In this talk, I review the possibility that CPT and Lorentz symmetry might be spontaneously broken in nature by effects originating in a theory beyond the standard model, and I discuss some existing and future experimental tests.

1 Introduction

This talk provides a short review of some theoretical and experimental results relevant to the possibility that observable CPT violation could be generated in a theory beyond the standard model.

The product CPT of the discrete transformations involving charge conjugation, parity reflection, and time reversal is predicted theoretically to be an exact invariance of local relativistic field theories of point particles. This prediction agrees with many experimental tests performed in various systems, some to considerable accuracy. The generality of the theoretical prediction and the existence of high-precision experimental tests means that CPT violation is an interesting possible signature for new physics that could emerge from a fundamental theory such as strings.

Among existing approaches to a fundamental theory, strings currently remain the most promising avenue for the development of a complete and consistent quantum description of all fundamental interactions and particles. For string theory, standard assumptions in the proofs of the CPT theorem are open to question because strings are extended objects. In Sec. 2, I outline a mechanism for spontaneous Lorentz and CPT violation that arises in this context and mention some theoretical tests of these ideas.

If indeed spontaneous CPT violation occurs in nature, then it can be studied at presently accessible energies through an effective theory that allows for suitable CPT-violating interactions. Section 3 outlines some results leading to a general extension of the standard model incorporating additional interactions that could arise from spontaneous Lorentz and CPT violation. These terms maintain the known gauge symmetries and are power-counting renormalizable.
The standard-model extension can be used to investigate consequences of spontaneous CPT and Lorentz breaking. For example, experiments that measure or bound the coefficients of the additional terms in the standard-model extension provide quantitative constraints on possible CPT and Lorentz violation in nature. Section 4 outlines some results involving CPT tests using neutral-meson oscillations. The neutral-meson systems are particularly interesting because their interferometric nature makes them exceptionally sensitive to CPT violation. Tests of spontaneous CPT violation are possible in the $K$ system, the two $B$ systems, and the $D$ system.

Tests of CPT are also feasible in other systems. Section 5 summarizes some results concerning CPT studies using measurements of the electron and positron anomalous magnetic moments and the possibility that CPT violation might play a significant role in baryogenesis.

The minuscule spontaneous CPT and Lorentz breakings that are considered in this talk can be understood completely within conventional quantum mechanics. Violations of conventional quantum mechanics that might lead to CPT breaking have been proposed as possibly arising in the context of quantum gravity. Experiments in the $K$ system would produce very different signatures for the two kinds of CPT breaking.

2 Spontaneous Lorentz and CPT Violation

Suppose the fundamental theory of nature is dynamically Lorentz invariant but involves more than four spacetime dimensions. Since we observe only four dimensions, it is plausible that the higher-dimensional Lorentz group is spontaneously broken.

In string theory, which is naturally formulated in higher dimensions, a mechanism exists that could generate spontaneous Lorentz violation. There exist interactions in string field theory, emerging from string nonlocality, that are compatible with string gauge invariances and the infinite number of particle fields. Comparable interactions are absent in conventional four-dimensional renormalizable gauge theories. These stringy interactions can destabilize the static potentials for Lorentz tensor fields if certain scalars develop expectation values. The stable solution of the theory may then involve nonzero expectation values for some Lorentz tensor fields, which means Lorentz invariance is spontaneously broken. In particular, any expectation values involving tensors with an odd number of spacetime indices spontaneously break CPT.

The above ideas can be examined directly using the string field theory of the open bosonic string. The set of extremals of the action can systematically be established in a level-truncation scheme. By allowing only particle fields
below a specified level number $N$, the action and then the equations of motion can be analytically derived. Among the solutions to the equations of motion are ones that break Lorentz and CPT invariance. These can be determined and compared with analogous ones obtained for different values of $N$. The existence of a corresponding extremum of the full theory is plausible if the solutions not only persist but also appear to converge to a definite set of nonzero expectation values as $N$ increases. Under certain circumstances, it has been possible to use symbolic manipulation routines to examine more than 20,000 nonvanishing terms in the static potential obtained from the action. The resulting solutions exhibit Lorentz and CPT properties that are compatible with those expected from more general considerations of the theoretical mechanism.

3 Standard-Model Extension

It is natural to ask if the above mechanism for spontaneous Lorentz and CPT violation generates observable effects at low energies. This would seem plausible theoretically, as there is no evident reason why four dimensions would be preferred. Since neither Lorentz nor CPT violations have been observed, any effects at the level of the standard model must be highly suppressed.

From the perspective of a fundamental theory, the standard model can be regarded as an effective low-energy model at the electroweak scale $m_{\text{ew}}$. If the scale controlling the fundamental theory is the Planck mass $m_{\text{Pl}}$, then there is a natural suppression factor $r \sim m_{\text{ew}}/m_{\text{Pl}} \approx 10^{-17}$ for Planck-scale effects at the electroweak scale. Note that with a suppression at this level, relatively few Lorentz- and CPT-violating effects are potentially observable. Some possible signals are discussed in later sections.

The spontaneous CPT and Lorentz violation might thus produce suppressed low-energy contributions to the standard model. For example, a generic contribution to the fermionic sector of the standard model could arise from terms in a compactified string theory of the form:

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

Terms of this type are Lorentz and CPT breaking by virtue of nonzero expectation values of Lorentz tensors $T$. The tensors are coupled to four-dimensional fermions $\psi$ and $\chi$ via derivatives $i\partial$ and a gamma-matrix structure $\Gamma$. If $\lambda$ is taken as a dimensionless coupling constant, then a suitable power of one or more large mass scales $M$ (possibly the Planck or compatification scales) must also appear.

It is of interest to determine a general extension of the standard model that allows for all types of effects that could in principle arise from sponta-
neous Lorentz and CPT breaking. These include, for example, extra terms of the form (1) when the fermions $\psi$ and $\chi$ are identified with appropriate fermions in the standard model. Imposing the usual $SU(3) \times SU(2) \times U(1)$ gauge invariance and requiring power-counting renormalizability significantly restricts the possibilities. The general extension of the standard model, including Lorentz-breaking terms both with and without CPT breaking, has been established. The derivation includes a framework for treating theoretically the effects of CPT and Lorentz breaking. It appears that several of the usual difficulties are avoided by the spontaneous nature of the breaking, which reflects the noninvariance of solutions to the equations of motion rather than dynamical violations in the action.

The remainder of the talk summarizes some possible observable consequences of the standard-model extension. To date, these have been most fully explored in the neutral-meson systems, as is outlined in the next section. Other possible signals exist, however, as is briefly reviewed in Sec. 5.

4 Tests in Neutral-Meson Systems

The neutral-meson systems provide excellent hunting grounds for CPT violation because their interferometric nature makes them potentially sensitive to Planck-scale effects. There are four neutral-meson systems to consider: $K$, $D$, $B_d$, and $B_s$. In what follows, the symbol $P$ is used to denote any one of these. In the next subsection some theoretical considerations are given, while the subsequent one summarizes the current experimental situation.

4.1 Theory

Among the terms in the extension of the standard model are ones involving quark fields. For example, if $\psi$ and $\chi$ are regarded as valence quarks in a neutral meson $P$, then the terms (1) modify the $2 \times 2$ effective hamiltonian $\Lambda$ governing the $P$-meson time evolution.

From a purely phenomenological viewpoint, independent of any underlying theory except the assumptions of conventional quantum mechanics, two types of (indirect) CP violation might occur in $\Lambda$. One is given by the usual CP violating parameter $\epsilon_P$, which violates T but preserves CPT. The other is given by a complex CP violating parameter $\delta_P$, which preserves T but breaks CPT.

Within the usual standard model, nonzero parameters $\epsilon_P$ for different $P$ can be understood in terms of the CKM matrix. Similarly, the CPT-violating extension of the standard model mentioned above permits an understanding of possible nonzero values of the parameters $\delta_P$ for different $P$. 
Within the framework of spontaneous CPT and Lorentz breaking, the parameter $\delta_P$ for a given $P$ system is given by

$$\delta_P = \frac{i}{\sqrt{\Delta m^2 + \Delta \gamma^2/4}} \frac{h_{q_1} - h_{q_2}}{\sqrt{\Delta m^2 + \Delta \gamma^2/4}} e^{i\phi},$$

(2)

where the experimental observables $\Delta m$ and $\Delta \gamma$ are mass and rate differences, while $\phi = \tan^{-1}(2\Delta m/\Delta \gamma)$. The parameters $h_{q_i} = r_{q_i} \lambda_{q_i} \langle T \rangle$ are controlled by the fundamental theory and by effects $r_{q_i}$ of the quark-gluon sea. They originate from terms in the standard-model extension of the form (1).

The underlying fundamental theory and the standard-model extension are assumed to be hermitian. It follows that the $h_{q_i}$ are real, which determines a relation involving experimental observables between the real and imaginary components of $\delta_P$:

$$\text{Im} \delta_P = \pm \frac{\Delta \gamma}{2\Delta m} \text{Re} \delta_P.$$

(3)

If indeed the suppression ratio for Planck-scale effects is $r \approx 10^{-17}$, then detection of direct CPT violation in the $P$-meson decay amplitudes is excluded. The condition (3) is therefore expected to be a key signature for CPT violation within the present framework.

In the context of the standard-model extension the CPT-violating couplings could be very different for the different quarks, in analogy to the Yukawa couplings that vary over some six orders of magnitude. Equivalently, the dimensionless coupling constants $\lambda_{q_i}$ of (3) could change with quark flavor $q_i$. It is therefore possible that the CPT-violating quantities $\delta_P$ determined in (2) could vary significantly for different $P$ mesons.

Since $\delta_P$ might differ for distinct $P$, it is important to test CPT experimentally in more than one neutral-meson system. There are also other implications. For example, the relatively weak bounds presently available on $B_d$-meson CP violation still allow the possibility that conventional CP violation through $\epsilon_{B_d}$ is smaller than CP violation through the CPT-violating parameter $\delta_{B_d}$. This would induce interesting experimental signals in the proposed $B$ factories.

4.2 Experiment

Indirect CP violation in a given $P$ system, including both indirect T and CPT violations, can be experimentally studied with correlated $P\overline{P}$ pairs arising from quarkonium decays or with uncorrelated tagged $P$ mesons. The relevant experimental variables are appropriate asymmetries of decay probabilities into different final states. Suitable asymmetries, including ones with time dependences, now exist for all $P$ for both correlated and uncorrelated situations.
They can be adopted for detailed Monte-Carlo simulations of realistic experimental data including acceptances and background effects, as well as for relatively straightforward analytical estimates of CP reach. What follows is a brief summary of the status of indirect CPT tests for each possible $P$ system. More details can be found in the literature.

The best neutral-meson bound on CPT violation has been established in the $K$ system. Published limits on $|\delta_K|$ are of order $10^{-3}$. Improved bounds are expected in the near future, coming from completed experiments (e.g., CPLEAR at CERN) or ongoing ones (e.g., KTeV at Fermilab). There are also good future prospects from $\phi$ factories designed to produce a large flux of correlated $K-K'$ pairs.

Unlike the $K$ system, mixing has not been experimentally seen in the $D$ system. Moreover, theoretical estimates are uncertain, possibly by orders of magnitude, due to the combination of strong dispersive effects and the possibility of contributions from beyond the standard model. Under favorable conditions some tests of CPT symmetry may be feasible in the $D$ system using attainable experimental methods and possibly even with current data. The increased statistics available from future facilities offers interesting possibilities for developing CPT bounds.

Since the $B_d$ system involves the $b$ quark, it has the potential to generate the largest CPT violation and is therefore particularly interesting for CPT tests. Until very recently, no limit on $\delta_{B_d}$ had been established, although enough data for this purpose have already been obtained in the CERN LEP experiments and in CLEO experiments at Cornell. The OPAL collaboration at CERN has now placed a limit on $\text{Im}\,\delta_{B_d}$ of about $2 \times 10^{-2}$. The CLEO data could be used to bound $\text{Re}\,\delta_{B_d}$ at the level of about 10%. The $B$ factories and other $B$-dedicated experiments currently under development are expected to improve this bound considerably.

5 Other Effects

The discussion of spontaneous Lorentz and CPT violation in the context of a fundamental theory and the corresponding standard-model extension suggest the possibility of signals of Lorentz and CPT violation in systems other than neutral mesons. In this section, a short outline is given of a few of these that have been elucidated.

If conditions are suitable, terms of the form (3) might provide an acceptable mechanism for baryogenesis in thermal equilibrium. The mechanism could produce a large asymmetry at grand-unification scales that is subsequently reduced to the experimental value, for example, through sphaleron dilution. In
contrast, conventional approaches require nonequilibrium processes and C- and CP-breaking interactions, which in grand-unified theories are chosen to match the observed baryon asymmetry without relation to experimentally measured CP violation within the standard model.

Other possible observable signals could arise in the context of quantum electrodynamics. For example, experiments determining the difference between the anomalous magnetic moments of the electron and positron have the potential to constrain tightly CPT violation. Indeed, the conventional figure of merit adopted in these experiments provides a misleading measure of CPT violation. A more appropriate figure of merit suggests that bounds on CPT violation could be placed on leptonic systems comparable to those in neutral mesons. Other bounds may be imposed from known properties of photons. A variety of experimental tests is essential because the effects in the different sectors are controlled by different parameters in the standard-model extension.

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 Confer-
ence 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/9211114).

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; Indiana University preprint IUHET 359 (1997).
16. D. Colladay and V.A. Kostelecký, *Phys. Lett.* B 344 (1995) 259.
17. V.A. Kostelecký and R. Van Kooten, *Phys. Rev.* D 54 (1996) 5585.
18. D. Colladay and V.A. Kostelecký, *Phys. Rev.* D 52 (1995) 6224.
19. R. Bluhm, V.A. Kostelecký, and N. Russell, *Phys. Rev. Lett.* 79 (1997) 1432.
20. O. Bertolami, D. Colladay, V.A. Kostelecký, and R. Potting, *Phys. Lett.* B 395 (1997) 178.
21. S.W. Hawking, *Phys. Rev.* D 14 (1976) 2460.
22. D. Page, *Phys. Rev. Lett.* 44 (1980) 301.
23. R.M. Wald, *Phys. Rev.* D 21 (1980) 2742.
24. J. Ellis, J.L. Lopez, N.E. Mavromatos, and D.V. Nanopoulos, *Phys. Rev.* D 53 (1996) 3846; D.V. Nanopoulos, these proceedings.
25. P. Huet, these proceedings.
26. L.K. Gibbons et al., *Phys. Rev.* D 55 (1997) 6625.
27. R. Carosi et al., *Phys. Lett.* B 237 (1990) 303.
28. P. Kokas, these proceedings.
29. P. Franzini, these proceedings.
30. D. Kaplan, these proceedings.
31. OPAL Collaboration, R. Ackerstaff et al., CERN preprint CERN-PPE/97-036 (April 1997).
32. A.D. Sakharov, *JETP Lett.* 5 (1967) 24.