CPT VIOLATION, STRINGS, AND NEUTRAL-MESON SYSTEMS

V. Alan Kostelecký
Physics Department
Indiana University
Bloomington, IN 47405
U.S.A.

INTRODUCTION

Symmetry under the discrete transformation CPT is a general theoretical condition holding for local relativistic field theories of point particles [1]-[7]. This symmetry has been investigated experimentally under different circumstances and to a high degree of precision [8]. The broad theoretical validity of CPT symmetry for particles and the availability of high-precision tests makes CPT violation an interesting candidate experimental signal for fundamental theories such as string theory [9, 10, 11].

In this talk, I consider the possibility that CPT symmetry might be violated in nature by effects arising in a theory beyond the standard model. One example is string theory, which presently provides the most promising framework for a consistent quantum theory of gravity incorporating also the known interactions and particles. Strings are extended objects, so the usual assumptions underlying proofs of CPT symmetry do not hold. Indeed, spontaneous CPT violation can occur in string theory [9, 10], via a mechanism outlined in the next section.

If physics beyond the standard model includes spontaneous CPT violation, it can be described at low energy by additional terms in an effective theory. It is possible to establish the general form of such terms that are compatible with known gauge symmetries [11, 12]. This analysis in turn suggests possible consequences of CPT violation such as baryogenesis [13] and, in particular, quantitative experimental tests of CPT. Among the most promising tests are those involving neutral-meson oscillations, where specific signatures appear in experiments involving either correlated or uncorrelated mesons. These are outlined briefly for the various neutral-meson systems in subsequent sections. Further details about these effects and experiments can be found in the original literature on the $K$ system [11, 12, 13], the two $B$ systems [11, 14, 15], the $D$ system [11, 16].

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The possible spontaneous CPT violations discussed here, which are tied to minuscule spontaneous violations of Lorentz invariance \[17\], lie entirely within the framework of conventional quantum mechanics. It has also been suggested \[18\]–\[20\] that violations of conventional quantum mechanics possibly arising in the context of quantum gravity might lead to CPT breaking. The experimental signatures of the two types of CPT violation in the kaon system are entirely distinct \[21\].

**SPONTANEOUS CPT VIOLATION**

If a fundamental theory underlying nature involves more than four spacetime dimensions and is dynamically Poincaré invariant, some type of spontaneous breaking of the higher-dimensional Poincaré group presumably occurs to generate a four-dimensional effective theory. String theory is most naturally formulated in higher dimensions and indeed has a mechanism that can trigger spontaneous Lorentz violation \[17\]. In string field theory, this mechanism involves certain interactions that do not appear in conventional four-dimensional renormalizable gauge theories. The string gauge invariance admits these interactions as a consequence of string nonlocality or, equivalently, as a consequence of the appearance of an infinite number of particle fields. If scalar fields in the string theory acquire vacuum expectation values, these interactions can cause destabilizing effects on the static potentials for Lorentz tensor fields. A stable vacuum can then become one in which Lorentz tensor fields have nonzero expectation values, thereby spontaneously breaking Lorentz invariance. If these tensors include ones with an odd number of spacetime indices, the spontaneous Lorentz breaking also involves CPT breaking.

The string field theory of the open bosonic string provides a useful explicit testing ground for these ideas. A level-truncation scheme can be used to explore the space of extrema for the action in a systematic way. The idea is to construct the action and the equations of motion analytically, using all particle fields up to a given level number. The solutions to the equations of motion that break Lorentz and CPT invariance can be found and compared with similar solutions for truncations at different level numbers. Solutions of interest are those that, as the level number is increased, both persist and are corrected by smaller and smaller amounts. For some situations, symbolic-manipulation techniques have enabled us to treat over 20,000 nonvanishing terms in the action. The Lorentz and CPT properties expected from the theoretical mechanism agree with those of the solutions found via the level-truncation approach.

**CPT-VIOLATING EXTENSION TO THE STANDARD MODEL**

An interesting issue is whether the mechanism outlined above could produce breaking of CPT (and Lorentz invariance) in our four spacetime dimensions. It would seem natural for this to occur, since there is no apparent reason why four dimensions should be preferentially selected in the higher-dimensional theory. However, no CPT violation has been experimentally detected, so any such breaking must be highly suppressed in the standard model. In a realistic string theory and treating the standard model as an effective low-energy model, the natural dimensionless suppression factor that appears would be the ratio \( r \) of the low-energy scale to the Planck scale, \( r \sim 10^{-17} \). This sup-
pression factor would produce only a few potentially observable CPT-violating effects, among which are ones in principle detectable in the kaon and other neutral-meson systems [9, 11].

A generic CPT-violating contribution to the effective four-dimensional low-energy theory (the standard model) that could emerge from a compactified string theory could have the form [10, 11]:

$$\mathcal{L} \sim \frac{\lambda}{M_k} \langle T \rangle \cdot \overline{\psi} \Gamma(i\partial) \chi + h.c. \quad (1)$$

Here, $\langle T \rangle$ is the expectation value of a Lorentz tensor $T$. The four-dimensional fermions $\psi$ and $\chi$ are contracted in spinor space through a gamma-matrix structure $\Gamma$, with couplings to $T$ possibly involving derivatives $i\partial$. The factors of the (Planck or compactification) mass $M$ must be present on dimensional grounds, and $\lambda$ is taken to be a dimensionless coupling constant.

A particularly interesting CPT-violating extension of the standard model can be obtained from terms of the form (1) by identifying the fermions $\psi$ and $\chi$ with ones appearing in the standard model and requiring that the usual SU(3) × SU(2) × U(1) gauge invariance is maintained. The possible terms compatible with naive power-counting renormalizability have been explicitly given in ref. [12], along with a framework for treating theoretically the accompanying CPT and Lorentz breaking.

The next sections summarize some of the observable consequences of such terms in neutral-meson systems. Other effects are also possible. For example, under suitable circumstances terms of the form (1) could produce baryogenesis in thermal equilibrium [13]. This mechanism for generating the observed baryon asymmetry is distinct from more conventional ones that require nonequilibrium processes and C- and CP-breaking interactions [22].

**NEUTRAL-MESON OSCILLATIONS**

To investigate possible CPT-violating signals in neutral-meson systems, $\psi$ and $\chi$ can be taken as the quarks comprising the neutral meson, denoted generically by $P$ ($P \equiv K, D, B_d$, or $B_s$). Terms of the form (1) then produce contributions to the $2 \times 2$ effective hamiltonian $\Lambda$ governing the time evolution of the meson system. Within the context of conventional quantum mechanics, there are two kinds of (indirect) CP violation that can appear in $\Lambda$: T-violating contributions that preserve CPT, and CPT-violating contributions that preserve T. The corresponding complex parameters are denoted $\epsilon_P$ and $\delta_P$, respectively. A plausible theoretical framework for understanding the appearance of a nonzero value of the T-violating parameter $\epsilon_P$ exists in the context of the standard model, using the CKM matrix.

The CPT-breaking extension of the standard model mentioned in the previous section provides a basis for understanding the origin of a possible nonzero value of the CPT-violating quantity $\delta_P$ in terms of spontaneous CPT and Lorentz breaking as might occur in the string scenario, for example. An analysis shows that $\delta_P$ can be expressed within this framework as [10, 11]

$$\delta_P = i \frac{h_q_1 - h_q_2}{\sqrt{\Delta m^2 + \Delta \gamma^2 / 4}} e^{i\hat{\phi}} \quad (2)$$
In this equation, $\Delta m$ and $\Delta \gamma$ are mass and rate differences and $\hat{\phi} = \tan^{-1}(2\Delta m/\Delta \gamma)$. These are experimental observables. The quantities $h_{q_i} = r_{q_i}\lambda_{q_i}\langle T \rangle$ originate from the terms (1) and from the effects of the quark-gluon sea, parametrized by $r_{q_i}$.

Since the underlying fundamental theory is assumed to be hermitian and since the CPT and Lorentz breaking are spontaneous, the quantities $h_{q_i}$ are real. This implies the relationship

$$\text{Im} \delta_P = \pm \cot \hat{\phi} \text{ Re} \delta_P , \quad (3)$$

connecting the real and imaginary parts of $\delta_P$ through an experimental observable. The small size of the suppression ratio $r$ precludes experimental detection of any direct CPT violation in the decay amplitudes of the $P$ meson, so if CPT violation is indeed detected using neutral mesons then the result (3) would be the primary signature.

**EXPERIMENTAL TESTS**

Experimental tests of CPT violation can be envisaged in any of the $K$, $D$, $B_d$, and $B_s$ neutral-meson systems [11]. Within the string-based framework described in the previous section, the CPT-violating parameters $\delta_P$ given by (2) depend on dimensionless coupling constants $\lambda_{q_i}$ that are presumably of different magnitude for different quark flavors $q_j$. This means the $\delta_P$ should differ for distinct $P$ mesons. An analogous situation occurs for the standard-model Yukawa couplings, which range over some six orders of magnitude.

One implication of this degree of freedom is that CPT symmetry should be tested experimentally in more than one neutral-meson system. Another is that some startling possibilities might occur in the behavior of heavy neutral mesons. In the $B_d$ system, for instance, there are currently no bounds on CPT violation and the bounds on T violation are relatively weak. It is therefore conceivable that CPT violation could exceed the expected conventional T violation, which would produce unexpected signals in the proposed $B$ factories.

Experiments investigating indirect CP violation use either uncorrelated neutral mesons $P$ or correlated $P-\bar{P}$ pairs arising from quarkonium decays. Typical experimental signatures for CPT and T violation involve asymmetries of decay probabilities into different final states. Appropriate asymmetries with and without time dependence and for both correlated and uncorrelated cases are presently available for all neutral-meson systems. These have been used both for relatively simple theoretical estimates and as input for detailed Monte-Carlo simulations of realistic experimental data, including background effects and acceptances.

In the remainder of this section, I provide a few remarks about the current status of CPT violation in the various neutral-meson systems. The reader is referred to the original literature [9]-[16] for a more complete treatment.

The $K$ system presently offers the only neutral-meson limit on CPT violation. The published bounds [8 23 24] correspond to limits on $|\delta_K|$ of order $10^{-3}$. Data from various experiments recently completed (e.g., CPLEAR at CERN) or now underway (e.g., KTeV at Fermilab) are likely to lead to an improved bound within the near future.

In the $D$ system, no mixing has yet been observed experimentally and strong
dispersive effects make theoretical calculations uncertain. Estimating the CPT reach of future experiments is therefore relatively difficult. Nonetheless, under theoretically favorable circumstances there are some interesting possibilities for placing bounds on $\delta_D$ with available techniques and perhaps even from existing data.

The $B_d$ system is of especial interest for CPT tests because it involves the heaviest quark and so might generate the largest CPT violation. Currently, no limit on $\delta_{B_d}$ has been published. However, enough data have been obtained to place a bound on $\delta_{B_d}$. A conservative Monte-Carlo simulation with realistic experimental data [15] suggests a limit of order 10% on $\delta_{B_d}$ could be extracted by analyzing existing data from CERN and Cornell. In any event, the planned $B$ factories are expected to improve this significantly.

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