Lorentz- and CPT-Violating Extension of the Standard Model

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Abstract. The formulation and some experimental implications of a general Lorentz-violating extension of the standard model are reviewed. The theory incorporates both CPT-preserving and CPT-breaking terms. It is otherwise a conventional quantum field theory, obtained under the assumption that Lorentz symmetry is spontaneously broken in an underlying model. The theory contains the usual standard-model gauge structure, and it is power-counting renormalizable. Energy and momentum are conserved. Despite the violation of Lorentz symmetry, the theory exhibits covariance under Lorentz transformations of the observer inertial frame. A general Lorentz-violating extension of quantum electrodynamics can be extracted. The standard-model extension implies potentially observable effects in a wide variety of experiments, including among others measurements on neutral-meson oscillations, comparative studies in Penning traps, spectroscopy of hydrogen and antihydrogen, bounds on cosmological birefringence, measurements of muon properties, clock-comparison tests, and observations of the baryon asymmetry.

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1. Introduction

The standard model of particle physics is invariant under the discrete operation CPT, which combines charge conjugation C, parity inversion P, and time reversal T. Indeed, the product CPT is the only remaining combination of C, P, T generally believed to be an exact symmetry of nature. The standard model also exhibits symmetry under continuous Lorentz transformations, which include both rotations and boosts. Both CPT and Lorentz symmetries are connected via the CPT theorem, which states under mild technical assumptions that CPT is an exact symmetry of local Lorentz-covariant field theories of point particles [1, 2].

Other than theoretical prejudice, there is strong support from high-precision experiments in favor of Lorentz and CPT symmetry of nature. For example, the Particle Data Group identifies [3] the sharpest figure of merit for CPT tests as one involving the kaon particle-antiparticle mass difference, currently constrained by experiments at Fermilab and CERN to

\[
\frac{|m_K - m_{\bar{K}}|}{m_K} < 10^{-18}.
\]  

(1)

Tight constraints on possible Lorentz violations also exist.

The presence of a general CPT theorem for Lorentz-covariant particle theories and the establishment of high-precision experimental tests implies that the observation of Lorentz or CPT violation would represent a sensitive signal for unconventional physics beyond the standard model. Possible theoretical mechanisms through which Lorentz or CPT symmetry might be violated are therefore worth investigating [3]. However, straightforward approaches typically require radical revisions of conventional quantum field theory or contain physical features such as infinite-spin particles that seem unlikely to be realized in nature.

Despite this, at least one promising theoretical possibility exists that allows Lorentz and CPT violation in the context of the standard model. It is based on the idea of spontaneous breaking of Lorentz and CPT symmetry in an underlying theory [4, 5], and it appears to be compatible both with experiment and with established quantum field theory. This theory leads to a general phenomenology for Lorentz and CPT violation at the level of the standard model and quantum electrodynamics (QED) [5, 6].

The resulting standard-model extension indicates that apparent breaking of Lorentz and CPT symmetry could be observable in a variety of existing or feasible experiments. Relatively few experiments testing Lorentz and CPT symmetry have the necessary sensitivity to observe possible signals. However, a few high-precision ones already bound some of the parameters for Lorentz and CPT violation in the standard-model extension. Among the ones investigated to date are experiments with neutral-
meson oscillations [4, 7, 8, 10, 11, 12], comparative tests of QED in Penning traps [13, 15, 16, 17], spectroscopy of hydrogen and antihydrogen [18, 19], measurements of muon properties [20], clock-comparison experiments [21, 22], measurements of cosmological birefringence [23, 24, 25], and observations of the baryon asymmetry [26]. Effects on cosmic rays have also been investigated in a restricted version of the standard-model extension [27].

In the remainder of this talk, the formulation and experimental implications of the general Lorentz- and CPT-breaking standard-model extension are briefly described. Some different approaches to unconventional space-time physics beyond the standard model are discussed in other presentations at this meeting [28, 29, 30, 31].

2. Theoretical framework

Developing a satisfactory microscopic theory allowing Lorentz and CPT breaking is a difficult task. It is therefore tempting to avoid the issue via a purely phenomenological approach, in which one introduces a parametrization of observable quantities that allows for Lorentz or CPT violation. An illustration is provided by the phenomenology of CPT violation in neutral-kaon oscillations [32]. In this case, the physical kaon eigenstates $K_S$ and $K_L$ are formed as linear combinations of the strong-interaction eigenstates $K^0$ and $K^0$ involving two complex quantities that parametrize CP violation. One quantity, $\epsilon_K$, parametrizes T violation with CPT symmetry while the other, $\delta_K$, parametrizes CPT violation with T symmetry. In the usual standard model, a mechanism for T violation exists so that a nonzero value of $\epsilon_K$ is calculable in principle. In contrast, CPT is a symmetry of the usual standard model and $\delta_K$ therefore vanishes.

Introducing the parameter $\delta_K$ is in this context a purely phenomenological choice, without basis in a microscopic theory. In fact, it is unclear a priori whether this parametrization can make physical sense in a microscopic theory. Certainly, without a microscopic description $\delta_K$ cannot be related to different phenomenological parameters for CPT violation in other systems. Similar difficulties face other phenomenological descriptions of Lorentz and CPT violation. It would therefore seem more desirable to develop an explicit microscopic theory for such effects. Ideally, one would like a theoretical framework at the level of the standard model from which one could extract a quantitative and general phenomenology for Lorentz and CPT violation in any system of interest. If available, such a theory would permit direct comparisons between experiments, calculation of phenomenological parameters, and possibly the prediction of signals.

A microscopic theory of this type can be obtained within the framework of spontaneous Lorentz and CPT breaking [6, 7]. The basic notion is
that apparent violation of Lorentz and CPT symmetries could emerge from spontaneous symmetry breaking in a fully Lorentz- and CPT-covariant fundamental theory of nature. This mechanism appears theoretically viable and is therefore a relatively elegant way to break Lorentz and CPT invariance. Spontaneous breaking has the advantage that many desirable features of a Lorentz-covariant theory can be anticipated because the dynamics remains covariant, even though the solutions and the physics of the resulting theory exhibit Lorentz and CPT violations. In contrast, other types of Lorentz and CPT breaking are typically inconsistent with theoretical notions such as probability conservation or microcausality.

In some respects, the behavior of a particle in a vacuum with spontaneous Lorentz and CPT violation is related to that of a conventional particle moving inside a biaxial crystal [9]. The presence of the crystal typically breaks both rotational and boost symmetry, but these features are compatible with a consistent theoretical description and properties such as causality. Instead of being associated with fundamental problems, the lack of Lorentz covariance here merely follows from the existence of the background crystal fields. In fact, microcausality can explicitly be demonstrated in some simple models emerging from spontaneous Lorentz and CPT breaking [9].

Spontaneous breaking of Lorentz and CPT symmetry can be triggered in a Lorentz-covariant theory by certain types of interaction among Lorentz-tensor fields that destabilize the naive vacuum and lead to nonzero Lorentz-tensor expectation values. The true vacuum fills with these tensor expectation values, producing spontaneous Lorentz breaking [6], together with spontaneous CPT breaking if the tensor expectation values have an odd number of spacetime indices [7]. Apparent violations of Lorentz and CPT symmetry could arise at the level of the standard model [8] if some components of the tensor expectation values lie along the four macroscopic spacetime dimensions. Some of the possible observable effects in experiments that could result from this are discussed below.

The destabilizing Lorentz-tensor interactions required to trigger spontaneous Lorentz violation are absent in conventional four-dimensional renormalizable gauge theories, including the usual standard model. Suitable tensor interactions do occur, however, in some string (M) theories. The issue of realizing spontaneous Lorentz violation in this context can be investigated, for example, using string field theory in the particular case of the open bosonic string. For this case, the action and equations of motion for particle fields below a specified level number \( N \) can be derived analytically. One can then obtain the associated solutions and identify those that persist as \( N \) increases [6]. This procedure has been completed for some cases to a depth of over 20,000 terms in the static potential [7]. Solutions that spontaneously break Lorentz symmetry are among those remaining
stable as $N$ increases.

When a continuous global symmetry is spontaneously broken in a conventional field theory, corresponding massless modes arise in accordance with the Nambu-Goldstone theorem. Similarly, spontaneous breaking of a continuous global Lorentz symmetry would also lead to massless modes. In contrast, when a global spontaneously broken symmetry is promoted to a local gauge symmetry the Higgs mechanism occurs, in which the massless modes disappear and a mass is generated for the gauge boson. However, although the inclusion of gravity promotes Lorentz invariance to a local symmetry, there is no analogue to the Higgs effect because connection depends on derivatives of the metric rather than directly on the metric itself. Thus, when local Lorentz symmetry is spontaneously broken, the graviton propagator is modified but no graviton mass is generated.

3. Standard-Model Extension and QED Limit

For consistency with known experimental limits, any apparent breaking of Lorentz and CPT symmetries occurring at the level of the SU(3)×SU(2)×U(1) standard model and QED must be highly suppressed. If indeed this originates in spontaneous breaking in a Planck-scale fundamental theory, then the natural dimensionless suppression factor is the ratio of a low-energy scale associated with the standard model to the Planck scale. This heavy suppression implies that only limited effects of Lorentz or CPT violation would be observable.

At low energies, effects from any apparent Lorentz and CPT violation would be governed by a standard-model extension that arises as the low-energy limit of the fundamental theory. Intuition about the structure of the standard-model extension can be obtained by considering various possible couplings in the low-energy limit of the fundamental theory and examining the resulting form when Lorentz tensors acquire expectation values. For instance, possible trilinear couplings between fermions and one or more boson tensor fields can produce terms in the low-energy theory of the form

$$L \sim \frac{\lambda}{M^k} \langle T \rangle \cdot \overline{\psi} \Gamma (i\partial)^k \chi + h.c.,$$

where the tensor expectation values are denoted $\langle T \rangle$. The Lorentz properties of the bilinear in the fermion fields $\psi, \chi$ are fixed by the gamma-matrix structure $\Gamma$ and the $k$ spacetime derivatives $i\partial$, and these properties establish the associated apparent Lorentz and CPT violation in the low-energy theory. In addition to the expectation value $\langle T \rangle$, the coefficient of the Lorentz-breaking fermion bilinear involves a dimensionless coupling $\lambda$ and an appropriate power of some large (compactification or Planck) scale $M$. 
General considerations along the above lines make it possible to establish all terms at the level of the standard model that are compatible with an origin in spontaneous Lorentz and CPT breaking, no matter what the form of the fundamental theory. Imposing also the requirements of SU(3)×SU(2)×U(1) gauge invariance and power-counting renormalizability produces a general hermitian standard-model extension allowing for Lorentz violation with both CPT-even and CPT-odd terms [9]. This theory at present appears to be the only candidate for a consistent standard-model extension originating in a microscopic theory of Lorentz violation.

Since the apparent Lorentz and CPT violation arises from spontaneous breaking in a fully Lorentz-covariant theory, the resulting standard-model extension has a number of attractive features common to the usual Lorentz-covariant field theories [9]. For example, standard quantization methods can be used, and properties such as positivity of the energy and microcausality can be expected to hold. Assuming the tensor expectation values are independent of spacetime location (no soliton solutions), then energy and momentum are conserved. It can also be shown that the usual gauge-symmetry breaking to the electromagnetic U(1) occurs, so the usual gauge structure is unaffected. Moreover, the theory is covariant under observer Lorentz transformations: rotations or boosts of the observer’s inertial frame leave unaffected the physics because the background expectation values transform covariantly along with the localized fields. Instead, the apparent Lorentz violations are associated with particle Lorentz transformations: rotations or boosts of the localized fields in a fixed observer inertial frame can change the physics because they leave untouched the background expectation values.

The usual forms of QED can be extracted as suitable limits from the conventional standard model. Similarly, Lorentz-violating QED extensions emerge by taking suitable limits of the standard-model extension [9]. Both the fermion and the photon sectors acquire apparent Lorentz-violating terms with CPT-even and CPT-odd contributions. Since there exist many high-precision experiments with QED, the Lorentz-violating QED extensions are of particular interest.

The simplest explicit example is the extension of QED that involves only electrons, positrons, and photons. The usual lagrangian is:

\[
L_{\text{QED}} = \bar{\psi} \gamma^\mu \left( \frac{i}{2} \not\partial - qA_\mu \right) \psi - m \bar{\psi} \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}.
\] (3)

The limiting QED case from the standard-model extension produces CPT-odd terms,

\[
L_{c}^{\text{CPT}} = -a_\mu \bar{\psi} \gamma^\mu \psi - b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi,
\]

\[
L_{\gamma}^{\text{CPT}} = \frac{1}{2} (k_{AF} \gamma^\gamma) \epsilon_{\gamma\lambda\mu\nu} A^\lambda F^{\mu\nu}.
\] (4)
and CPT-even ones,

\[ \mathcal{L}_{\text{Lorentz}} = c_{\mu \nu} \bar{\psi} \gamma^\mu \left( \frac{1}{2} i \gamma^\nu - q A^\nu \right) \psi + d_{\mu \nu} \bar{\psi} \gamma_5 \gamma^\mu \left( \frac{1}{2} i \gamma^\nu - q A^\nu \right) \psi - \frac{1}{2} H_{\mu \nu} \bar{\psi} \sigma^{\mu \nu} \psi \]

\[ \mathcal{L}_{\text{γ Lorentz}} = -\frac{1}{4} (k_F)_{\kappa \lambda \mu \nu} F^{\kappa \lambda} F_{\mu \nu} . \] (5)

All coefficients of the extra terms can be regarded as minuscule Lorentz- and CPT-violating couplings. All the extra terms are invariant under observer Lorentz transformations but break particle Lorentz covariance. Note that some of the coefficient components are unobservable physically, because field redefinitions must be taken into account. For instance, coefficients of the type \( a_{\mu} \) can be directly detected only in flavor-changing experiments, and so at leading order they are unobservable in experiments restricted to electrons, positrons, and photons. Ref. [9] provides additional information about the properties of the above expressions, including details of the notation and conventions.

4. Experiment

A variety of high-precision experimental tests of Lorentz and CPT symmetry can be quantitatively investigated and compared within the standard-model extension described above, and in favorable cases potentially observable signals can be identified. The remainder of this talk provides a short overview of some of the results obtained to date.

4.1. Neutral-Meson Oscillations

Four neutral-meson systems are known to exhibit flavor oscillations: \( K \), \( D \), \( B_d \), and \( B_s \). In what follows, a generic neutral meson is denoted by \( P \). The time evolution of a neutral-meson state is governed by a non-hermitian two-by-two effective hamiltonian in the meson-antimeson state space. Two complex parameters controlling indirect CP violation appear in the effective hamiltonian: \( \epsilon_P \) and \( \delta_P \). The quantity \( \epsilon_P \) parametrizes T violation, while \( \delta_P \) parametrizes CPT violation. For the \( K \) system, \( \epsilon_K \) and \( \delta_K \) are the phenomenological quantities discussed in section 2. Bounds on the magnitude of \( \delta_P \) provide constraints on CPT violation in the neutral-meson systems.

The quantity \( \delta_P \) vanishes in the context of the usual standard model because CPT is a symmetry. However, \( \delta_P \) can be derived in the context of the standard-model extension [12]. At leading order, it can be shown that \( \delta_P \) varies with only one kind of Lorentz- and CPT-violating term in the standard-model extension, of the form \( -a_q^q \bar{q} \gamma^\mu q \). Here, \( q \) represents a valence quark field in the \( P \) meson and the quantity \( a_q^q \) varies with quark
flavor $q$ but is spacetime constant. An expression for $\delta P$ in the frame in which the quantities $a_{\mu}^q$ are specified, valid at leading order in all coupling coefficients in the standard-model extension, is

$$\delta P \approx i \sin \hat{\phi} \exp(i\hat{\phi}) \gamma(\Delta a_0 - \hat{\beta} \cdot \Delta \vec{a})/\Delta m. \quad (6)$$

Here, $\beta^\mu \equiv \gamma(1, \vec{\beta})$ denotes the four-velocity of the $P$-meson. Its appearance in the expression for $\delta P$ represents a variation with the boost and orientation of the $P$ meson and is a reflection of the breaking of Lorentz symmetry in the standard-model extension. In Eq. (6), $\Delta a_\mu \equiv a_{\mu}^2 - a_{\mu}^1$, where $q_1$ and $q_2$ are the valence-quark flavors for the $P$ meson, and $\hat{\phi} \equiv \tan^{-1}(2\Delta m/\Delta \gamma)$, where $\Delta m$ and $\Delta \gamma$ are the mass and decay-rate differences, respectively, between the $P$-meson eigenstates. Note that subscripts $P$ have been omitted for simplicity.

The result (6) implies several interesting features of tests of Lorentz and CPT symmetry with neutral mesons and makes several predictions. For example, the dependence on $a_{\mu}^q$ and the independence of other coefficients for Lorentz violation in the standard-model extension, together with the involvement of flavor-changing effects, means that neutral-meson tests are independent at leading order of any results from other experiments discussed in this talk. Another point is that the real and imaginary parts of $\delta P$ are predicted to be proportional.

Equation (6) also suggests that the magnitude of $\delta P$ may differ for distinct $P$ as a result of the flavor dependence of the coefficients $a_{\mu}^q$. One possible scenario would be that the coefficients $a_{\mu}^q$ grow with mass, as do the usual Yukawa couplings, in which case the heavier neutral mesons such as $D$ or $B_d$ may exhibit large CPT-violating effects. Other interesting effects are predicted from the dependence of the result (6) on the meson boost magnitude and orientation. For instance, distinct experiments may have inequivalent Lorentz and CPT reach even if the statistical sensitivity is comparable. This could occur if the mesons in one experiment have a $4\pi$ distribution while those for another are well collimated, or if the meson-momentum spectra differ greatly in the two experiments. Another possibility would be variations of the data with sidereal time, arising from the rotation of the Earth relative to the orientation of the coefficients for Lorentz violation. Since the data in neutral-meson experiments are typically taken over an extended time period, the consequences of time averaging must be taken into account to provide a complete analysis of CPT violation.

Observations of the neutral-$K$ system currently provide the sharpest clean experimental constraints on CPT violation. Both time-averaged limits on $\delta K$ and limits on the amplitude of sidereal variations are now available. The heavier neutral-meson systems have also been used to
place some CPT bounds. Two collaborations [11] at CERN have studied the issue of whether existing data suffice to constrain CPT violation. The OPAL collaboration has published the measurement $\text{Im} \delta_{B_d} = -0.020 \pm 0.016 \pm 0.006$, while the DELPHI collaboration has announced a preliminary result of $\text{Im} \delta_{B_d} = -0.011 \pm 0.017 \pm 0.005$. Additional theoretical and experimental studies are in progress for all these systems.

4.2. QED Experiments

A practical approach to obtaining high-precision comparative data for particles and antiparticles is to trap them individually for extended time periods. Experiments of this type can yield sharp CPT bounds and thereby constrain the coefficients for Lorentz violation in the fermion sector of the QED extension [14]. One option is to use a Penning trap to perform comparative studies of anomaly and cyclotron frequencies for particles and antiparticles [13]. Several effects are predicted by the QED extension, including direct signals in the form of frequency shifts and variations of frequencies with sidereal time as the Earth rotates [14]. Various experimental analyses along these lines have been performed, and for a given experimental scenario one can estimate the attainable sensitivity and introduce appropriate figures of merit for the different effects.

An immediate CPT test is provided by comparisons of the anomalous magnetic moments of electrons and positrons. This generates a constraint on the spatial components of the coefficient $b_\mu$ in the laboratory frame. A recent reanalysis of data from earlier experiments has placed a bound of $1.2 \times 10^{-21}$ on the associated figure of merit [16]. Another test, which requires measurements only on the electron anomaly frequency, involves searching for frequency variations with sidereal time. A new experimental result with a figure of merit bounded at $6 \times 10^{-21}$ has recently been obtained [17]. Experiments similar to the above but performed with protons and antiprotons would be of interest.

Comparisons of particle and antiparticle cyclotron frequencies are also possible. An elegant recent experiment determines the cyclotron frequencies of antiprotons and $H^-$ ions caught in the same trap [15]. In the context of the standard-model extension, leading-order effects in this experiment are sensitive to Lorentz violation, and the associated figure of merit is constrained to $4 \times 10^{-25}$.

The possibility also exists of testing Lorentz and CPT symmetry to high precision by comparing spectroscopic data from trapped hydrogen and antihydrogen [18, 19]. Various experimental signals can be considered. Within the context of the standard-model and QED extensions, certain 1S-2S and hyperfine transitions in magnetically trapped hydrogen and antihydrogen provide direct sensitivity to parameters for Lorentz and CPT violation.
For some specific transitions, theoretically clean signals for Lorentz and CPT violation exist that are unsuppressed by powers of the fine-structure constant.

Clock-comparison experiments \[21\] provide an exceptionally sensitive means of searching for Lorentz violation. Typically, they constrain possible spatial anisotropies by bounding the relative change of two hyperfine or Zeeman transition frequencies as the Earth rotates. Limits from experiments already performed have recently been analyzed in the context of the standard-model extension \[22\]. The possible signals depend on the species of atom used as the clocks. The resulting experimental effects are controlled by a combination of proton, neutron, and electron parameters for Lorentz and CPT violation, with bounds on suitable combinations of parameters ranging from \(10^{-25}\) to \(10^{-30}\) GeV under certain simplifying assumptions.

In the photon sector, combining theoretical factors with terrestrial, astrophysical, and cosmological experiments on electromagnetic radiation provides sharp bounds on Lorentz-violating terms in the QED extension. The pure-photon CPT-violating term in Eq. (4) is known to contribute negatively to the energy \[23\] which would appear to restrict its viability and indicate that the coefficient \((k_{AF})^\nu\) should vanish \[9\]. This theoretical difficulty is absent from the CPT-even term in the following equation, which is known to maintain a positive conserved energy \[9\].

Solving the extended Maxwell equations in the presence of Lorentz- and CPT-breaking effects generates two independent propagating degrees of freedom \[9\], in agreement with the conventional case. However, in the extended Maxwell case there are different dispersion relations for the two modes, an effect that differs qualitatively from the usual propagation of electromagnetic waves in vacuum. In fact, in the presence of Lorentz and CPT violation, an electromagnetic wave traveling in the vacuum exhibits effects closely analogous to those displayed by an electromagnetic wave in conventional electrodynamics that is passing through a transparent optically anisotropic and gyrotropic crystal with spatial dispersion of the axes \[9\]. This effect leads to sharp experimental limits on the coefficients for Lorentz violation in the extended Maxwell theory, extracted from bounds on the birefringence of radio waves on cosmological distance scales. For the CPT-odd coefficient \((k_{AF})^\mu\), present constraints on cosmological birefringence place a limit of the order of \(\lesssim 10^{-42}\) GeV on its components \[23, 33\]. For the CPT-even dimensionless coefficient \((k_F)^{\kappa\lambda\mu\nu}\), the single rotation-invariant irreducible component is constrained to \(\lesssim 10^{-23}\) by the existence of cosmic rays \[27\] and other tests. All other irreducible components of \((k_F)^{\kappa\lambda\mu\nu}\) are associated with violations of rotation invariance, and in principle it should be possible to bound these coefficients at the level of about \(10^{-27}\) with existing methods for measuring cosmological birefringence \[9\].
However, no such bounds presently exist.

The theoretically favored zero value of the coefficient \((k_{AF})_\mu\) is compatible with the sharp experimental constraints obtained from the absence of cosmological birefringence. However, a zero tree-level value of \((k_{AF})_\mu\) is not protected by any symmetry, and so one might plausibly anticipate that \((k_{AF})_\mu\) would acquire a finite contribution from radiative corrections involving CPT-violating couplings in the fermion sector. Remarkably, this difficulty can be avoided by an anomaly-cancellation mechanism, which ensures the finiteness of the net sum of all one-loop radiative corrections. Although the contribution from each individual radiative correction is ambiguous \([9, 24, 25]\), the anomaly-cancellation mechanism can be applied even if the theory is defined such that each individual radiative correction is nonzero. A tree-level CPT-odd term is therefore unnecessary for one-loop renormalizability. Related cancellations may occur at higher loops. The freedom to select a zero tree-level value for a CPT-odd term that appears unprotected by any symmetry represents a significant theoretical test of the internal consistency of the standard-model extension. In contrast, it can be shown that no such mechanism exists for the CPT-even Lorentz-violating pure-photon term \([8]\). Explicit calculation at the one-loop level demonstrates the existence of divergent radiative corrections. Future observation of a nonzero cosmological birefringence associated with this term therefore remains an open possibility.

A variety of other potentially observable Lorentz and CPT signals are known. For instance, under suitable conditions the observed baryon asymmetry can be produced in thermal equilibrium through Lorentz- and CPT-violating bilinear terms \([26]\). In the usual picture without CPT violation, nonequilibrium processes and C- and CP-breaking interactions are needed \([34]\). In contrast, the unconventional scenario with CPT violation can generate a relatively large baryon asymmetry at grand-unified scales that subsequently dilutes to the observed value through sphaleron or other effects.

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