosmology of the universe is not affected. Nevertheless, as we shall discuss below, the early D-particle populations may still have important effects in generating leptogenesis.
neutrino-antineutrino populations differences (asymmetries), which are then communicated to the baryon sector via the standard sphaleron processes [21] or B-L conserving GUT symmetries in unified particle physics models.

To this end, we need to consider the effective dispersion relation of a (anti)neutrino field in a brane space-time punctured with statistically significant populations of D-particles. The latter is a dynamical population, consisting of defects crossing the brane all the time, thereby appearing to a brane observer as flashing “on” and “off” space-time “foamy” structures. The (anti)neutrino excitations are represented as matter open strings with their ends attached on the brane. The number density of (anti) neutrinos on the brane world is limited by the requirement that they do not overclose the universe. In [22] we estimated the modification of the dispersion relations of neutrinos in such a “media” of D-particles in the early universe. The interaction of a string with a D-particle implies that at least one of the ends of the string is attached to the D-particle defect. Furthermore, the simultaneous creation of virtual strings stretched between the defect and the brane, describes the recoil of the D-particle. During the interaction time, the D-particle undergoes motion characterized by non-trivial “recoil” velocities, \( u_\parallel = \frac{g_s}{M_s} \Delta p_i = \frac{g_s}{M_s} r_i \ p_i \) along the brane longitudinal dimensions, where \( r_i \) denotes the proportion of the incident neutrino momentum that corresponds to the momentum transfer \( \Delta p_i \) during the scattering, and \( u_\perp \) in directions transverse to the brane world [80]. As discussed in detail in [80, 39], one may assumed that \( r_i \) are stochastic, that is

\[
u_i = \frac{g_s}{M_s} \Delta p_i \rightarrow g_s r_i \frac{p_i}{M_s}, \text{ no sum over } i, \quad \ll r_i \gg = 0, \quad \ll r_i r_j \gg = \Delta^2 \delta_{ij}.
\]

The dispersion relations then of neutrino and antineutrinos of mass \( m \) propagating on such a deformed isotropic stochastically fluctuating space-time background can be found to be [22]:

\[
\ll E_\nu \gg = \sqrt{p^2 + m^2} \left(1 + \frac{1}{2} \sigma^2 \right) - \frac{1}{2} \frac{M_s}{g_s} \sigma^2, \quad \ll E_\nu \gg = \sqrt{p^2 + m^2} \left(1 + \frac{1}{2} \sigma^2 \right) + \frac{1}{2} \frac{M_s}{g_s} \sigma^2
\]

with \( E_\nu > 0 \) representing the positive energy of a physical antiparticle and \( \sigma^2 = \frac{g_s^2}{M_s^2} \Delta^2 p^2 \). In our analysis above we have made the symmetric assumption that the recoil-velocities fluctuation strengths are the same between particle and antiparticle sectors. (Scenarios for which this symmetry was not assumed have also been considered in an early work [39]). There can thus be local CPTV in the sense that the effective dispersion relation between neutrinos and antineutrinos are different. This is a consequence of the local violation of Lorentz symmetry (LV), as a result of the non-trivial recoil velocities of the D-particle [22]. The discussion of CPTV in such foamy universes now follows the line of argument adopted by others and mentioned previously: the difference in the dispersion relations between particles and antiparticles will imply differences in the relevant populations of neutrinos \((n)\) and antineutrinos \((\bar{n})\), (cf. the dispersion (18)). This difference between neutrino and antineutrino phase-space distribution functions in D-foam backgrounds generates a matter-antimatter lepton asymmetry in the relevant densities, which decreases with decreasing temperature up to a freeze-out point, which occurs at temperatures \( T_d \) at which the Lepton-number violating processes decouple. The lepton asymmetry in the D-foam scenario has the form [22]

\[
\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} = \frac{2 \Delta^2 g_s T_d}{M_s}.
\]

The phenomenologically realistic scenario in string theory frameworks, like the present one, seems to be the one in which one has GUT scale lepton-number violating processes, which freeze out the lepton-antilepton number at temperatures \( T_d \sim 10^{15} \) GeV, which characterises GUT scale
Lepton-Violating processes, (e.g those involving heavy Majorana neutrinos $N_I \rightarrow H \nu, \overline{H} \overline{\nu}$), in the context of D-particle brane Universe one may assume that at such early epochs one has a sufficiently dense D-particle gas in the bulk and on the brane, so that phenomenologically realistic Leptogenesis takes place. The latter then can be communicated via B-L conserving GUT processes to the baryon sector. After the GUT scale freeze out the bulk population of D-particles can be depleted, in the sense that the brane world representing our Universe passes through an area with scarce D-particle populations, so that late eras of the Universe are characterised by a more-or-less conventional Cosmology. From (19), we observe that for a GUT-like freeze-out temperature $T_d \sim 10^{15}$ GeV, the phenomenological value $\Delta L \sim 10^{-10}$ is attained for $M_\nu > 10^{25}$ GeV. For $\Delta^2 \sim 10^{-6}$ a Planck size D-particle mass $M_s/g_s \sim 10^{19}$ GeV is required so that the D-foam provides the physically observed Lepton and, thus, Baryon Asymmetry. For the unnaturally small $\Delta^2 < 10^{-21}$ one arrives at $M_s/g_s \sim 10$ TeV. Unfortunately, for $\Delta^2 \sim O(1)$ transplanckian D-particle masses are required. We stress once more that the D-foam approach to leptogenesis is distinguished from others in that a local effective field theoretical description is not adopted.

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