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CPT violation and *B*-meson oscillations

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Recent evidence for anomalous *CP* violation in *B*-meson oscillations can be interpreted as resulting from *CPT* violation. This yields the first sensitivity to *CPT* violation in the B_s^0 system, with the relevant coefficient for *CPT* violation constrained at the level of parts in 10^{12}.

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Experimental studies of spacetime symmetries involving the discrete transformations under charge conjugation *C*, parity inversion *P*, time reversal *T*, and their products *CP* and *CPT* have played a major role in establishing the standard model (SM) of particle physics. All these symmetries are known to be broken except *CPT*, and their description in terms of the SM has been in excellent agreement with laboratory experiments. Among the most powerful tools available for investigations of these symmetries are the neutral-meson systems, in which particles and antiparticles mix interferometrically and thereby offer high sensitivity to deviations from exact symmetry.

The D0 Collaboration has recently presented data supporting an anomalous like-sign dimuon charge asymmetry in *B*-meson mixing [1,2], interpreting it as evidence for *CPT*-invariant *CP* violation beyond the SM. Here, we show that this anomalous asymmetry could also arise from *T*-invariant *CP* violation in B_s^0-$\bar{B}_s^0$ mixing. A *CPT*-violating effect in *B*-meson mixing was predicted some time ago [3] as potentially arising from spontaneous breaking of Lorentz symmetry in an underlying unified theory [4], and the usual requirement of *CPT*-invariant *CP* violation for baryogenesis [5] can be evaded in this context [6]. The B_s^0-$\bar{B}_s^0$ system is of particular interest for studies of *CPT* violation because several complete particle-antiparticle oscillations occur within a meson lifetime [7]. As part of the analysis here, we show that the anomalous like-sign dimuon charge asymmetry offers sensitivity to *CPT* breaking, and we use this asymmetry to obtain the first quantitative measure of *CPT* violation in the B_s^0-$\bar{B}_s^0$ system.

An appropriate framework for investigating *CPT* violation in neutral mesons is effective field theory. In this context, *CPT* violation is necessarily accompanied by Lorentz violation [8]. We can therefore work here within the comprehensive effective field theory describing general Lorentz violation at attainable energies known as the standard-model extension (SME) [9]. Each *CPT*-violating term in the SME Lagrange density is the product of a *CPT*-violating operator and a controlling coefficient. The SME contains both the SM and general relativity, so it serves as a realistic theory for analyzing experimental data for signals of *CPT* violation. Several SME-based searches for *CPT* violation with neutral-meson oscillations [10–13] and numerous investigations using a wide variety of other physical systems [14] have been performed over the past decade.

The analysis of meson mixing in the SME context reveals the four neutral-meson systems K^0-$\bar{K}^0$, D^0-$\bar{D}^0$, B_d^0-$\bar{B}_d^0$, and B_s^0-$\bar{B}_s^0$ contain a total of 16 independent observables for *CPT* violation [15]. The corresponding 16 combinations of SME coefficients are conventionally denoted as $(\Delta a^K)_\mu$, $(\Delta a^D)_\mu$, $(\Delta a^{B_d})_\mu$, $(\Delta a^{B_s})_\mu$. These coefficients are known to be observable only in flavor-changing experiments with neutral mesons or neutrinos [16] and in gravitational experiments [17]. Several experimental searches have yielded high sensitivities to certain components of $(\Delta a^K)_\mu$, $(\Delta a^D)_\mu$, and $(\Delta a^{B_d})_\mu$ [10–13]. In this work, we report the first sensitivity to the coefficient $(\Delta a^{B_s})_\mu$. We also outline a procedure that could improve on this result using the full D0 data set.

The D0 Collaboration measures the dimuon charge asymmetry

$$A_{\rm sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \qquad (1)$$

where N_b^{++} and N_b^{--} represent the number of events in which two *b* hadrons decay semileptonically into two positive muons and two negative muons, respectively. One measurement of this asymmetry is obtained by correcting the raw like-sign dimuon sample for various backgrounds, yielding [2]

$$A_{\rm sl}^b = -0.007\,36 \pm 0.002\,66 \pm 0.003\,05, \qquad (2)$$

where the first error is statistical and the second systematic. Combining in quadrature yields an effect at 1.8 standard deviations. The D0 Collaboration also studies the inclusive "wrong-charge" muon charge asymmetry $a_{\rm sl}^b$ of semileptonic decays of *b* hadrons to muons with charge opposite to that of the original *b* quark,

$$a_{\rm sl}^b = \frac{\Gamma(\bar{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\bar{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)}. \qquad (3)$$

This asymmetry is a measure of *CPT*-invariant *CP* violation and hence of *T* violation. Assuming *CPT* symmetry holds and under other mild assumptions such as no direct *CP* violation, it can be shown that $A_{\rm sl}^b = a_{\rm sl}^b$ [18], which enables a second measurement of $A_{\rm sl}^b$. This second measurement is consistent with no effect at 0.4 standard deviations. The final D0 result for $A_{\rm sl}^b$ is obtained by combining the two measurements to minimize systematic uncertainties. It reveals a signal 3.2 standard deviations away from the SM prediction for *CPT*-preserving *T* violation, which is [2,19]

$$A_{\rm sl}^b({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}. \tag{4}$$

For our present purposes, the second measurement using the asymmetry (3) and the combined measurement both turn out to be irrelevant, so only the first result (2) for $A_{\rm sl}^b$ is involved in the analysis that follows.

In this work, we allow for *T*-invariant *CP* violation in B_s^0-$\bar{B}_s^0$ oscillations. A measure of this *CPT* violation is given by the inclusive "right-charge" muon charge asymmetry $\mathcal{A}_{CPT}^b$ of semileptonic decays of *b* hadrons to muons with the same charge as that of the original *b* quark,

$$\mathcal{A}^{\,b}_{CPT} = \frac{\Gamma(\bar{B} \to \mu^- X) - \Gamma(B \to \mu^+ X)}{\Gamma(\bar{B} \to \mu^- X) + \Gamma(B \to \mu^+ X)}. \tag{5}$$

In terms of this *CPT* asymmetry and the *T* asymmetry (3), we find the dimuon charge asymmetry $A_{\rm sl}^b$ of Eq. (1) can be written in the nested form

$$A_{\rm sl}^b = \frac{\left(\frac{1+a_{\rm sl}^b}{1-a_{\rm sl}^b} - \frac{1+\mathcal{A}_{\rm CPT}^b}{1-\mathcal{A}_{\rm CPT}^b}\right)}{\left(\frac{1+a_{\rm sl}^b}{1-a_{\rm sl}^b} + \frac{1+\mathcal{A}_{\rm CPT}^b}{1-\mathcal{A}_{\rm CPT}^b}\right)} \approx a_{\rm sl}^b - \mathcal{A}_{CPT}^b, \tag{6}$$

where the last expression assumes small *T* and *CPT* violation at first order in the asymmetries. This expression reveals that the dimuon charge asymmetry $A_{\rm sl}^b$ is sensitive to *CPT* violation as well as *T* violation. In what follows, the result (6) is used to obtain the first quantitative measure of *CPT* violation in the B_s^0-$\bar{B}_s^0$ system.

For definiteness, we assume the only source of *T* violation is the SM contribution $a_{\rm sl}^b({\rm SM}) = A_{\rm sl}^b({\rm SM})$ given by Eq. (4). Combining with the D0 dimuon asymmetry (2) yields the value

$$\mathcal{A}^{\,b}_{CPT} = 0.007\,13 \pm 0.004\,05, \tag{7}$$

where the D0 statistical and systematic errors are combined in quadrature. Our goal is to interpret this result as a measure of *CPT* violation in *B*-meson mixing, and, in particular, in the B_s^0-$\bar{B}_s^0$ system.

In general, oscillations of neutral mesons are governed by a 2×2 effective Hamiltonian Λ [20]. The *CPT*-violating contributions to Λ are controlled by the difference $\Delta\Lambda = \Lambda_{11} - \Lambda_{22}$ of the diagonal terms of Λ, while the off-diagonal terms govern *T* violation. The size of *CPT* violation is unknown *a priori*. We adopt here the $w\xi$ formalism for Λ [15], which is independent of phase conventions and allows for *CPT* violation of arbitrary size. In this formalism, *CPT* violation is governed by a complex parameter ξ of any magnitude, and $\Delta\Lambda = -(\Delta m + \frac{1}{2} i \Delta\Gamma)\xi$. For the B_s^0-$\bar{B}_s^0$ system, $\Delta m \equiv \Delta m_s = m_H - m_L$ is the mass difference between the heavy and light eigenstates, $\Delta\Gamma \equiv \Delta\Gamma_s = \Gamma_L - \Gamma_H$ is their width difference, and the parameter for *CPT* violation is denoted ξ_s. We also adopt the standard notation $x_s = \Delta m_s/\Gamma_s$, $y_s = \Delta\Gamma_s/2\Gamma_s$, $2\Gamma_s = \Gamma_L + \Gamma_H$.

Since *CPT* violation comes with Lorentz violation [8], the complex parameter ξ cannot be a scalar. Instead, it must depend on the meson 4-momentum and is therefore a frame-dependent quantity. For example, the rotation of the Earth relative to the constant vector $\Delta\vec{a}$ typically generates a variation with sidereal time in ξ [21]. The canonical frame used in studies of *CPT* and Lorentz violation is the Sun-centered frame with coordinates (T, X, Y, Z) [22]. In this frame, the *CPT*-violating parameter $\xi \equiv \xi(T, \vec{p}, \Delta a_\mu)$ is a function of sidereal time *T*, meson 4-momentum $(E(\vec{p}), \vec{p})$, and the four constant SME coefficients Δa_μ for *CPT* violation for the given meson system. The explicit functional form of ξ can be found using perturbation theory for the SME and is given as Eq. (14) of Ref. [15]. Hermiticity of the Lagrange density ensures the reality of $\Delta\Lambda$, which for the B_s^0-$\bar{B}_s^0$ system implies the condition $y_s\,{\rm Re}\xi_s + x_s\,{\rm Im}\xi_s = 0$.

For our present purposes, it suffices to average over the sidereal time and the meson 4-momentum spectrum. Since the particle distributions from *b*-hadron decay for the Fermilab collider are symmetric in local detector polar coordinates for D0, the dependence on spatial components $(\Delta a^{B_s})_J$ cancels through this procedure. We obtain the averaged value

$$\overline{{\rm Im}\xi_s} = \frac{y_s}{x_s^2 + y_s^2} \frac{\bar{\gamma}(\Delta a^{B_s})_T}{\Gamma_s}, \tag{8}$$

where $\bar{\gamma} \simeq 4.1$ is the mean gamma boost factor for the B_s^0 mesons in the D0 experiment.

Given the result (8), we can extract a measurement of $(\Delta a^{B_s})_\mu$ from the value (7) once an expression for $\mathcal{A}_{\rm CPT}^b$ is known in terms of $\overline{{\rm Im}\xi_s}$. To derive this relationship for $\mathcal{A}_{\rm CPT}^b$, we note that

$$\mathcal{A}^{\,b}_{CPT} = \frac{R^- - R^+}{R^- + R^+}, \tag{9}$$

where $R^\pm$ represents the number of right-sign decays into $\mu^\pm X$. As measured at D0, these quantities are a sum over contributions from the B_d^0-$\bar{B}_d^0$ system, from the B_s^0-$\bar{B}_s^0$ system, and from all other *b* hadrons. Labeling these three sources as $q = d, s, u$ and using an overbar to identify quantities for the *b* quark, we can write [18]

$$\begin{aligned} R^+ &= f_d T_d \Gamma_d^{\rm sl} + f_s T_s \Gamma_s^{\rm sl} + f_u T_u \Gamma_u^{\rm sl}, \\ R^- &= \bar{f}_d \bar{T}_d \bar{\Gamma}_d^{\rm sl} + \bar{f}_s \bar{T}_s \bar{\Gamma}_s^{\rm sl} + \bar{f}_u \bar{T}_u \bar{\Gamma}_u^{\rm sl}, \end{aligned} \tag{10}$$

where we denote the production fractions as f_q, the time-integrated probabilities for $B \to B$, $\bar{B} \to \bar{B}$, or direct decay of nonmixing states as T_q, and the semileptonic decay rates as $\Gamma_q^{\rm sl}$.

Taking for definiteness zero direct T and CPT violation in semileptonic decays, we have $\bar{\Gamma}_q^{\rm sl} = \Gamma_q^{\rm sl}$. It is also a reasonable approximation to take $\Gamma_d^{\rm sl} = \Gamma_s^{\rm sl} = \Gamma_u^{\rm sl}$. Symmetric production implies $\bar{f}_q = f_q$, while $f_u = 1 - f_d - f_s$. The absence of mixing for $q = u$ implies $T_u = 1/\Gamma_u$, where Γ_u is the total decay rate for the nonmixing b hadrons, which include the $B^\pm$ mesons and the b baryons. The time-dependent mixing and decay probabilities for neutral B mesons in the $w\xi$ formalism are given explicitly as Eq. (19) of Ref. [15]. These can be integrated over all time t to yield T_d and T_s.

For simplicity, suppose the only source of CPT violation comes from B_s^0-$\bar{B}_s^0$ mixing. Then, integrating the probability for $B_d^0 \to B_d^0$ over all time t gives $T_d = z_{d+}/2\Gamma_d$, while the integration for $B_s^0 \to B_s^0$ yields

$$T_s = \frac{1}{2\Gamma_s}(z_{s+} + 2z_{s-}x_s\,\overline{\mathrm{Im}\xi_s} + z_{s-}z_{s0}(\overline{\mathrm{Im}\xi_s})^2). \quad (11)$$

In these equations, we define

$$z_{q\pm} = \frac{1}{(1-y_q^2)} \pm \frac{1}{(1+x_q^2)}, \qquad z_{q0} = (x_q^2 + y_q^2)/y_q^2. \quad (12)$$

Applying CPT gives the additional relations $\bar{T}_d = T_d$ and $\bar{T}_s = T_s(\xi_s \to -\xi_s)$.

Collecting the results, we finally obtain the CPT asymmetry

$$\mathcal{A}^b_{CPT} = \frac{2f_s z_{s-}x_s\,\overline{\mathrm{Im}\xi_s}}{f_d z_{d+} + f_s z_{s+} + 2f_u + f_s z_{s-}z_{s0}(\overline{\mathrm{Im}\xi_s})^2}. \quad (13)$$

We remark in passing that the form of this result for $\mathcal{A}^b_{\rm CPT}$ holds also in the unaveraged case, provided Eq. (8) is replaced with the complete expression for $\mathrm{Im}\xi_s(T, \vec{p}, (\Delta a^{B_s})_\mu)$ and the reasonable approximation is made that the decays occur over times t negligible compared to the sidereal variation with T.

To match the theoretical expression (13) to the result (7) obtained from the D0 experiment, we adopt the values $x_d = 0.774 \pm 0.008$, $y_d = 0$, $x_s = 26.2 \pm 0.5$, $y_s = 0.046 \pm 0.027$, $f_d = 0.323 \pm 0.037$, and $f_s = 0.118 \pm 0.015$ [2,23]. Inverting the expression (13) yields

$$\overline{\mathrm{Im}\xi_s} = (2.3 \pm 1.7) \times 10^{-3}. \quad (14)$$

We can also extract the desired measurement of the SME coefficient $(\Delta a^{B_s})_T$ for CPT violation, which is

$$(\Delta a^{B_s})_T = (3.7 \pm 3.8) \times 10^{-12}\ \mathrm{GeV}, \quad (15)$$

where $\Gamma_s = (4.47 \pm 0.08) \times 10^{-13}$ GeV [23]. This corresponds to the bound

$$-3.8 \times 10^{-12} < (\Delta a^{B_s})_T < 1.1 \times 10^{-11} \quad (16)$$

at the 95% confidence level.

The value (15) represents the first sensitivity to CPT violation in the B_s^0-$\bar{B}_s^0$ system. The result (14) for $\mathrm{Im}\xi_s$ is consistent with no effect at 1.4 standard deviations, which is a reasonable result given the size of the systematic errors in the basic D0 asymmetry (2) and the SM-corrected asymmetry (7). The fractional error on the coefficient $(\Delta a^{B_s})_T$ for CPT violation is greater, due primarily to the comparatively large uncertainty in the value of y_s.

For the D0 study of CPT-invariant CP violation, the signal of 3.2 standard deviations was obtained by reducing the systematics on $A^b_{\rm sl}$ by combining the result (2) with an independent measurement of $a^s_{\rm sl}$. We observe here that a similar technique could be used in the present context of CPT violation. The basic idea is to reduce the systematics by combining the result (2) for $A^b_{\rm sl}$ with an independent measurement of CPT violation. The relevant quantity for the latter measurement is the asymmetry $\mathcal{A}^b_{\rm CPT}$ for inclusive "right-charge" muon semileptonic decays defined in Eq. (5). The overall CPT reach including the result (15) might be substantially sharpened via this method. However, extracting the asymmetry $\mathcal{A}^b_{\rm CPT}$ requires access to the full D0 data set and hence lies outside our scope.

For a neutral meson containing valence quark q_1 and antiquark q_2, the observable Δa_μ is given by $\Delta a_\mu \approx r_{q_1}a_\mu^{q_1} - r_{q_2}a_\mu^{q_2}$. The coefficients $a_\mu^{q_1}$, $a_\mu^{q_2}$ appear in the SME Lagrange density in terms of the form $-a_\mu^q\bar{q}\gamma^\mu q$ for each quark q, while r_{q_1} and r_{q_2} are quantities of order one arising from quark-binding and normalization effects [3]. The value of Δa_μ is then primarily determined by the heaviest valence quark. Note this implies that the zero-sum rule

$$(\Delta a^K)_\mu - (\Delta a^{B_d})_\mu + (\Delta a^{B_s})_\mu \approx 0 \quad (17)$$

holds to a good approximation.

For B_d^0-$\bar{B}_d^0$ mixing, the *BABAR* Collaboration has obtained the measurement [13]

$$(\Delta a^{B_d})_T - 0.30(\Delta a^{B_d})_Z = (-3.0 \pm 2.4) \times 10^{-15}(\Delta m_d/\Delta\Gamma_d)\ \mathrm{GeV}. \quad (18)$$

The ratio $\Delta m_d/\Delta\Gamma_d \gtrsim 10.6$ in this case [23], so this measurement is compatible with the result (15) and the zero-sum rule (17). For the D^0-$\bar{D}^0$ system, the FOCUS Collaboration has obtained the measurement [12]

$$(\Delta a^D)_T - 0.60(\Delta a^D)_Z = (1.8 \pm 3.0) \times 10^{-16}(\Delta m_D/\Delta\Gamma_D)\ \mathrm{GeV}. \quad (19)$$

The ratio $\Delta m_D/\Delta\Gamma_D \simeq 0.6$ is smaller here, yielding an improved sensitivity [23], albeit to effects involving other quark flavors and SME coefficients. Several results have also been obtained for the K^0-$\bar{K}^0$ system. By studying different processes, the KLOE Collaboration has obtained the independent measurements [11]

$$(\Delta a^K)_T = (0.4 \pm 1.8) \times 10^{-17}\ \mathrm{GeV}, \quad (\Delta a^K)_Z = (2.4 \pm 9.7) \times 10^{-18}\ \mathrm{GeV}. \quad (20)$$

Using data from the Fermilab E773 experiment [24], a constraint of

$$|(\Delta a^K)_T - 0.60(\Delta a^K)_Z| \lesssim 5 \times 10^{-21}\ \text{GeV} \qquad (21)$$

has also been obtained [21]. These values are all compatible with the result (15) and the zero-sum rule (17).

More general analyses of the D0 data could in principle be countenanced. Given sufficient statistics and a good understanding of the spectrum, the spatial coefficients $(\Delta a^{B_s})_J$ for *CPT* violation could be measured and disentangled by combining a search for sidereal variations with spectral analysis. Sidereal sensitivities have already been obtained by KTeV [10], KLOE [11], FOCUS [12], and *BABAR* [13]. All the sidereal results are compatible with the result (15).

Another option for future investigation is to allow for nonzero contributions from $\mathrm{Im}\xi_d$ in the B_d^0-$\bar{B}_d^0$ system simultaneously with ones from $\mathrm{Im}\xi_s$. This requires a nonzero value of y_d. With both effects present, and averaging over 4-momentum and sidereal time as before, the asymmetry (13) acquires a term in the numerator proportional to $\overline{\mathrm{Im}\xi_d}$, while the denominator contains an additional term proportional to $(\overline{\mathrm{Im}\xi_d})^2$. This analysis would therefore yield a constraint involving both $(\Delta a^{B_d})_T$ and $(\Delta a^{B_s})_T$, albeit with a large error due to the current uncertainty in the value of y_d. A global fit of this type could also combine data from different experiments for the B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ systems. Ideally, information from K^0-$\bar{K}^0$ experiments would be incorporated via Eq. (17) to extend further the *CPT* reach.

Analyses along these lines are also well suited to other ongoing experiments investigating neutral mesons. Searches with high statistics and high boost, such as those feasible at the LHCb experiment [25] with average boost factor $\bar{\gamma} \simeq 15$–20, offer the capability to study *CPT* violation in *B* mesons with sensitivities unattained to date. The results presented here outline a potential window for the exploration of physics beyond the SM and can serve as an impetus for future studies of *CPT* violation.

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