CPT, STRINGS, AND NEUTRAL-MESON SYSTEMS

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This talk provides an overview of a string-based mechanism for spontaneous CPT violation. A summary is given of theoretical developments. The mechanism could generate CPT-violating contributions to a four-dimensional low-energy effective theory and thereby produce detectable consequences for candidate experiments with neutral-meson systems.

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1. Introduction

Invariance under CPT, which is the combined operation of charge conjugation C, parity reversal P, and time reversal T, is a basic theoretical feature of local relativistic field theories of point particles [1]-[6]. It has been tested experimentally to great precision in a broad variety of settings [7]-[9]. The combination of the powerful theoretical result about CPT in particle physics together with the existence of high-precision experiments means that CPT violation is well suited as a candidate signature for new, non-particle physics such as string theory [10, 11].

Since strings are extended objects, they violate assumptions normally imposed in theoretical proofs of CPT invariance. In fact, a stringy mechanism that can induce spontaneous Lorentz symmetry breaking [12] with accompanying CPT violation is known [10, 13]. These effects are briefly described in section 2 below.

If spontaneous CPT violation occurs in a realistic theory, then its consequences for low-energy physics can be modeled. It turns out that effects could appear in any of the neutral-meson systems, with specific experimental signatures. Various schemes can be examined for detecting CPT violation in each neutral-meson system. Potentially interesting experiments can be performed with either correlated or uncorrelated mesons. Sections 3, 4 and 5 below contain a brief description of some aspects of the above ideas. For more details about any of these topics, the reader is referred to the original literature on the \( K \) system [10, 11, 14], the two \( B \) systems [14, 15, 16], and the \( D \) system [14, 17].

Note that the type of CPT violation discussed in refs. [10]-[17] is different from that possibly arising in the context of quantum gravity [18]-[20], which involves unconventional quantum mechanics and has an entirely different experimental signature in the kaon system [21, 22].

2. Spontaneous CPT Breaking

In any higher-dimensional Lorentz-invariant theory that purports to be realistic, spontaneous Lorentz breaking must occur in some form. In string theory, there exists a natural mechanism inducing spontaneous Lorentz violation [12]. The origin of the effect is most readily seen at the level of string field theory, where it is due to the appearance of certain interactions that cannot occur in conventional four-dimensional renormalizable gauge theories. The existence of these interactions is compatible with string gauge invariance because string field theory involves an infinite number of particle fields, which in turn is a consequence of string nonlocality.

When nonzero expectation values for scalars arise, these interactions can generate contributions to the mass matrices for Lorentz tensor fields. The signs of the contributions can be
such as to trigger instabilities in the effective potentials of the tensors, which then in turn can acquire nonzero expectation values. This causes spontaneous Lorentz breaking, which can be accompanied by CPT breaking [10].

The mechanism as described above is not specific to any model. Some direct support for its occurrence in an explicit theory emerges from the study of the solution space of the string field theory for the open bosonic string [13]. It is possible to construct analytically the leading terms of the action in a level-truncation scheme. The equations of motion can then be obtained, and a search can be performed for Lorentz- and CPT-breaking extrema of the action that persist as the level number is increased in the truncation scheme. Over 20,000 nonvanishing terms in the action have been examined in some cases. Since a given solution takes the form of a set of expectation values, their Lorentz- and CPT-breaking properties can be examined. These are in agreement with features anticipated from the generic theoretical mechanism.

3. Low-Energy Model

Assuming that the Universe can be modeled with a realistic string theory, the mechanism discussed in section 2 might produce CPT-violating contributions to the effective four-dimensional low-energy theory, which is the standard model. Since the Universe is found experimentally to be CPT invariant to a high degree of precision, any CPT breaking must be suppressed. A natural dimensionless suppression factor is provided by the ratio \( r \sim 10^{-17} \) of the low-energy scale to the Planck scale. A suppression of this size can create effects of comparable or somewhat smaller magnitude to the present experimental sensitivity in the kaon and other neutral-meson systems [10, 14].

To make this suggestion more definite, one can consider a generic CPT-breaking contribution to the effective low-energy theory arising from a compactified string theory [11, 14]:

\[
\mathcal{L} \sim \frac{\lambda}{M} \langle T \rangle \cdot \bar{\psi} \Gamma(i\partial)^k \chi + h.c. .
\]  

(1)

Here, \( \psi \) and \( \chi \) are four-dimensional fermions taken as component quark fields of the meson, coupled via a gamma-matrix structure \( \Gamma \). The expectation \( \langle T \rangle \) involves a Lorentz tensor \( T \). The mass scale \( M \) is an appropriate large scale such as the Planck mass or a compactification scale, and it compensates for the derivative couplings. The parameter \( \lambda \) is a dimensionless coupling constant.

4. Neutral-Meson Systems

It is possible to analyse the effects of terms of the form (2) on the effective hamiltonian governing the time evolution of a neutral-meson system. At a purely phenomenological level,
CP violation in a neutral-meson effective Hamiltonian can be parametrized by two quantities. One governs T violation and is usually denoted $\epsilon_K$ for the kaon system. The other controls CPT violation and is denoted $\delta_K$. Similar parameters exist for the other neutral mesons, denoted generically as $P$ mesons in what follows.

The standard model provides a theoretical framework for understanding the origin of a nonzero value of $\epsilon_P$ via the CKM matrix. Analogously, string-inspired spontaneous CPT breaking of the form (1) in the low-energy effective theory could be used to understand a nonzero value of $\delta_P$. It can be shown that

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

where the factors $h_{q_j} = r_{q_j} \lambda_{q_j} \langle T \rangle$ arise from the coefficients of the interaction (1) and from contributions $r_{q_j}$ from the quark-gluon sea in the meson. The mass and rate differences $\Delta m$ and $\Delta \gamma$ are experimental observables, as is the phase $\phi = \tan^{-1}(2\Delta m/\Delta \gamma)$. It follows that the string scenario predicts the relationship

$$\text{Im} \delta_P = \pm \cot \phi \text{ Re} \delta_P.$$

It can also be shown that contributions from this mechanism to direct CPT violation in decay amplitudes are negligible.

5. Experimental Tests in Neutral-Meson Systems

There are several neutral-meson systems that can be considered as candidates for CPT tests: the $K$, $D$, $B_d$, and $B_s$ systems [14]. In this regard, note one especially interesting feature of the theoretical expression for the CPT-violating parameter $\delta_P$ in the string scenario: its magnitude depends on couplings that could differ for distinct quark flavors, as for example do the Yukawa couplings in the standard model. It is therefore of interest to test for CPT breaking in neutral-meson systems other than the $K$ system. As an extreme example, it is presently even possible that CPT violation in the $B$ system could be larger than the expected (but as yet unobserved) conventional T violation, even though the corresponding possibility is experimentally excluded for the kaon system.

In each neutral-meson system, experiments can be envisaged that involve either correlated mesons produced via decay of appropriate quarkonia or uncorrelated ones produced by a variety of means. At present, a basic theoretical catalogue of interesting experimental asymmetries has been created for all the systems. For some cases, the theoretical analysis now includes Monte-Carlo simulations of realistic experimental data incorporating acceptances and background effects. Here are a few very brief comments about results for the $K$, $D$, and $B$ systems in turn. More details can be found in the original literature [10]-[17].
At present, CPT violation in the neutral-meson systems is bounded only in the kaon case. The current limits on $\text{Re} \delta_K$ are of order $10^{-3}$ while those on $\text{Im} \delta_K$ are of order $10^{-4}$ [23]-[27]. Under favorable circumstances, perhaps incorporating data from $\phi$ factories [28]-[30], reliable bounds improved by an order of magnitude could be envisaged.

Attainable bounds on CPT using the $D$ system are harder to estimate because $D$ mixing has not been observed and has theoretically uncertain magnitude. However, possibilities for placing definite experimental bounds on CPT violation could include limiting direct CPT violation and bounding one or both of the $K$- and $D$-system parameters $\delta_K$ and $\delta_D$.

There is presently no limit in the literature on the CPT-violating parameter $\delta_B$ for the $B_d$ system. This is an especially interesting arena for future exploration because the $b$ quark is involved and in certain string scenarios CPT breaking could be greatest there. It has recently been shown that sufficient data have already been taken to limit the CPT-violating parameter $\delta_B$ at about the 10% level [10]. This would be comparable to the current bound on conventional indirect $T$ violation in the $B$ system, which is presently of order 5%. Tighter limits could be attained in planned experiments at various $B$ factories.

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