Testing CPT with B Mesons

V. Alan Kostelecký

Physics Department, Indiana University, Bloomington, IN 47405

Abstract. Apparent violations of CPT and Lorentz symmetry might arise in nature as a result of spontaneous symmetry breaking in a theory beyond the standard model. This talk summarizes a few relevant theoretical and experimental issues, with some emphasis on implications for CPT tests with neutral-\(B\) mesons.

INTRODUCTION

In this talk, a brief survey is provided of theoretical and experimental issues relevant to the notion that spontaneous CPT and Lorentz breaking might occur in a theory underlying the standard model. The primary focus in the present work is the possibility that observable effects could appear at accessible energies from apparent CPT violation of this type.

For local relativistic field theories of point particles, the CPT theorem [1–7] states that the combination of the three discrete operations of charge conjugation \(C\), parity reflection \(P\), and time reversal \(T\) is an exact symmetry. Various experiments have tested this theorem to high precision [8]. The existence of a powerful theorem and a wide variety of accurate experimental tests suggests that apparent CPT violation is a promising signal for new physics, such as might emerge from a fundamental theory beyond the standard model [9–11]. At present, string theory is the most promising approach to the construction of a consistent and complete quantum theory of all fundamental particles and interactions. However, strings are extended objects, so the conventional axioms underlying the proof of the CPT theorem for particle models do not necessarily apply.

In the next section, a possible mechanism arising within string theory for spontaneous CPT [9,10] and Lorentz [12] breaking is briefly summarized. The mechanism can be studied explicitly in certain theories [13,14]. If spontaneous CPT breaking does arise in a realistic fundamental model, it might be apparent in nature at presently accessible energies. The subsequent section outlines the results of an
effective-theory approach to incorporating possible CPT-violating interactions in a low-energy model. A general extension of the standard model [11,15] is described that includes extra terms originating from spontaneous CPT and Lorentz breaking but maintains the usual gauge invariances and power-counting renormalizability.

Experimental implications of spontaneous CPT and Lorentz breaking can be investigated within the framework of this extension of the standard model. In particular, quantitative constraints can be placed on the occurrence of CPT and Lorentz breaking in nature by bounding the coefficients of the extra terms in the theory. The remaining parts of this talk summarize a few of these possible experimental tests of CPT. Some of the most sensitive searches for apparent CPT breaking can be performed in neutral-meson systems. The associated flavor oscillations provide interferometric tests of CPT symmetry in the two $B$ systems [11,16,17] and the $D$ system [11,18] as well as in the more conventional setting of the $K$ system [9–11]. Other sensitive measures of CPT breaking also exist. They include comparative measurements of anomalous magnetic moments of electrons and positrons or of protons and antiprotons [19]. It is also possible that CPT breaking is important for baryogenesis [20].

**SPONTANEOUS CPT AND LORENTZ VIOLATION**

The most natural mathematical setting for string theories appears to involve more than four spacetime dimensions. Assuming the fundamental theory underlying nature includes higher dimensions and is Lorentz and CPT symmetric, then it is plausible that the higher-dimensional Lorentz invariance is spontaneously broken to the four observed dimensions.

A mechanism that could trigger this effect is known in string theory [12]. The nonlocality of strings generates interactions in string field theory that do not appear in the context of usual renormalizable four-dimensional gauge theory but that are compatible with the infinite number of particle fields and the string gauge invariances. If appropriate scalar fields in the theory acquire nonzero vacuum expectation values, the static interaction potentials for Lorentz tensor fields can be destabilized by stringy interactions of this kind. Some of these Lorentz tensors may then obtain expectation values, so that Lorentz invariance is spontaneously broken in the true ground state of the theory. It can be shown that CPT is also spontaneously broken if any Lorentz tensor field with an odd number of spacetime indices acquires an expectation value [9,10].

The string field theory of the open bosonic string provides an explicit example within which the mechanism for spontaneous Lorentz and CPT violation can be studied. A level-truncation scheme permits a systematic exploration of the possible extrema of the action [13,14]. It is feasible to construct the action analytically by incorporating only particle fields with level number less than a chosen value $N$. The equations of motion can subsequently be found and solved for extrema of the action. The procedure can be repeated and the solutions obtained can be compared
for different values of $N$. A given solution consists of a definite set of nonzero expectation values. It is of interest if it persists and appears to converge as $N$ increases, since it is then plausible that the complete theory contains an extremum involving similar expectation values.

Following this procedure and using symbolic manipulation routines, it has been feasible to study aspects of the static interaction potential for the open bosonic string to a depth of over 20,000 nonzero terms. Nontrivial solutions to the equations of motion emerge, including ones violating Lorentz and CPT invariance. These exhibit properties that are to be expected from general considerations of the theoretical mechanism.

EXTENSION OF THE STANDARD MODEL

A question of immediate relevance is whether the occurrence of spontaneous CPT and Lorentz breaking in a fundamental theory could generate apparent violations at low energies. This would happen if the breaking extends to the four large spacetime dimensions, which is natural mathematically. Otherwise, a definite mechanism would be needed to explain the existence of the four-dimensional symmetry.

No CPT or Lorentz violations have been found experimentally. A high degree of suppression is therefore implied for any possible effects at low energies. The standard model is known to provide an excellent description of nongravitational physics in this regime. It can be viewed as an effective model emerging at the electroweak scale $m_{ew}$ from a more fundamental theory, presumably governed by the Planck scale $m_{Pl}$. The natural suppression factor for Planck-scale effects in the standard model would then be $r \sim m_{ew}/m_{Pl} \approx 10^{-17}$. Relatively few CPT- and Lorentz-violating effects would be accessible to experiment if this strong suppression occurs. The sections below describe a few of the possible signals.

Suppose the spontaneous CPT and Lorentz violation indeed generates minuscule effects at the level of the electroweak scale. These effects can be studied by extending the standard model to include possible terms originating in spontaneous CPT and Lorentz violation. In the fermion sector, for example, possible terms of the general form [10,11]

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

could appear as a low-energy consequence of spontaneous symmetry breaking in a compactified string theory. Terms of this type are Lorentz- and possibly CPT-violating, as a result of the nonzero expectation values of Lorentz tensors $T$ that can appear in interactions terms coupling $T$ with fermions $\psi$ and $\chi$ via derivatives $i \partial$ and a gamma-matrix structure $\Gamma$. In Eq. (1), $\lambda$ is assumed dimensionless, so one or more large mass scales $M$ such as the compatification or Planck scales must also appear. The fermions $\psi$ and $\chi$ in Eq. (1) can be identified with leptons or quarks in the standard model.
A general extension of the standard model has been obtained [15] that includes Lorentz-breaking terms both with and without CPT breaking and allows also for possible effects in the gauge and Higgs sectors. The analysis is developed around a theoretical framework for treating CPT and Lorentz breaking that appears to bypass some standard difficulties, largely because the breaking is spontaneous while the underlying theory remains Lorentz and CPT invariant. The derivation therefore includes the constraint that any new effects must be compatible with an origin in spontaneous Lorentz breaking. Invariance under the gauge group SU(3) × SU(2) × U(1) and power-counting renormalizability are also required.

The next sections outline some possible measurable signals that are implied by this standard-model extension. Detailed treatments exist at present for effects in neutral-meson systems and for effects in certain experiments in the context of quantum electrodynamics.

**TESTS WITH NEUTRAL MESONS**

In the four neutral-meson systems, K, D, B_d, B_s, the small mass differences between weak-interaction eigenstates offer an interferometric sensitivity to highly suppressed effects such as might arise from Planck-scale physics [11]. This section has three subsections. One summarizes theoretical issues, one outlines general experimental issues and some established results, and the third discusses the case of the B_d system.

**Theoretical Issues**

The time evolution of a neutral-P meson, where the symbol P denotes any of the four neutral mesons, is governed by a 2 × 2 effective hamiltonian Λ_P. Assuming conventional quantum mechanics, there are two types of indirect CP violation that might be described by phenomenological parameters appearing in Λ_P. The first is the usual CP-violating parameter ε_P that breaks T but preserves CPT. The second is a complex CP-violating parameter δ_P that preserves T but breaks CPT. Note that this parametrization of CP violation is independent of any underlying model and is at a purely phenomenological level.

In the context of the usual standard model, parameters in the CKM matrix can be regarded as controlling the parameters ε_P for each P. No such understanding exists for possible nonzero values of δ_P. However, the CPT-violating extension of the standard model outlined in the previous section does provide a theoretical basis for nonzero δ_P. For instance, terms of the type shown in Eq. (1), which appear in the quark sector of the general standard-model extension when the fermions ψ and χ are identified with quark fields, act to change the time evolution of a neutral-P meson in a δ_P-dependent way. The point is that the propagators of the (valence) quarks are affected and generate CPT-violating effects.
A general expression for the quantity $\delta_P$ for a given $P$ system can be obtained in the context of spontaneous CPT and Lorentz breaking. It is [10,11]:

$$\delta_P = i \frac{h_{q_1} - h_{q_2}}{\sqrt{\Delta m^2 + \Delta \gamma^2/4}} e^{i\phi}.$$  \hspace{1cm} (2)

In this equation, $\Delta m$ and $\Delta \gamma$ are the $P$-meson mass and rate differences, which are experimentally observable. They are used to define the angle $\phi$ by $\phi \equiv \tan^{-1}(2\Delta m/\Delta \gamma)$. The quantities $h_{q_j}$ are determined by parameters in the standard-model extension arising from the spontaneous CPT violation in the fundamental theory and by the effects $r_{q_j}$ of the quark-gluon sea: $h_{q_j} = r_{q_j} \lambda_{q_j}(T)$.

The hermiticity of the underlying theory and the extension of the standard model implies that the quantities $h_{q_j}$ are real. This in turn can be used to show that the real and imaginary parts of $\delta_P$ are proportional, with proportionality constant determined by experimentally measurable rate and mass differences. Explicitly, the result is

$$\text{Im} \delta_P = \pm \frac{\Delta \gamma}{2\Delta m} \text{Re} \delta_P.$$  \hspace{1cm} (3)

This can be regarded as a determining signature for CPT breaking arising within the present framework. Assuming a suppression factor of $r \simeq 10^{-17}$ along the lines of the discussion above, it also follows that direct CPT violation arising in the $P$-meson decay amplitudes is too small to observe.

Within the present framework, it is plausible that the values of the CPT-violating quantities $\delta_P$ could be significantly different for distinct $P$-meson systems. The point is that the dimensionless coupling constants $\lambda_{q_j}$, appearing in terms of the form given in Eq. (1), might depend on the quark flavor $q_j$. The corresponding CPT-violating quark couplings within the extension of the standard model would then also be flavor dependent. A related effect occurs for the Yukawa couplings, which take values for different quark flavors that range over about six orders of magnitude. The possibility of flavor-dependent CPT violation means that the values of $\delta_P$ might vary with $P$, so it might be crucial to perform experimental tests of CPT symmetry in more than one neutral-meson system. Moreover, under some circumstances the experimental signals could be startling. For instance, only relatively weak limits have been obtained as yet on $B_{s}$-meson CP violation, which means it is possible that CP violation parametrized by the CPT-violating quantity $\delta_{B_s}$ could be larger than conventional CP breaking parametrized by $\epsilon_{B_s}$ and therefore could produce unexpected results in proposed experiments at $B$ factories.

**Experimental Issues and Results**

This subsection provides a short outline of some experimental issues and the present status of established tests of indirect CPT violation with neutral-$P$ mesons. Tests with neutral-$B$ mesons are discussed in the following subsection.
Searches for indirect CP violation in a neutral-$P$ system can be performed with experimental data taken from decays either of uncorrelated tagged $P$ mesons or of correlated $P$-$\overline{P}$ pairs produced through prior quarkonia decay. Both indirect $T$ and CPT violation are in principle accessible. Time-dependent and fully integrated decay-probability asymmetries, sensitive to the various CP parameters, have now been established in each $P$-meson system for both correlated and uncorrelated situations. These can be applied to analyses of real data, or can be used in theoretical estimates of CP reach performed either analytically or through detailed Monte-Carlo simulations with acceptances and background effects.

To date, the sharpest bound on CPT violation in a neutral-meson system comes from analyses of $K$ oscillations. There already exist published bounds on $|\delta_K|$ of order $10^{-3}$ [8,21,22]. Analyses currently underway or experiments being performed or planned are anticipated to provide even tighter limits.

In the $D$ system, mass mixing has yet to be detected. Furthermore, the expected strong dispersive effects and the complication of dominant contributions arising from physics beyond the standard model makes theoretical predictions difficult and subject to uncertainties potentially of orders of magnitude. Nonetheless, in circumstances that are favorable theoretically, certain tests of CPT invariance in the $D$ system might produce signals when performed with current techniques and perhaps even with data that already exist [18]. The expected increase in reconstructed events to be obtained in various future machines provides an interesting arena for establishing CPT bounds from the $D$ system.

The Neutral-$B$ System

Tests of CPT with neutral-$B_d$ mesons are of interest both theoretically and experimentally. Theoretically, if indeed the dimensionless couplings corresponding to $\lambda$ in Eq. (1) are flavor dependent and follow the same general pattern as the Yukawa couplings, then the strength of the CPT violation is related to the mass of the valence quarks that are bound in the neutral meson. In this case, since the $b$ quark is involved, it is possible that any CPT violation would be larger in the $B$ system than in other neutral-meson systems [11,17]. On the experimental front, large numbers of $B_d$ events have already been obtained, and future machines and detectors under construction are expected to produce high-statistics event samples.

Several studies have been performed to estimate the likely constraints on CPT violation that could be obtained from experiments with $B_d$ mesons [11,16,17]. The most detailed treatment uses Monte-Carlo simulations to model experiments performed with uncorrelated, correlated unboosted, or correlated boosted mesons [17]. Backgrounds, resolutions, and acceptances are incorporated in simulating realistic experimental data that might be obtained at typical detectors at LEP, CESR, and the future $B$ factories. One result from this analysis is that data already taken suffice to place meaningful bounds on $\delta_{B_d}$.

Until recently, no bound existed on $\delta_{B_d}$. Early in 1997, the OPAL collaboration at
LEP obtained the first experimental constraint on CPT violation in the neutral-\(B_d\) system [23]. The relevant experimental observable is an asymmetry derived in Ref. [17] that is sensitive to \(\text{Im} \delta_{B_d}\) and \(\text{Re} \epsilon_{B_d}\). The time evolution of this asymmetry can be extracted from the experiment and used to bound both these quantities. The result is a constraint on the value of \(\text{Im} \delta_{B_d}\) of less than \(3 \times 10^{-2}\) at the 95% confidence limit.

An interesting feature of the \(B_d\) system is that Eq. (3) predicts that the real part of \(\delta_{B_d}\) is greater than the imaginary part because the value of \(2\Delta m/\Delta \gamma\) is believed to be large. In contrast, the real and imaginary parts of \(\delta_P\) for the \(K\) system and perhaps also the \(D\) system would be comparable. The analysis of Ref. [17] suggests that data already taken with the CLEO detector at CESR could be used to bound \(\text{Re} \delta_{B_d}\). The expected relatively large size of this quantity compared to \(\text{Im} \delta_{B_d}\) implies that even a limit of order \(20\%\) would be of interest.

The \(B\) factories and other \(B\)-dedicated experiments now under construction should be capable of improving on bounds obtained from current data. Moreover, the corresponding detectors are also expected to be sensitive to both \(\text{Re} \delta_{B_d}\) and \(\text{Im} \delta_{B_d}\) [17]. This opens the possibility in principle of testing Eq. (3) in a single experiment, should CPT violation indeed be discovered.

**EFFECTS IN OTHER SYSTEMS**

Effects from spontaneous CPT and Lorentz violation could also be manifest in contexts other than neutral-meson oscillations. In the standard-model extension, distinct quantities govern CPT and Lorentz breaking in, for example, the quark and lepton sectors. A wide variety of experiments outside the neutral-meson systems is therefore potentially crucial for uncovering effects. This section briefly describes some possibilities of this type.

The standard description of baryogenesis requires CP- and C-violating interactions and nonequilibrium processes [24] as well as baryon-number violating effects. In grand-unified theories, for example, the CP breaking is selected in a range suitable for reproducing the known baryon asymmetry and is unrelated to the observed CP violation in the standard model. The presence of CPT-breaking processes of the type given in Eq. (1) suggests an alternative possibility for baryogenesis that could occur in thermal equilibrium without the need for additional CP violation. An analysis [20] shows that under suitable circumstances a mechanism of this kind could result in a large baryon asymmetry at grand-unification scales that diminishes to the observed value by a process such as sphaleron dilution.

Another implication of the CPT- and Lorentz-violating extension of the standard model is a modification of some conventional results in quantum electrodynamics [15]. One example concerns comparative measurements of the anomalous magnetic moments of the electron and positron. It has recently been shown [19] that the standard figure of merit used in these experiments is misleading. However, a more appropriate measure can be defined that is directly sensitive to some of the addi-
tional terms appearing in the modified version of quantum electrodynamics. With current experimental techniques, constraints on CPT violation could be attained with a precision similar to those from neutral-meson systems. Related experiments with protons and antiprotons may provide interesting limits on CPT violation. Bounds on CPT and Lorentz breaking are also possible from precision experiments using cyclotron frequencies [19] and photon properties [15].

ACKNOWLEDGMENTS

I thank Orfeu Bertolami, Robert Bluhm, Don Colladay, Rob Potting, Neil Russell, Stuart Samuel, and Rick Van Kooten for collaborations. This work was supported in part by the United States Department of Energy under grant number DE-FG02-91ER40661.

REFERENCES

1. J. Schwinger, Phys. Rev. 82 (1951) 914.
2. G. Lüders, Det. Kong. Danske Videnskabernes Selskab Mat.-fysiske Meddelelser 28, no. 5 (1954).
3. J.S. Bell, Ph.D. thesis (Birmingham University, England, 1954); Proc. Roy. Soc. (London) A 231 (1955) 479.
4. W. Pauli, in Niels Bohr and the Development of Physics, ed. W. Pauli, (McGraw-Hill, New York, 1955), p. 30.
5. G. Lüders and B. Zumino, Phys. Rev. 106 (1957) 385.
6. R.F. Streater and A.S. Wightman, PCT, Spin and Statistics, and All That (Benjamin Cummings, Reading, 1964).
7. R. Jost, The General Theory of Quantized Fields (AMS, Providence, 1965).
8. See, for example, R.M. Barnett et al., Review of Particle Properties, Phys. Rev. D 54 (1996) 1.
9. V.A. Kostelecký and R. Potting, Nucl. Phys. B 359 (1991) 545.
10. V.A. Kostelecký, R. Potting, and S. Samuel, in Proceedings of the 1991 Joint International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics, eds. S. Hegarty et al. (World Scientific, Singapore, 1992); V.A. Kostelecký and R. Potting, Gamma Ray–Neutrino Cosmology and Planck Scale Physics, ed. D.B. Cline (World Scientific, Singapore, 1993) (hep-th/9211116).
11. V.A. Kostelecký and R. Potting, Phys. Rev. D 51 (1995) 3923.
12. V.A. Kostelecký and S. Samuel, Phys. Rev. D 39 (1989) 683; ibid., 40 (1989) 1886; Phys. Rev. Lett. 63 (1989) 224; ibid., 66 (1991) 1811.
13. V.A. Kostelecký and S. Samuel, Nucl. Phys. B 336 (1990) 263; Phys. Rev. Lett. 64 (1990) 2238; Phys. Rev. D 42 (1990) 1289.
14. V.A. Kostelecký and R. Potting, Phys. Lett. B 381 (1996) 389.
15. D. Colladay and V.A. Kostelecký, Phys. Rev. D 55 (1997) 6760; preprint IUHET 359 (1997), Phys. Rev. D, in press (hep-ph/9809521).
16. D. Colladay and V.A. Kostelecký, \textit{Phys. Lett.} B \textbf{344} (1995) 259.
17. V.A. Kostelecký and R. Van Kooten, \textit{Phys. Rev.} D \textbf{54} (1996) 5585.
18. D. Colladay and V.A. Kostelecký, \textit{Phys. Rev.} D \textbf{52} (1995) 6224.
19. R. Bluhm, V.A. Kostelecký, and N. Russell, \textit{Phys. Rev. Lett.} \textbf{79} (1997) 1432; \textit{Phys. Rev.} D \textbf{57} (1998) 3932.
20. O. Bertolami \textit{et al.}, \textit{Phys. Lett.} B \textbf{395} (1997) 178.
21. L.K. Gibbons \textit{et al.}, \textit{Phys. Rev.} D \textbf{55} (1997) 6625.
22. R. Carosi \textit{et al.}, \textit{Phys. Lett.} B \textbf{237} (1990) 303.
23. OPAL Collaboration, R. Ackerstaff \textit{et al.}, \textit{Z. Phys. C} \textbf{76} (1997) 401; DELPHI Collaboration, M. Feindt \textit{et al.}, preprint DELPHI 97-98 CONF 80 (July 1997).
24. A.D. Sakharov, \textit{JETP Lett.} \textbf{5} (1967) 24.