A short review is given of some theoretical approaches to CPT violation. A potentially realistic possibility is that small apparent breaking of CPT and Lorentz symmetry could arise at the level of the standard model from spontaneous symmetry breaking in an underlying theory. Some experimental constraints are described.

1 Introduction

Among the observed symmetries of nature are CPT and Lorentz invariance. The discrete transformation CPT is the product of charge conjugation C, parity reflection P, and time reversal T, while the Lorentz transformations include rotations and boosts. These symmetries are connected via the CPT theorem, which under mild assumptions states that CPT is an exact symmetry of local Lorentz-covariant field theories of point particles.

Both CPT and Lorentz invariance have been tested to a high degree of precision and in a variety of experiments. For example, the sharpest figure of merit for CPT tests quoted by the Particle Data Group involves the kaon particle-antiparticle mass difference, which has been bounded by experiments at Fermilab and CERN to

$$r_K \equiv \frac{|m_K - m_{\bar{K}}|}{m_K} \lesssim 10^{-18}.$$  \hspace{1cm} (1)

At present, CPT is the sole combination of C, P, T observed as an exact symmetry of nature at the fundamental level.

Since the CPT theorem holds generally for relativistic particle theories and since there exist high-precision experimental tests, the observation of CPT violation would represent a powerful signal for unconventional physics. It is therefore of interest to examine possible theoretical mechanisms through which CPT might be broken.

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In the next part of this talk, I briefly review some approaches that have been taken in the literature to address the possibility of CPT violation. It turns out that most suggestions either have physical features that seem unlikely to be realized in nature and/or involve radical revisions of conventional quantum field theory. However, there exists at least one promising possibility, based on spontaneous breaking of CPT and Lorentz symmetry, that appears to be compatible with experimental constraints and with established quantum field theory. Its formulation and experimental implications are described in later parts of this talk.

2 Approaches to CPT Violation

Perhaps the simplest approach to CPT violation is a purely phenomenological one, avoiding the issue of developing a microscopic theory allowing CPT breaking. This can be implemented for a given experimental situation by introducing a parametrization of the observable quantities that allows for the possibility of CPT violation. The method has the advantages that it can be relatively straightforward in principle and that it is to some degree independent of possible origins of the CPT-violating effects. Among the disadvantages are the impossibility of relating the bounds obtained to those from other experiments and the absence of predictive power.

A well-established example of the phenomenological approach to CPT violation can be found in the literature on kaon oscillations. The physical eigenstates $K_S$ and $K_L$ can be expressed as linear combinations of the strong-interaction eigenstates $K^0$ and $\bar{K}^0$. Two complex parameters denoted $\epsilon_K$ and $\delta_K$ appear in these combinations. Both parametrize CP violation, but $\epsilon_K$ governs T violation while $\delta_K$ governs CPT violation. The standard model of particle physics has a mechanism for T violation, and so $\epsilon_K$ is at least in principle a calculable and nonzero quantity. However, the standard model preserves CPT and so predicts that $\delta_K$ is identically zero. Allowing for a nonzero value of $\delta_K$ is from this viewpoint a purely phenomenological choice. It has no grounds in a microscopic theory and $\delta_K$ is therefore not a calculable quantity. Moreover, it cannot be linked to other phenomenological parameters for CPT tests in different experiments.

A more interesting (and harder) approach from the theoretical perspective is to construct an explicit microscopic theory for CPT violation. Any such effort must somehow avoid one or more of the assumptions of the CPT theorem.

An immediate possibility is to construct a theory that directly violates one of the major axioms leading to the CPT theorem. For example, nonlocal field theories might be considered. Examples of these have been provided by
Carruthers, who studied a class of models that are Lorentz covariant and involve conventional quantization but for which the imposition of self-conjugacy and half-integer isospin suffices to produce nonlocal field operators. In these models CPT is broken, and the violation of the CPT theorem can be traced to the nonlocality of the operators. No multiplets of this type are known in nature.

A more subtle possibility is to consider models that violate one of the technical requirements of the CPT theorem that otherwise might appear relatively unimportant. For example, one assumption of the CPT theorem is that the fields lie in finite-dimensional representations of the Lorentz group. Oksak and Todorov have given examples of models that involve infinite-spin multiplets but are Lorentz covariant. Despite the Lorentz covariance, these models break CPT. The seeming failure of the CPT theorem is a consequence of the appearance of infinite-dimensional Lorentz representations needed to describe the infinite-spin fields. Again, no such multiplets have been identified in nature.

Another approach is to consider models beyond the framework of particle field theory. For example, string (M) theories are qualitatively different from particle theories because they involve extended objects and it is unclear a priori whether the CPT theorem applies. Although certain solutions to a subset of string models are known to be CPT invariant, it has been shown that in some string theories CPT violation may occur through a mechanism based on spontaneous breaking of Lorentz symmetry. This mechanism can be understood within conventional quantum field theory. It may lead to observable effects at the level of the standard model as is described in later sections below. At the level of the standard model, the appearance of CPT violation is compatible with the CPT theorem because it is accompanied by breaking of the Lorentz symmetry.

A more radical suggestion has been made by Hawking that quantum mechanics might be violated by effects from quantum gravity and that CPT violation might be among the consequences. It is unclear how to incorporate effects of this type in the context of a conventional field theory such as the standard model, which relies on the usual structure of quantum mechanics. An extension of this idea has been suggested in the context of string theory. It would produce a signature in the kaon system requiring at least six phenomenological parameters other than δK.

In searching for attractive possibilities for CPT violation, the ideal would be a microscopic theory valid at a fundamental level that also provides a quantitative connection to experiment in the framework of the standard model. This would then allow the calculation of phenomenological parameters, direct con-
parisons between experiments, and perhaps the prediction of signals. Some progress towards the development of such a theory has been made in the context of the idea of spontaneous CPT symmetry breaking, which is described in the next section.

3 Spontaneous CPT Violation

Even if the underlying theory of nature has a Lorentz- and CPT-covariant action, apparent violations of these symmetries could result from spontaneous symmetry breaking. To my knowledge, there are at present no theoretical problems that would appear to exclude the possibility of small spontaneous Lorentz breaking, so this could represent a relatively attractive way to violate CPT and Lorentz invariance. Moreover, spontaneous Lorentz breaking of some type must be a property of any Lorentz-covariant higher-dimensional theory that purports to underly nature because only four macroscopic dimensions are observed.

In general, spontaneous breaking is merely a feature of the solutions and leaves unchanged the symmetry of the underlying dynamics, and so it hides a symmetry rather than directly breaking it. Many of the desirable features of a Lorentz-covariant theory would therefore be expected to remain intact under spontaneous Lorentz breaking, as distinct from other types of Lorentz breaking that are likely to be inconsistent with desirable theoretical properties. For example, microcausality can be explicitly verified in certain simple models arising from spontaneous Lorentz breaking. Indeed, the physics of a particle in a Lorentz-breaking vacuum is in some respects similar to that of a particle moving inside a biaxial crystal. The behavior of the latter is not typically rotation or boost Lorentz covariant. Rather than being a fundamental problem, this is merely indicative of the presence of the background crystal fields, and properties such as causality remain unaffected.

Spontaneous breaking of Lorentz symmetry could occur in a theory with Lorentz-covariant dynamics that contains certain types of interaction among Lorentz-tensor fields. If such interactions destabilize the naive vacuum and produce nontrivial expectation values, then the presence in the true vacuum of a small Lorentz-tensor expectation means that Lorentz symmetry is spontaneously broken. This mechanism may occur in some string theories because suitable interactions are known to appear, unlike the case of conventional four-dimensional renormalizable gauge theories such as the standard model. If any of the tensor expectation values involves a field with an odd number of space-time indices, CPT is spontaneously broken too. If any components of the expectation values lie along the four macroscopic spacetime dimensions, ap-
parent violations of Lorentz symmetry and possibly also CPT could emerge at
the level of the standard model.

For the (unrealistic) case of the open bosonic string, the mechanism of
spontaneous Lorentz breaking can be investigated using string field theory. The
action and the corresponding equations of motion can be obtained analyti-
cally for particle fields below some fixed level number \( N \). Deriving and comparing
solutions for different \( N \) permits the identification of solutions that persist as
\( N \) is increased. In some cases this procedure has been performed to a depth of
over 20,000 terms in the static potential. Among the solutions found are ones
spontaneously breaking Lorentz invariance that remain stable as \( N \) increases.

If Lorentz symmetry is regarded as global, then its spontaneous break-
ing would entail the appearance of massless modes in accordance with the
Nambu-Goldstone theorem. When gravity is included, Lorentz invariance is
promoted to a local symmetry. In conventional gauge theories, the promotion
of a global spontaneously broken symmetry to a local one is associated with
the Higgs mechanism, by which the massless modes disappear and the vector-
mitic propagator is modified to include a mass term. However, there is no
analogous effect in gravity: when local Lorentz symmetry is spontaneously
broken, the graviton propagator is affected but the dependence of the connec-
tion on derivatives of the metric rather than the metric itself ensures that no
graviton mass is generated.

4 **Standard-Model Extension and QED Limit**

Since there is at present no compelling evidence for either Lorentz or CPT vi-
olation, any effects from spontaneous breaking must be suppressed at the level
of the minimal SU(3) × SU(2) × U(1) standard model. If the relevant dimen-
sionless suppression factor is determined by the ratio of the scale of the standard
model to the scale of an underlying fundamental theory at the Planck mass,
only a few observable effects of Lorentz or CPT violation are likely to exist.
These effects should be derivable from an extension of the standard model that
is obtained as the low-energy limit of the fundamental theory.

As an example, consider the following class of possible additional terms in
the fermionic sector of the low-energy limit of the underlying theory:

\[
\mathcal{L} \sim \frac{\lambda}{M^k} \langle T \rangle \cdot \bar{\psi} \Gamma(i\partial)^k \chi + \text{h.c.}.
\]

Terms of this type could arise, for instance, from the coupling between one
or more bosonic tensor fields and fermion bilinears when the tensors acquire
an expectation value \( \langle T \rangle \). In the above expression, the bilinear in the fermion
fields $\psi, \chi$ contains a gamma-matrix structure $\Gamma$ and the coupling involves $k$ spacetime derivatives $i\partial$, which together would produce apparent Lorentz and CPT violation in the low-energy theory. The coupling constant in this example is a combination of a dimensionless coupling $\lambda$ and a suitable power of a large scale $M$ associated with the fundamental theory, such as the Planck or compaficification scale.

An analysis of this type can be used to incorporate the effects of spontaneous Lorentz and CPT breaking at the level of the standard model. The procedure is to add to the lagrangian all possible extra terms that apparently break these symmetries and that could arise from spontaneous symmetry breaking in a more fundamental theory.

By restricting attention to the subset of allowed hermitian terms that preserve both $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ gauge invariance and power-counting renormalizability, a general Lorentz-violating extension of the standard model that includes both CPT-even and CPT-odd terms has been constructed. This theory appears at present to be the sole candidate for a consistent extension of the standard model based on a microscopic theory of Lorentz violation. By construction, it must be the low-energy limit of any underlying theory (not necessarily string theory) that contains spontaneous Lorentz and CPT violation and that reduces to the standard model in the limiting case of exact Lorentz invariance.

As might be anticipated from the discussion of spontaneous symmetry breaking in the previous section, this standard-model extension displays several attractive features despite the apparent violation of Lorentz and CPT symmetry. Since Lorentz covariance is a property of the underlying theory, properties like microcausality and positivity of the energy are to be expected. Also, since the standard-model extension is based on otherwise conventional field theory, the usual quantization methods are unaffected. Provided the vacuum tensor expectation values arising from the spontaneous breaking are independent of spacetime position, i.e., disregarding possible solitonic solutions, energy and momentum are conserved. Covariance under rotations or boosts of the observer’s inertial frame (observer Lorentz transformations) remains a feature of the theory. The apparent Lorentz violations appear only when (localized) fields are rotated or boosted (particle Lorentz transformations) relative to the vacuum tensor expectation values. Moreover, although not evident a priori, it turns out that the usual gauge symmetry breaking to the electromagnetic U(1) occurs.

Many of the high-precision experiments sensitive to CPT and Lorentz violation are associated with quantum electrodynamics (QED). It is therefore useful to extract from the standard-model extensions various limiting cases
that represent generalizations of the usual versions of QED. Modifications to QED from Lorentz- and CPT-breaking effects can appear in both the photon and fermion sectors.

As an example, consider the limiting case of the standard-model extension that reduces in the absence of Lorentz breaking to the normal quantum field theory of photons, electrons, and positrons. The usual lagrangian is:

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

Extra terms that break Lorentz invariance appear in both the photon and fermion sectors, and they can be CPT even or CPT odd. The CPT-violating terms are:

$$L_{\text{CPT}}^e = -a_\mu \bar{\psi} \gamma^\mu \psi - b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi ,$$

$$L_{\text{CPT}}^\gamma = \frac{1}{2} (k_A F)^\kappa \epsilon_{\kappa\lambda\mu\nu} A^\lambda F^{\mu\nu}.$$  \hspace{1cm} (4)

The CPT-even terms are:

$$L_{\text{Lorentz}}^e = c_{\mu\nu} \bar{\psi} \gamma^\mu (\frac{1}{2i} \not{\partial} - qA^\nu) \psi + d_{\mu\nu} \bar{\psi} \gamma_5 \gamma^\mu (\frac{1}{2i} \not{\partial} - qA^\nu) \psi - \frac{1}{2} H_{\mu\nu} \bar{\psi} \sigma^{\mu\nu} \psi ,$$

$$L_{\text{Lorentz}}^\gamma = -\frac{1}{2} (k_F)^{\kappa\lambda} \epsilon_{\kappa\lambda\mu\nu} F^{\mu\nu} F^{\mu\nu}.$$  \hspace{1cm} (5)

All these terms violate particle Lorentz covariance, although observer Lorentz covariance is maintained. The conventions and notation used in these equations are discussed in the literature along with various other issues. The coefficients of the extra terms above behave as Lorentz- and CPT-violating couplings, and in accordance with the discussion at the beginning of this section they are expected to be minuscule. Note that field redefinitions can be used to demonstrate that not all the components are physically observable. For example, coefficients of the type $a_\mu$ can only be detected directly in flavor-changing experiments and so are unobservable at leading order in any situation where only electrons, positrons, and photons are involved.

5 Experiments

Present-day experiments seeking evidence for the Lorentz-violating couplings in the standard-model extension face the difficult task of overcoming a suppression factor likely to be about 17 orders of magnitude, comparable to the ratio of the standard-model and Planck scales. Most experiments would lack the necessary precision to detect possible signals, but a few exceptionally sensitive tests can already place interesting bounds on some of the coupling coefficients.

The standard-model extension described in the previous section provides a quantitative basis within which to analyze and compare different experiments.
on CPT and Lorentz symmetry, and in some situations it can suggest possibilities for observable signals. In this context, several existing and planned experimental tests have been studied. They include observations of neutral-meson oscillations, comparative tests of QED in Penning traps, spectroscopy of hydrogen and antihydrogen, measurements of cosmological birefringence, and observations of the baryon asymmetry. In the remaining parts of this talk, a short summary of a subset of these investigations is given. Other work along these lines and currently underway includes a study of limits attainable in clock-comparison experiments.

5.1 Neutral-Meson Oscillations

Several neutral-meson systems exhibit or are expected to exhibit flavor oscillations, including $K$, $D$, $B_d$, and $B_s$. The time evolution of a neutral-meson state is controlled by a two-by-two effective hamiltonian in the meson-antimeson state space. Denoting the neutral meson by $P$, this non-hermitian hamiltonian contains complex parameters $\epsilon_P$ and $\delta_P$ that govern (indirect) CP violation. For the $K$ system, these are the same phenomenological quantities already mentioned in the section of this talk about approaches to CPT violation. The parameter $\epsilon_P$ measures $T$ violation with CPT invariance, while $\delta_P$ measures CPT violation with $T$ invariance. Experiments observing $P$-meson oscillations can constrain the magnitude of $\delta_P$ and hence place limits on possible CPT breaking.

As mentioned before, $\delta_P$ is necessarily zero in the context of the usual standard model, which preserves CPT. However, in the context of the standard-model extension an expression for $\delta_P$ can be derived. Remarkably, at leading order this expression depends only on one particular kind of extra coupling in the standard-model extension, of the form $-a_q^\mu \gamma^\mu q$. Here, $q$ represents one of the valence quark fields in the $P$ meson, and the quantity $a_q^\mu$ is spacetime constant but depends on the quark flavor $q$.

The presence of Lorentz breaking means that the expression for $\delta_P$ varies with the boost and orientation of the $P$ meson. If the $P$-meson four-velocity is given as $\beta^\mu \equiv \gamma(1, \vec{\beta})$ in the frame in which the quantities $a_q^\mu$ are specified, then $\delta_P$ is given at leading order in all coupling coefficients by

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

Subscripts $P$ have been omitted on the right-hand side for simplicity. In this expression, $\Delta a_\mu \equiv a_\mu^q - a_\mu^q$, where $q_1$ and $q_2$ are the valence-quark flavors for the $P$ meson. Also, $\hat{\phi} \equiv \tan^{-1}(2 \Delta m / \Delta \gamma)$, where $\Delta m$ and $\Delta \gamma$ are the mass and decay-rate differences between the $P$-meson eigenstates, respectively.
An immediate implication of this result is that tests of CPT and Lorentz symmetry with neutral mesons are independent at leading order of other types of tests mentioned in this talk. The point is that $\delta_P$ is sensitive only to $a_q^{\mu}$, and moreover this is due to flavor-changing effects. No other tests mentioned here involve flavor changes, and so, as mentioned at the end of the previous section, it can be shown that none can observe effects from nonzero values of $a_q^{\mu}$.

The result (6) also has direct implications for experiments with neutral mesons. It predicts that the real and imaginary parts of $\delta_P$ are proportional and that the magnitude of $\delta_P$ may be different for different $P$ due to the flavor dependence of the coefficients $a_q^{\mu}$. It is even conceivable that the heavier neutral mesons such as $D$ or $B_d$ exhibit much larger CPT-violating effects if, for instance, the coefficients $a_q^{\mu}$ behave like conventional Yukawa couplings and grow with mass.

A more striking prediction is that signals for Lorentz and CPT violation in neutral-meson experiments would depend on the boost magnitude and orientation of the mesons involved, which implies several effects. One is that experiments with otherwise comparable statistical sensitivity to CPT effects may in fact have inequivalent CPT reach. This might happen if the mesons involved have very different momentum spectra or if they are well collimated as opposed to having a $4\pi$ distribution.

The tightest experimental constraints on CPT violation presently in the literature come from observations of the $K$ system. The possibility of CPT violation in the heavier neutral-meson systems has received relatively little experimental attention, although two collaborations at CERN have performed analyses to study the possibility that existing data could suffice to constrain CPT violation. A measurement $\text{Im} \, \delta_{B_d} = -0.020 \pm 0.016 \pm 0.006$ has been published by the OPAL collaboration, while a preliminary result of $\text{Im} \, \delta_{B_s} = -0.011 \pm 0.017 \pm 0.005$ has been given by the DELPHI collaboration. There are additional theoretical and experimental studies in progress.

5.2 QED Experiments

An ingenious type of high-precision experiment is based on the idea of trapping individual particles for extended time periods so that accurate measurements of properties can be made. Comparisons of results for particles and antiparticles then provide useful CPT tests. It can be shown that these experiments are sensitive to effects in the fermion sector of the QED extension.

Comparative measurements of particle and antiparticle anomaly and cyclotron frequencies have been obtained using Penning traps. In the context of
the QED extension, there are both direct signals and effects arising from diurnal variations in a comoving Earth-laboratory frame. Appropriate figures of merit for the various signals have been defined and the attainable experimental sensitivity estimated.

As one example, experiments comparing the anomalous magnetic moments of electrons and positrons could generate a sharp bound on the spatial components of the coefficient $\delta_\mu$ in the laboratory frame. A minor change in experimental procedure would permit a bound of order $10^{-20}$ on the associated figure of merit to be obtained with existing technology, and indeed data from a suitable experiment are now being analyzed. Similar experiments for protons and antiprotons might be envisaged.

Another possibility is to compare cyclotron frequencies of various particles and antiparticles. An ingenious experiment comparing the cyclotron frequencies of $H^-$ ions and antiprotons in the same trap has been performed by Gabrielse and coworkers. In the context of the standard-model extension, the leading-order effects in this experiment provide a test of Lorentz violation with an associated figure of merit bounded at $4 \times 10^{-25}$.

A somewhat different class of tests can be performed with trapped hydrogen and antihydrogen. The idea is to obtain high-precision spectroscopic data for the two systems, which can then be compared to provide CPT tests. Within the context of the standard-model and QED extensions, an investigation of the possible experimental signals involving $1S-2S$ and hyperfine transitions has been completed. It turns out that specific transitions for magnetically trapped hydrogen and antihydrogen are directly sensitive to CPT- and Lorentz-violating couplings, without any suppression factors associated with the fine-structure constant. Moreover, certain experimental tests could in principle provide a theoretically clean signal for particular types of coupling that break Lorentz and CPT symmetry.

A variety of constraints can be placed on the photon sector of the QED extension from theoretical considerations and from terrestrial, astrophysical, and cosmological experiments on electromagnetic waves. On the theoretical front, a consistency constraint may arise on the pure-photon term appearing in Eq. (4) because it can provide negative contributions to the energy. This contrasts with the CPT-even term appearing in the following equation, which maintains a positive conserved energy, and suggests the coefficient $(k_{AF})^\tau$ should be zero.

A theoretical treatment of the extended Maxwell equations including CPT- and Lorentz-breaking effects shows that, as usual, the solutions involve two independent propagating degrees of freedom. However, unlike the conventional propagation of electromagnetic waves in vacuum, the dispersion relations of the
two modes differ and so the vacuum is birefringent. The effects of the Lorentz and CPT violation on an electromagnetic wave traveling in the vacuum are closely analogous to those exhibited by an electromagnetic wave in conventional electrodynamics that is passing through an optically anisotropic and gyrotropic transparent crystal with spatial dispersion of the axes.

On the experimental front, the tightest constraints emerge from the observed absence of birefringence on cosmological distance scales. For the pure-photon term in Eq. (4), this absence translates into a bound on the components of the CPT-odd coefficient \((k_{AF})_\mu\) of the order of \(\lesssim 10^{-42}\) GeV. A disputed claim\(^{12}\) for a nonzero effect at the level of \(|k_{AF}| \sim 10^{-41}\) GeV has been made.

For the pure-photon term in Eq. (5), the single rotation-invariant irreducible component of the CPT-even coefficient \((k_F)_{\kappa\lambda\mu\nu}\) is constrained to \(\lesssim 10^{-23}\) by the existence of cosmic rays\(^{12}\) and other tests. All other irreducible components of \((k_F)_{\kappa\lambda\mu\nu}\) break rotation invariance. At present, no bounds from cosmological birefringence have been placed on these components, but in principle they could be constrained experimentally with known techniques.\(^{12}\) An estimate suggests the dimensionless coefficient \((k_F)_{\kappa\lambda\mu\nu}\) could be bounded at the level of about \(10^{-27}\).

Evidently, the zero value of \((k_{AF})_\mu\) needed to avoid negative-energy contributions is compatible with the tight experimental constraints obtained. However, since no symmetry protects a zero tree-level value of \((k_{AF})_\mu\), one might expect \((k_{AF})_\mu\) to be shifted away from zero by radiative corrections involving CPT-violating couplings in the fermion sector. Remarkably, it turns out\(^{12}\) that the one-loop radiative corrections are finite, which means a tree-level CPT-odd term is unnecessary for one-loop renormalizability. Higher loops may exhibit similar effects. Note that there is no similar mechanism for the CPT-even pure-photon term, for which calculations have explicitly demonstrated\(^{12}\) the existence of divergent radiative corrections at the one-loop level and which would leave open the possibility of detecting a nonzero effect in cosmological birefringence. The feasibility of setting to zero an otherwise allowed CPT-odd pure-photon term represents a nontrivial consistency check on the standard-model extension.

As a final remark about possible observable CPT effects, it has been shown\(^{23}\) that under appropriate conditions the observed baryon asymmetry could be produced in thermal equilibrium as a result of the existence of CPT-violating bilinear terms of the general form in Eq. \(\text{(3)}\). At grand-unified scales, a relatively large baryon asymmetry could be generated that could ultimately be diluted to the observed value through sphaleron or other effects. This would represent an alternative to conventional baryogenesis, for which nonequilibrium processes and C- and CP-breaking interactions are required\(^{33}\).
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