This talk summarizes some theoretical features and experimental implications of a general Lorentz-violating extension of the minimal SU(3) × SU(2) × U(1) standard model that allows for both CPT-even and CPT-odd effects. The theory would arise as the low-energy limit of a fundamental theory that is Lorentz and CPT covariant but in which spontaneous Lorentz breaking occurs. The use of neutral-meson oscillations and various QED systems to bound the apparent CPT and Lorentz violations is described.

1 Introduction

A successful description of particle physics at presently attainable energy scales is offered by the minimal standard model. However, at higher scales this is presumably replaced by an underlying theory incorporating both gravity and quantum mechanics. Experimental clues about the nature of the underlying theory are difficult to obtain because the electroweak scale is about 17 orders of magnitude smaller than the Planck scale and so it is likely that any telltale effects are heavily suppressed at present energies.

In seeking Planck-scale effects, one method is to consider experimental searches for physics that cannot occur in conventional renormalizable gauge theories. Experiments of particular interest in this regard are those with high sensitivity to qualitatively new effects predicted in candidate underlying theories. A promising example is string (M) theory, for which such effects at the Planck scale might generate low-energy signals.

This talk considers the possibility that the new effects are generated from spontaneous Lorentz symmetry breaking, which could arise in certain Lorentz-covariant theories with suitable interactions among Lorentz-vector or tensor fields, including perhaps some string theories. If components of the tensor

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expectation values generated by the spontaneous Lorentz breaking are associated with the physical four spacetime dimensions, then apparent violations of Lorentz symmetry could arise. Since Lorentz invariance underlies the CPT theorem, apparent breaking of CPT could also occur.

Any apparent violations of Lorentz and CPT symmetry would be effects from the underlying theory that are potentially observable and that lie outside conventional renormalizable gauge theory. In light of the probable heavy suppression, detection of effects is likely only in highly sensitive experiments.

2 Standard-Model and QED Extensions

To include possible effects from spontaneous Lorentz and CPT violation in a description at the level of the standard model, extra terms that break these symmetries and that are compatible with an origin in spontaneous symmetry breaking can be added to the lagrangian. A general standard-model extension of this type, including both CPT-even and CPT-odd terms, has explicitly been given. It maintains the usual gauge structures, including the gauge-symmetry breaking, and is hermitian and power-counting renormalizable. By construction, it is the low-energy form of any underlying theory with spontaneous Lorentz and CPT violation that generates the minimal standard model.

The origin of the standard-model extension in a microscopic theory of spontaneous Lorentz violation means that it exhibits many conventional properties of Lorentz-covariant theories despite the apparent Lorentz breaking. Thus, standard quantization methods can be applied, and microcausality and positivity of the energy are expected. Also, if the tensor expectation values arising from spontaneous symmetry breaking are independent of spacetime position, energy and momentum are conserved.

Another attractive feature of the standard-model extension is that the apparent noninvariance under Lorentz transformations is restricted to rotations or boosts of the (localized) fields only (particle Lorentz transformations). Under rotations or boosts of the observer’s inertial frame (observer Lorentz transformations), the background tensor expectation values change along with the field observables so the standard-model extension remains observer Lorentz covariant. A related issue is the role of the Nambu-Goldstone modes that might be expected from the spontaneous breaking of the global Lorentz symmetry in the standard model. The inclusion of gravity promotes Lorentz invariance to a local symmetry, and by analogy with the Higgs mechanism in gauge theories one might expect these modes to generate a mass for the graviton. It turns out, however, that although the graviton propagator is modified no gravitational Higgs effect occurs because the gravitational analogue of the gauge field is not
the metric but involves instead its spacetime derivatives.

Given the standard-model extension, it is possible to extract a variety of interesting limiting theories that are relevant for experimental tests, just as is normally done for the minimal standard model. Among the useful theories that can be obtained are Lorentz-violating generalizations of the usual forms of quantum electrodynamics (QED). As an example, in the special case of the theory of photons, electrons, and positrons, the extended lagrangian includes extra terms in both the photon and the fermion sectors that describe apparent Lorentz and CPT violations. The usual QED lagrangian is

\[ L_{\text{QED}} = \overline{\psi} \gamma^\mu \left( \frac{i}{2} \partial^\mu - q A^\mu \right) \psi - m \overline{\psi} \psi - \frac{1}{4} F_{\mu \nu} F^{\mu \nu}, \] (1)

There are several possible Lorentz-violating but CPT preserving terms:

\[ L_{\text{QED}}^{\text{even}} = c_{\mu \nu} \overline{\psi} \gamma^\mu \left( \frac{i}{2} \partial^\nu - q A^\nu \right) \psi + d_{\mu \nu} \overline{\psi} \gamma_5 \gamma^\mu \left( \frac{i}{2} \partial^\nu - q A^\nu \right) \psi \]
\[ - \frac{1}{2} H_{\mu \nu} \overline{\psi} \sigma^{\mu \nu} \psi - \frac{1}{4} (k F)^{\kappa \lambda \mu \nu} F_{\kappa \lambda \mu \nu}, \] (2)

as well as Lorentz- and CPT-violating terms:

\[ L_{\text{QED}}^{\text{odd}} = - a_{\mu} \overline{\psi} \gamma^\mu \psi - b_{\mu} \overline{\psi} \gamma_5 \gamma^\mu \psi + \frac{1}{2} (k F)^{\kappa} \epsilon_{\kappa \lambda \mu \nu} A^{\lambda \mu \nu}. \] (3)

Their coefficients are expected to be heavily suppressed at accessible energy scales. The reader can find more information about the above expressions in the literature, including issues such as the observability of the new couplings.

3 Experimental Tests

The standard-model and QED extensions described above provide a general microscopic theory of Lorentz and CPT violation that can serve as a quantitative basis for experimental purposes. For example, these include the identification of potentially sensitive experiments, the analysis of data obtained, and the comparison of bounds from different experiments.

Relatively few experiments are sufficiently sensitive to place constraints of interest on the extra coupling coefficients in the standard-model extension. Among those of exceptional sensitivity known to generate bounds on the standard-model and QED extension are tests of CPT and Lorentz symmetry from neutral-meson oscillations, Penning-trap measurements, hydrogen and antihydrogen spectroscopy, photon properties, and baryogenesis. The remainder of the talk briefly summarizes some of these results. Studies presently being performed include an analysis of constraints that could be obtained from clock-comparison experiments.
3.1 Neutral-Meson Systems

There are four neutral-meson systems in which oscillation experiments could be performed to investigate CPT and Lorentz symmetry: $K$, $D$, $B_d$, and $B_s$. In the following, a neutral meson is generically denoted by $P$.

The effective hamiltonian for the time evolution of a neutral-meson state is a two-by-two matrix with complex entries. Two kinds of (indirect) CP violation can be studied within this framework. One is the usual case of $T$ violation with CPT invariance, which for a $P$ meson is phenomenologically described by the standard parameter $\epsilon_P$. The other is CPT violation with $T$ invariance, involving a complex parameter $\delta_P$.

In the usual minimal standard model, $\epsilon_P$ can be calculated in terms of other parameters in the model and $\delta_P$ is identically zero. However, in the CPT- and Lorentz-violating standard-model extension $\delta_P$ is nonzero and can be derived in terms of other parameters. It turns out that these include only the type of coupling coefficient that appears in certain CPT-breaking terms quadratic in the quark fields $q$, of the form $-a^q_{\mu}q_{\gamma\mu}q$. In this expression, the coupling $a^q_{\mu}$ is quark-flavor dependent but spacetime independent. The derivation of the expression for $\delta_P$ shows that it depends on $a^q_{\mu}$ as a direct result of flavor-changing effects. Moreover, experiments without flavor changes are insensitive to couplings of the type $a^q_{\mu}$, so the results of CPT tests with neutral-meson oscillations are independent of results of other CPT tests such as those mentioned in the next subsection.

The conjuncture of Lorentz violations with the CPT breaking also produces interesting effects. For example, it can be shown that the parameter $\delta_P$ depends on the boost and orientation of the meson. If the neutral-meson four-velocity is $\beta_\mu \equiv \gamma(1, \vec{\beta})$, then at leading order in all coupling coefficients $\delta_P$ can be expressed as

$$\delta_P \approx i \sin \hat{\phi} \exp(i\hat{\phi})\gamma(\Delta a_0 - \vec{\beta} \cdot \Delta \vec{a})/\Delta m.$$  \hspace{1cm} (4)

In this equation, $\Delta a_\mu \equiv a^{q_2}_\mu - a^{q_1}_\mu$, where $q_1$ and $q_2$ denote the $P$-meson valence-quark flavors. Also, $\hat{\phi} \equiv \tan^{-1}(2\Delta m/\Delta \gamma)$, where $\Delta \gamma$ and $\Delta m$ are the differences between the decay rates and masses, respectively, of the $P$-meson eigenstates. In Eq. (4), subscripts $P$ are understood on all quantities.

Equation (4) shows that the size of $\delta_P$ may differ for distinct $P$-meson flavors. It is possible that relatively large CPT and Lorentz breaking occurs for non-kaon $P$ mesons, for which few data are available. Larger CPT violation in these systems would be plausible if, for instance, the couplings $a^q_{\mu}$ grow with the quark mass, as occurs with the conventional Yukawa couplings.
Another result following from Eq. (4) is that the real part of $\delta P$ is proportional to the imaginary part. This equation also shows that $\delta P$ varies with boost magnitude and orientation for a given $P$ meson, which implies several interesting consequences. For instance, experiments using mesons with large boosts could be more sensitive to CPT violation than otherwise comparable ones using mesons with lesser boosts because the CPT- and Lorentz-violating effects could be enhanced.

At present, experiments on the kaon system have yielded the tightest limits on CPT breaking. No bounds have as yet been extracted from experiments with $D$ or $B_s$ mesons, although for the $D$ and $B_d$ systems certain analyses of existing data can yield interesting constraints. Indeed, for the $B_d$ system, two LEP collaborations at CERN have performed CPT studies with existing data. A measurement of $\text{Im} \, \delta_{B_d}$ has been published by the OPAL collaboration: $\text{Im} \, \delta_{B_d} = -0.020 \pm 0.016 \pm 0.006$. A preliminary measurement has also been announced by the DELPHI collaboration: $\text{Im} \, \delta_{B_d} = -0.011 \pm 0.017 \pm 0.005$. Further investigations are being performed.

### 3.2 Quantum Electrodynamics

The remainder of this talk outlines some of the implications of the standard-model extension for a few QED experiments. One important category of CPT and Lorentz tests involves high-precision comparisons of particle and antiparticle properties. A Penning trap can confine a single particle for long periods during which properties such as anomaly and cyclotron frequencies can be measured. Predictions for signals in such experiments have been extracted from the fermion sector of the CPT- and Lorentz-violating standard-model and QED extensions. Suitable figures of merit have been defined, and estimates of the CPT and Lorentz reach obtained.

As an explicit example, measurements of the anomalous magnetic moments of the electron and the positron are sensitive to spatial components in the laboratory frame of the coupling $b_\mu$ in Eq. (3). For these experiments, a relatively minor change in experimental methodology could produce a bound on an appropriate figure of merit of about $10^{-20}$. Data from one such experiment are being analyzed. Another example is a comparison of the cyclotron frequencies of antiprotons and hydrogen ions, for which the associated figure of merit could be bounded at about $10^{-25}$.

Another class of important tests involves high-precision spectroscopy of hydrogen and antihydrogen. An analysis of possible signals within the context of the standard-model and QED extensions has been performed. It has been shown that certain 1S-2S transitions and hyperfine Zeeman lines are sensitive
at leading order to Lorentz-violating effects.

The extra terms in the photon sector of the QED extension are given in Eqs. (2) and (3). The CPT-even term in Eq. (2) provides a positive contribution to the energy but the CPT-odd term in Eq. (3) can generate a negative one. This is associated with some theoretical difficulties that would seem to indicate the associated coupling \( (k_{AF})^\mu \) should vanish.

The extended Maxwell equations can be shown to describe the propagation of two independent degrees of freedom with distinct dispersion relations. However, the Lorentz violation induces birefringence of the vacuum. In the presence of the Lorentz violation, an electromagnetic wave propagating in the vacuum exhibits features closely related to those found for the conventional Maxwell theory when an electromagnetic wave travels in an optically anisotropic and gyrotropic transparent crystal exhibiting spatial dispersion of the axes.

Some experimental bounds can be placed on the couplings in Eqs. (2) and (3). An important limit is obtained from the lack of observed anomalous birefringence of radio waves traveling over cosmological distances. The size of the components of the coupling \( (k_{AF})_{\mu} \) are presently bounded to \( \lesssim 10^{-42} \) GeV, although a disputed claim has been advanced for an observed effect at the level of \( |k_{AF}| \sim 10^{-41} \) GeV. The rotation-invariant irreducible component of the coupling \( (k_F)_{\kappa\lambda\mu\nu} \) is constrained to \( \lesssim 10^{-23} \) by several tests, including the existence of cosmic rays. Other irreducible components of \( (k_F)_{\kappa\lambda\mu\nu} \) violate rotation invariance. A cosmological-birefringence bound of order \( 10^{-27} \) on the size of \( (k_F)_{\kappa\lambda\mu\nu} \) may be feasible with present methods.

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