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Tests of CPT symmetry in $B^0$-$\bar{B}^0$ mixing and in $B^0 \to c\bar{c}K^0$ decays


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I. INTRODUCTION

The discovery of CP violation in 1964 [1] motivated searches for $T$ and CPT violation. Since $CPT = CP \times T$, violation of $CP$ means that $T$ or $CPT$ or both are also violated. For the $K^0$ system, the two contributions were first determined [2] in 1970, by using the Bell-Steinberger unitarity relation [3] for $CP$ violation in $K^0\bar{K}^0$ mixing: $T$ was violated with about $5\sigma$ significance and no $CPT$ violation was observed. Large $CP$ violation in the $B^0$ system was discovered in 2001 [4,5] in the interplay of $B^0,\bar{B}^0$ mixing and $B^0 \rightarrow c\bar{c}K^0$ decays, but an explicit demonstration of $T$ violation was given only recently [6]. In the present analysis, we test $CPT$ symmetry quantitatively in $B^0,\bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays.

Transitions in the $B^0,\bar{B}^0$ system are well described by the quantum-mechanical evolution of a two-state wave function

$$\Psi = \psi_1 |B^0\rangle + \psi_2 |B^0\rangle,$$

(1)

using the Schrödinger equation

$$\psi = -i\mathcal{H}\psi,$$

(2)

where the Hamiltonian $\mathcal{H}$ is given by two constant Hermitian matrices, $\mathcal{H}_{ij} = m_{ij} + i\Gamma_{ij}/2$. In this evolution, $CP$ violation is described by three parameters, $|q/p|$, Re$(Z)$, and Im$(Z)$, defined by

$$|q/p| = 1 - \frac{2\text{Im}(m_{12}\Gamma_{12})}{4|m_{12}|^2 + |\Gamma_{12}|^2},$$

$$Z = \frac{(m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2}{\Delta m - i\Delta \Gamma/2},$$

(3)

where $\Delta m = m(B_H) - m(B_L) \approx 2|m_{12}|$ and $\Delta \Gamma = \Gamma(B_H) - \Gamma(B_L) \approx +2|\Gamma_{12}|$ or $-2|\Gamma_{12}|$ are the mass and the width differences of the two mass eigenstates ($H = \text{heavy}, L = \text{light}$) of the Hamiltonian,

\[
B_H = (p\sqrt{1 + zB^0} - q\sqrt{1 - z\bar{B}^0})/\sqrt{2},
\]

\[
B_L = (p\sqrt{1 - zB^0} + q\sqrt{1 + z\bar{B}^0})/\sqrt{2}.
\]

(4)

Note that we use the convention with $+q$ for the light and $-q$ for the heavy eigenstate. If $|q/p| \neq 1$, the evolution violates the discrete symmetries $CP$ and $T$. If $z \neq 0$, it violates $CP$ and $CPT$. The normalizations of the two eigenstates, as given in Eq. (4), are precise in the lowest order of $r$ and $z$, where $r = |q/p| - 1$. Throughout the following, we neglect contributions of orders $r^2, z^2, rz$, and higher.

The $T$-sensitive mixing parameter $|q/p|$ has been determined in several experiments, the present world average [7] being $|q/p| = 1 + (0.8 \pm 0.8) \times 10^{-3}$. The $CPT$-sensitive parameter Im$(Z)$ has been determined by analyzing the time dependence of dilepton events in the decay $Y(4S) \rightarrow B^0\bar{B}^0 \rightarrow (\ell^+\nu\chi)(\ell^-\bar{\nu}\bar{\chi})$; the BABAR result [8] is Im$(Z) = (-13.9 \pm 7.3 \pm 3.2) \times 10^{-3}$. Since $\Delta \Gamma$ is very small, dilepton events are only sensitive to the product Re$(Z)\Delta \Gamma$. Therefore, Re$(Z)$ has so far only been determined by analyzing the time dependence of the decays $Y(4S) \rightarrow B^0\bar{B}^0$ with one $B$ meson decaying into $\ell\nu\chi$ and the other one into $c\bar{c}K$. With $8 \times 10^6 BB$ events, BABAR measured Re$(Z) = (19 \pm 48 \pm 7) \times 10^{-3}$ in 2004 [9], while Belle used $535 \times 10^6 BB$ events to measure Re$(Z) = (19 \pm 37 \pm 33) \times 10^{-3}$ in 2012 [10].

In our present analysis, we use the final data set of the BABAR experiment [11,12] with $470 \times 10^6 BB$ events for a new determination of Re$(Z)$ and Im$(Z)$. As in Refs. [9,10], this is based on $c\bar{c}K$ decays with amplitudes $A$ for $B^0 \rightarrow c\bar{c}K^0$ and $\bar{A}$ for $\bar{B}^0 \rightarrow c\bar{c}\bar{K}^0$, using the following two assumptions:

1. $c\bar{c}K$ decays obey the $\Delta S = \Delta B$ rule, i.e., $B^0$ states do not decay into $c\bar{c}\bar{K}^0$, and $\bar{B}^0$ states do not decay into $c\bar{c}K^0$.
measured time dependences of the four decay rates $B^0, \bar{B}^0 \rightarrow c\bar{c}K^0, B^0$, in $\Upsilon(4S)$ decays, $B^0$ and $\bar{B}^0$ mesons are produced in the entangled state $(B^0\bar{B}^0)/\sqrt{2}$. When the first meson decays into $f = f_1$ at time $t_1$, the state collapses into the two states $f_1$ and $B_2$. The later decay $B_2 \rightarrow f_2$ at time $t_2$ depends on the state $B_2$ and, because of $B^0-\bar{B}^0$ mixing, on the decay-time difference

$$t = t_2 - t_1 \geq 0. \tag{5}$$

Note that $t$ is the only relevant time here; it is the evolution time of the single-meson state $B_2$ in its rest frame.

The present analysis does not start from raw data but uses intermediate results from Ref. [6] where, as mentioned above, we used our final data set for the demonstration of large $T$ violation. This was shown in four time-dependent transition-rate differences

$$R(B_j \rightarrow B_i) - R(B_i \rightarrow B_j), \tag{6}$$

where $B_i = B^0$ or $\bar{B}^0$, and $B_j = B_1$ or $B_2$. The two states $B_i$ were defined by flavor-specific decays [13] denoted as $B^0 \rightarrow \epsilon^+X, \bar{B}^0 \rightarrow \epsilon^-X$. The state $B_2$ was defined as the remaining state $B_2$ after a $c\bar{c}K^0$ decay, and $B_1$ as $B_2$ after a $c\bar{c}K^0$ decay. In order to use the two states for testing $T$ symmetry in Eq. (6), they must be orthogonal; $\langle B_1 | B_2 \rangle = 0$, which requires the additional assumption

$(3)$ $|\tilde{A}/A| = 1$.

In the same 2012 analysis, we demonstrated that $CPT$ symmetry is unbroken within uncertainties by measuring the four rate differences

$$R(B_j \rightarrow B_i) - R(B_i \rightarrow B_j). \tag{7}$$

For both measurements in Eqs. (6) and (7), expressions

$$R_i(t) = N_i e^{-\Gamma t}(1 + C_i \cos \Delta mt + S_i \sin \Delta mt), \tag{8}$$

were fitted to the four time-dependent rates

$$i = \ldots 8,$$

for determining $\Delta \Gamma = 0$. The time $t \geq 0$ in these expressions is the time between the first and the second decay of the entangled $B^0\bar{B}^0$ pair as defined in Eq. (5). In our 2012 analysis, we named it $\Delta r$, equal to $t_{c\bar{c}K} - t_{\epsilon X}$ if the $\epsilon X$ decay occurred first, and equal to $t_{\epsilon X} - t_{c\bar{c}K}$ with $c\bar{c}K$ as the first decay. After fits, the $T$-violating and $CPT$-testing rate differences were evaluated from the obtained $S_i$ and $C_i$ results. The $CPT$ test showed no $CPT$ violation, i.e., it was compatible with $z = 0$, but no results for $Re(z)$ and $Im(z)$ were given in 2012.

Our present analysis uses the eight measured time dependences in the 2012 analysis, i.e., the 16 results $C_i$ and $S_i$ for determining $z$. This is possible without assumption (3) since we do not need to use the concept of states $B_1$ and $B_2$. We are therefore able to determine the decay parameter $|\tilde{A}/A|$ in addition to the mixing parameters $Re(z)$ and $Im(z)$. As in 2012, we use $\Delta \Gamma = 0$, but we show at the end of this analysis that the final results are independent of this constraint. Accepting assumptions (1) and (2), and in addition

$(4)$ that the amplitudes $A$ and $\tilde{A}$ have a single weak phase,

only two more parameters $|\tilde{A}/A|$ and $Im(q\tilde{A}/pA)$ are required in addition to $|q/p|$ and $z$ for a full description of $CP$ violation in time-dependent $B^0 \rightarrow c\bar{c}K^0$ decays. In this framework, $T$ symmetry requires $Im(q\tilde{A}/pA) = 0$ [14], and $CPT$ symmetry requires $|\tilde{A}/A| = 1$ [15].

II. B-MESON DECAY RATES

The time-dependent rates of the decays $B^0, \bar{B}^0 \rightarrow c\bar{c}K$ are sensitive to both symmetries $CPT$ and $T$ in $B^0, \bar{B}^0$ mixing and in $B^0$ decays. For decays into final states $f$ with amplitudes $A_f = A(B^0 \rightarrow f)$ and $\tilde{A}_f = A(\bar{B}^0 \rightarrow f)$, using

$$\lambda_f = q\tilde{A}_f/(pA_f)$$

and approximating $\sqrt{1 - z^2} = 1$, the rates are given by

$$R(B^0 \rightarrow f) = \frac{|A_f|^2 e^{-\Gamma t}}{4} |(1 - z + \lambda_f) e^{\Delta mt} e^{\Delta \Gamma t/4} + (1 + z - \lambda_f) e^{-\Delta \Gamma t/4}|^2,$$

$$R(\bar{B}^0 \rightarrow f) = \frac{|\tilde{A}_f|^2 e^{-\Gamma t}}{4} |(1 + z + 1/\lambda_f) e^{\Delta mt} e^{\Delta \Gamma t/4} + (1 - z - 1/\lambda_f) e^{-\Delta \Gamma t/4}|^2. \tag{9}$$

For the $CP$ eigenstates $c\bar{c}K^0 (CP = +1)$ and $c\bar{c}K^0 (CP = -1)$ with $A_{S(L)} = A[B^0 \rightarrow c\bar{c}K^0_{S(L)}]$ and $\tilde{A}_{S(L)} = A[\bar{B}^0 \rightarrow c\bar{c}K^0_{S(L)}]$, assumptions (1) and (2) give

$$A_S = A_L = A/\sqrt{2}$$

and $\tilde{A}_S = -\tilde{A}_L = \tilde{A}/\sqrt{2}$. In the following, we only need to use $\lambda_S = -\lambda_L = \lambda$. Setting $\Delta \Gamma = 0$ and keeping only first-order terms in the small quantities $|\lambda| - 1$, $z$, and $r = |q/p| - 1$, this leads to rate expressions as given in Eq. (8) with coefficients
CPT TESTS OF

The relations between the 16 observables \( y_i = S_1 \cdots C_8 \) in Eqs. (10) and (11) and the four parameters \( p_1 = (1 - |\lambda|^2)/2 \), \( p_2 = 2\text{Im}(\lambda)/(1 + |\lambda|^2) \), \( p_3 = \text{Im}(\lambda) \), and \( p_4 = \text{Re}(\lambda) \) are approximately linear. Therefore, the four parameters can be determined in a two-step linear \( \chi^2 \) fit using matrix algebra. The first-step fit determines \( p_1 \) and \( p_2 \) by fixing \( \text{Re}(\lambda) \) and \( \text{Im}(\lambda) \) in the products \( \text{Re}(\lambda) \text{Re}(\lambda) \), \( \text{Im}(\lambda) \text{Im}(\lambda) \), \( \text{Im}(\lambda) \text{Re}(\lambda) \), and \( \text{Re}(\lambda) \text{Re}(\lambda) \). After fixing these terms, the relation between the vectors \( y \) and \( p \) is strictly linear,

\[
y = M_1 p. 
\]

where \( M_1 \) uses \( \text{Im}(\lambda) = 0.67 \) and \( \text{Re}(\lambda) = -0.74 \), motivated by the results of analyses assuming \( CPT \) symmetry [7]. With this ansatz, \( \chi^2 \) is given by

\[
\chi^2 = (M_1 p - \hat{y})^T G (M_1 p - \hat{y}),
\]

where \( \hat{y} \) is the measured vector of observables, and the weight matrix \( G \) is taken to be

\[
G = [C_{\text{stat}}(y) + C_{\text{sys}}(y)]^{-1},
\]

where \( C_{\text{stat}}(y) \) and \( C_{\text{sys}}(y) \) are the statistical and systematic covariance matrices, respectively. The minimum of \( \chi^2 \) is reached for

\[
\hat{p} = M_1 \hat{y} \quad \text{with} \quad M_1 = (M_1^T G M_1)^{-1} M_1^T G,
\]

and the uncertainties of \( \hat{p} \) are given by the covariance matrices

\[
C_{\text{stat}}(p) = M_1 C_{\text{stat}}(y) M_1^T, \\
C_{\text{sys}}(p) = M_1 C_{\text{sys}}(y) M_1^T,
\]

with the property

\[
C_{\text{stat}}(p) + C_{\text{sys}}(p) = (M_1^T G M_1)^{-1}.
\]

This first-step fit yields

\[
p_1 = 0.001 \pm 0.023 \pm 0.017, \\
p_2 = 0.689 \pm 0.030 \pm 0.015.
\]

This leads to

\[
|\lambda| = 1 - p_1 = 0.999 \pm 0.023 \pm 0.017, \\
\text{Im}(\lambda) = (1 - p_1) p_2 = 0.689 \pm 0.034 \pm 0.019, \\
\text{Re}(\lambda) = -(1 - p_1) \sqrt{1 - p_1^2} \\
= -0.723 \pm 0.043 \pm 0.028,
\]
where the negative sign of Re(λ) is motivated by four measurements [19–22]. The results of all four favor cos 2β > 0, and in Ref. [22] cos 2β < 0 is excluded with 4.5σ significance.

In the second step, we fix the two λ values according to the p₁ and p₂ results of the first step, i.e. to the central values in Eqs. (19). Equations (12) to (17) are then applied again, replacing M₁ with the new relations matrix M₂. This gives the same results for p₁ and p₂ as in Eq. (18), and

\[
p_3 = \text{Im}(z) = 0.010 \pm 0.030 \pm 0.013,
\]

\[
p_4 = \text{Re}(z) = -0.065 \pm 0.028 \pm 0.014,
\]

with a χ² value of 6.9 for 12 degrees of freedom.

The Re(z) result deviates from 0 by 2.1σ. The result for |λ| can be easily converted into |Ā/A| by using the world average of measurements for |q/p|. With |q/p| = 1.0008 ± 0.0008 [7], we obtain

\[
|Ā/A| = 0.999 \pm 0.023 \pm 0.017,
\]

in agreement with CPT symmetry. Using the matrix algebra in Eqs. (12) to (17) allows us to determine the separate statistical and systematic covariance matrices of the final results, in agreement with the condition

\[
C_{\text{stat}}(p) + C_{\text{sys}}(p) = (M^TGM)^{-1},
\]

where M relates y and p after convergence of the fit. The statistical correlation coefficients are ρ[|Ā/A|, Im(z)] = 0.03, ρ[|Ā/A|, Re(z)] = 0.44, and ρ[Re(z), Im(z)] = 0.03. The systematic correlation coefficients are ρ[|Ā/A|, Im(z)] = 0.03, ρ[|Ā/A|, Re(z)] = 0.48, and ρ[Re(z), Im(z)] = −0.15.

IV. ESTIMATING THE INFLUENCE OF ΔΓ

Using an accept/reject algorithm, we have performed two “toy simulations,” each with ~2 × 10⁶ events, i.e. t values sampled from the distributions

\[
e^{-\Gamma t}[1 + \text{Re}(\lambda) \sinh(\Delta \Gamma t/2) + \text{Im}(\lambda) \sin(\Delta m t)],
\]

with ΔΓ = 0 for one simulation and ΔΓ = 0.01Γ for the other one, corresponding to one standard deviation from the present world average [7]. For both simulations we use Im(λ) = 0.67 and Re(λ) = −0.74 and sample t values between 0 and ±5/Γ. We then fit the two samples, binned in intervals of Δt = 0.25/Γ, to the expressions

\[
-N e^{-\Gamma t}[1 + C \cos(\Delta m t) + S \sin(\Delta m t)],
\]

with three free parameters N, C and S. The fit results agree between the two simulations within 0.002 for C and 0.008 for S. We, therefore, conclude that omission of the sinh term in Ref. [6] has a negligible influence on the three final results of this analysis.

V. CONCLUSION

Using 470 × 10⁶ BB events from BABAR, we determine

\[
\text{Im}(z) = 0.010 \pm 0.030 \pm 0.013,
\]

\[
\text{Re}(z) = -0.065 \pm 0.028 \pm 0.014,
\]

\[
|Ā/A| = 0.999 \pm 0.023 \pm 0.017,
\]

where the first uncertainties are statistical and the second uncertainties are systematic. All three results are compatible with CPT symmetry in B⁰–B̄⁰ mixing and in B → c̄κ decays. The uncertainties on Re(z) are comparable with those obtained by Belle in 2012 [10] with 535 × 10⁶ BB events, Re(z) = −0.019 ± 0.037 ± 0.033. The uncertainties on Im(z) are considerably larger, as expected, than those obtained by BABAR in 2006 [8] with dilepton decays from 232 × 10⁶ BB events, Im(z) = −0.014 ± 0.007 ± 0.003. The result of the present analysis for Re(z), −0.065 ± 0.028 ± 0.014, supersedes the BABAR result of 2004 [9].

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[9] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 70, 012007 (2004), inserting Re($\lambda$) = −0.73.

[13] In addition to prompt charged leptons from inclusive semileptonic decays $\ell^\pm \nu X$, Ref. [6] used charged kaons, charged pions from $D^\pm$ decays and high-momentum charged particles in the flavor-specific samples $\ell^\pm X$.