TESTING A CPT- AND LORENTZ-VIOLATING EXTENSION
OF THE STANDARD MODEL

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INTRODUCTION AND BACKGROUND

The standard model of particle physics is invariant under a variety of continuous
symmetry operations, including translations, Lorentz transformations, and gauge
transformations. The model is also invariant under the action of the product CPT
of charge conjugation C, parity reflection P, and time reversal T. Indeed, CPT
symmetry is known to be a characteristic of all local relativistic field theories of
point particles [1]. It has been experimentally tested to high accuracy in a variety of
situations [2]. The general validity of CPT symmetry for particle theories and the
existence of high-precision tests means CPT breaking is an interesting candidate
experimental signal for new physics beyond the standard model, such as might
emerge in the context of string theory [3, 4, 5].

In a talk [6] delivered at the previous meeting in this series (Orbis Scientiae
1997-I), I discussed the possibility that CPT and Lorentz symmetry might be bro-
en in nature by effects emerging from a fundamental theory beyond the standard
model. String theory, which currently represents the most promising framework for
a consistent quantum theory of gravity incorporating the known particles and inter-
actions, is a candidate theory in which effects of this type might occur. The point
is that strings are extended objects, so the standard axioms underlying proofs of
CPT invariance are inappropriate. In fact, it is known that spontaneous CPT and
Lorentz violation can occur in the context of string theory [3, 4].

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If the fundamental theory has Lorentz and CPT symmetry and is naturally formulated in more than four spacetime dimensions, then some kind of spontaneous breaking of the higher-dimensional Lorentz group presumably must occur to produce an effective low-energy theory with only four macroscopic dimensions. This situation exists for some string theories, for example. An interesting issue is whether the spontaneous breaking generates apparent Lorentz and CPT violation in our four spacetime dimensions. It might seem natural for this to happen, since there is no evident reason why four dimensions would be preferred in the higher-dimensional theory. However, no experimental evidence exists for Lorentz or CPT breaking, so if it occurs it must be highly suppressed at the level of the standard model. If the standard model is regarded as an effective low-energy theory emerging from a realistic string theory, then the natural dimensionless suppression factor for observable Lorentz or CPT violation would be the ratio \( r \) of the low-energy scale to the Planck scale, \( r \sim 10^{-17} \). Relatively few experiments would be sensitive to such effects.

In the previous talk [6], I outlined the low-energy description of effects from spontaneous Lorentz and CPT breaking in an underlying theory. At this level, the potentially observable Lorentz and CPT violations appear merely as consequences of the vacuum structure, so many desirable properties of Lorentz-invariant models are maintained. The low-energy theory acquires additional terms with a generic form [4, 5]. More specifically, at the level of the standard model, refs. [8, 9] have identified the most general terms that can arise from spontaneous Lorentz violation (both with and without CPT breaking) while maintaining SU(3) × SU(2) × U(1) gauge invariance and power-counting renormalizability. The existence of this explicit extension of the standard model offers the possibility of quantitative investigations of a variety of experimental signals for apparent Lorentz and CPT breaking.

Some possible consequences of the additional terms in the standard-model extension were presented at the previous meeting [6]. Among the most interesting quantitative tests of CPT are experiments with neutral-meson oscillations in the \( K \) system [3, 4, 5, 10], the two \( B \) systems [3, 11, 12], and the \( D \) system [5, 13]. Implications of CPT violation in other contexts, such as baryogenesis [14], were also described.

In the present talk, I provide an update of some developments that have occurred in the months since the previous meeting. Possible experimental tests of the QED limit of the standard-model extension have been examined [9, 15, 16]. The sensitivity of tests of CPT violation in neutral-meson systems has been investigated [11], and the first experimental results have been obtained constraining CPT violation in the neutral-\( B \) system [17, 18].

**EXTENDED QUANTUM ELECTRODYNAMICS**

The general Lorentz-violating extension of the standard model (including terms with and without CPT violation), explicitly given in refs. [8, 14], follows from imposing two requirements. One is that the form of the additional terms must be compat-
ible with an origin from spontaneous Lorentz breaking in an underlying theory. The other is that the usual properties of SU(3) × SU(2) × U(1) gauge invariance and power-counting renormalizability must be maintained. These criteria suffice to keep relatively small the number of new terms in the action. A framework for treating the implications of apparent Lorentz and CPT violation has also been presented in the above works.

One limit of this extended standard model is an extension of quantum electrodynamics (QED) [9]. This is of particular interest because QED is a well-established theory for which numerous experimental tests exist. Here, I give only the lagrangian for the extended theory of photons, electrons, and positrons, which has a relatively simple form.

The usual lagrangian is

$$\mathcal{L}^\text{QED} = \overline{\psi} \gamma^\mu \left( \frac{1}{2} i \stackrel{\leftrightarrow}{\partial}_\mu e - qA_\mu \right) \psi - \overline{\psi} \psi - \frac{1}{4} F^\mu_\nu F^{\mu\nu} \quad .$$

(1)

The CPT-violating terms are

$$\mathcal{L}_e^\text{CPT} = -a_\mu \overline{\psi} \gamma^\mu \psi - b_\mu \overline{\psi} \gamma_5 \gamma^\mu \psi \quad ,$$

$$\mathcal{L}_\gamma^\text{CPT} = \frac{1}{2} (k_A F)^\kappa_{\kappa\lambda\mu\nu} A^\lambda F^{\mu\nu} \quad .$$

(2)

The Lorentz-violating but CPT-preserving terms are

$$\mathcal{L}_e^\text{Lorentz} = c_{\mu\nu} \overline{\psi} \gamma^\mu \left( \frac{1}{2} i \stackrel{\leftrightarrow}{\partial}_\nu - qA_\nu \right) \psi + d_{\mu\nu} \overline{\psi} \gamma_5 \gamma^\mu \left( \frac{1}{2} i \stackrel{\leftrightarrow}{\partial}_\nu - qA_\nu \right) \psi - \frac{1}{2} F_{\mu\nu} \overline{\psi} \sigma^{\mu\nu} \psi$$

$$\mathcal{L}_\gamma^\text{Lorentz} = -\frac{1}{4} (k_F)^\kappa_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu} \quad .$$

(3)

The coefficients of the various terms can be regarded as Lorentz- and CPT-violating couplings. The reader is directed to refs. [8, 9] for details of notations and conventions as well as for more information about the various terms, including issues such as the effect of field redefinitions and the possibility of other couplings.

As mentioned above, many conventional tests of Lorentz and CPT symmetry are expected to be insensitive to effects from the additional terms in the extension of QED because of the expected small size of the couplings. Nonetheless, certain kinds of experiment can provide constraints.

First, consider the fermion sector. One important class of tests consists of Penning-trap experiments measuring anomaly and cyclotron frequencies with exceptional precision [19, 20, 21, 22]. These have been investigated in the present context in refs. [23], where possible signals are identified, appropriate figures of merit are introduced, and estimates are given of limits on Lorentz and CPT violation that would be attainable in present and future experiments. A summary of the results of these works can be found in a separate contribution to the present volume [13]. As one example, the spacelike components of the coefficient $b_\mu$ can be bounded by experiments comparing the anomalous magnetic moments of the electron and positron. The associated figure of merit for CPT violation could be constrained to
about one part in $10^{20}$. This is comparable to the ratio of the electron mass to the Planck scale at which suppressed but observable effects from an underlying theory might be expected. Some interesting constraints on a subset of couplings in the fermion sector of extended QED might also arise from high-precision experiments of various other kinds, including clock-comparison tests [22].

Next, consider the photon sector of the QED extension [8, 9]. The CPT-breaking term with coefficient $(k_{AF})_\mu$ has theoretical difficulties in that the associated canonical energy can be negative and arbitrarily large. This suggests that the coefficient should vanish, which in turn provides an interesting theoretical consistency check of the model. The point is that, even if this coefficient vanishes at tree level, it would typically be expected to acquire radiative corrections involving CPT-breaking couplings from the fermion sector, which in the present context could cause difficulty with the positivity of the theory. However, it has been shown [9] that no such radiative corrections arise in the context of the standard-model extension described above. At the experimental level, limits from cosmological birefringence restrict the components of $(k_{AF})_\mu$ to $\lesssim 10^{-42}$ GeV [24], although there exist disputed claims [25] for a nonzero effect corresponding to $|k_{AF}| \sim 10^{-41}$ GeV.

In contrast, a nonzero contribution from the CPT-preserving, Lorentz-breaking term in the photon sector of the QED extension would maintain the positivity of the total canonical energy density and appears to be theoretically allowed [9]. Moreover, even if the coefficients $(k_F)_{\kappa\lambda\mu\nu}$ vanish at tree level, one-loop corrections from the fermion sector are induced. It is therefore of interest to examine possible experimental constraints on this type of term. One irreducible component of $(k_F)_{\kappa\lambda\mu\nu}$ is rotation invariant and can be bounded to $\lesssim 10^{-23}$ by the existence of cosmic rays [20] or by other tests. The remaining components violate rotation invariance and might in principle be bounded by cosmological birefringence. The attainable bounds are substantially weaker than those discussed above for the CPT-breaking term because, unlike $(k_{AF})_\mu$, the coefficients $(k_F)_{\kappa\lambda\mu\nu}$ are dimensionless and so are suppressed by the energy scale of the radiation involved. Further details about the photon sector of the QED extension can be found in ref. [9].

**NEUTRAL-MESON OSCILLATIONS**

Since the last meeting in this series, there have been several developments concerning the possibility of testing the standard-model extension using neutral-meson oscillations. In what follows, a generic neutral meson is denoted by $P$, where $P \equiv K, D, B_d, \text{or } B_s$.

Interferometry with $P$ mesons can involve two types of (indirect) CP violation: T violation with CPT invariance, or CPT violation with T invariance. These are phenomenologically described by complex parameters $\epsilon_P$ and $\delta_P$, respectively, that are introduced in the effective hamiltonian for the time evolution of a neutral-meson state. Within the context of the standard-model extension, it can be shown that the CPT-violating parameter $\delta_P$ depends only on one of the types of additional coupling
Only CPT-violating terms in the lagrangian of the form $-a_\mu^q \gamma^\mu q$ are relevant, where $q$ is a quark field and the coupling $a_\mu^q$ is constant in spacetime but depends on the quark flavor $q$. It is also noteworthy that the parameters $\delta_P$ are the only quantities known to be sensitive to the couplings $a_\mu$.

To define $\delta_P$, one must work in a frame comoving with the $P$ meson. It can be shown that the CPT and Lorentz breaking introduces a dependence of $\delta_P$ on the boost and orientation of the meson. Let the $P$-meson four-velocity be $\beta^\mu \equiv \gamma(1, \vec{\beta})$. Then, at leading order in all Lorentz-breaking couplings in the standard-model extension, $\delta_P$ is given by

$\delta_P \approx i \sin \hat{\phi} \exp(i\hat{\phi})\gamma(\Delta a_0 - \vec{\beta} \cdot \Delta \vec{a})/\Delta m . \tag{4}$

In this expression, $\Delta a_\mu \equiv a_\mu^q - a_\mu^P$, where $q_1$ and $q_2$ denote the valence-quark flavors in the $P$ meson. The quantity $\hat{\phi}$ is given by $\hat{\phi} \equiv \tan^{-1}(2\Delta m/\Delta \gamma)$, where $\Delta m$ and $\Delta \gamma$ are the mass and decay-rate differences between the $P$-meson eigenstates, respectively. Note that a subscript $P$ is suppressed on all variables on the right-hand side of Eq. (4).

One implication of the above results for experiment is a proportionality between the real and imaginary components of $\delta_P$. A second is the possibility of a variation of the magnitude of $\delta_P$ with $P$, arising from the flavor dependence of the couplings $a_\mu^q$. Other implications arise from the momentum and orientation dependences in Eq. (4), which offer the possibility of striking signals for Lorentz and CPT breaking. The momentum and orientation dependences also imply an enhanced signal for boosted mesons and suggest that published bounds on $\delta_P$ from distinct experiments could represent different CPT sensitivities. Experiments involving highly boosted mesons, such as the $K$-system experiment E773 at Fermilab, would be particularly sensitive to Planck-scale effects.

The tightest neutral-meson bounds on CPT violation at present are from experiments with the neutral-$K$ system. The possibility exists that relatively large CPT violation might occur in the behavior of heavier neutral mesons. At the time of the previous meeting in this series, no bounds existed on CPT violation in the $D$ or $B$ systems. My talk at that meeting emphasized that sufficient data already existed to place bounds on CPT violation in the $B_d$ system. Since then, two experimental groups at CERN have performed the suggested measurement. The OPAL collaboration has published the result $\text{Im} \delta_{B_d} = -0.020 \pm 0.016 \pm 0.006$, while the DELPHI collaboration has released a preliminary measurement $\text{Im} \delta_{B_d} = -0.011 \pm 0.017 \pm 0.005$. Other analyses of CPT violation in heavy-meson systems are presently underway.

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