Title

Tests of CPT symmetry in B0-B¯0 mixing and in B0→cc¯K0 decays

Journal

Physical Review D, 94(1)

ISSN

2470-0010

Authors

Lees, JP
Poireau, V
Tisserand, V
et al.

Publication Date

2016-07-01

DOI

10.1103/physrevd.94.011101

PHYSICAL REVIEW D **94,** 011101(R) (2016)

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

J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] E. Grauges,[2] A. Palano,[3] G. Eigen,[4] D. N. Brown,[5] Yu. G. Kolomensky,[5] H. Koch,[6] T. Schroeder,[6] C. Hearty,[7] T. S. Mattison,[7] J. A. McKenna,[7] R. Y. So,[7] V. E. Blinov,[8a,8b,8c] A. R. Buzykaev,[8a] V. P. Druzhinin,[8a,8b] V. B. Golubev,[8a,8b] E. A. Kravchenko,[8a,8b] A. P. Onuchin,[8a,8b,8c] S. I. Serednyakov,[8a,8b] Yu. I. Skovpen,[8a,8b] E. P. Solodov,[8a,8b] K. Yu. Todyshev,[8a,8b] A. J. Lankford,[9] J. W. Gary,[10] O. Long,[10] A. M. Eisner,[11] W. S. Lockman,[11] W. Panduro Vazquez,[11] D. S. Chao,[12] C. H. Cheng,[12] B. Echenard,[12] K. T. Flood,[12] D. G. Hitlin,[12] J. Kim,[12] T. S. Miyashita,[12] P. Ongmongkolkul,[12] F. C. Porter,[12] M. Röhrken,[12] Z. Huard,[13] B. T. Meadows,[13] B. G. Pushpawela,[13] M. D. Sokoloff,[13] L. Sun,[13,*] J. G. Smith,[14] S. R. Wagner,[14] D. Bernard,[15] M. Verderi,[15] D. Bettoni,[16a] C. Bozzi,[16a] R. Calabrese,[16a,16b] G. Cibinetto,[16a,16b] E. Fioravanti,[16a,16b] I. Garzia,[16a,16b] E. Luppi,[16a,16b] V. Santoro,[16a] A. Calcaterra,[17] R. de Sangro,[17] G. Finocchiaro,[17] S. Martellotti,[17] P. Patteri,[17] I. M. Peruzzi,[17] M. Piccolo,[17] A. Zallo,[17] S. Passaggio,[18] C. Patrignani,[18,†] B. Bhuyan,[19] U. Mallik,[20] C. Chen,[21] J. Cochran,[21] S. Prell,[21] H. Ahmed,[22] A. V. Gritsan,[23] N. Arnaud,[24] M. Davier,[24] F. Le Diberder,[24] A. M. Lutz,[24] G. Wormser,[24] D. J. Lange,[25] D. M. Wright,[25] J. P. Coleman,[26] E. Gabathuler,[26] D. E. Hutchcroft,[26] D. J. Payne,[26] C. Touramanis,[26] A. J. Bevan,[27] F. Di Lodovico,[27] R. Sacco,[27] G. Cowan,[28] Sw. Banerjee,[29] D. N. Brown,[29] C. L. Davis,[29] A. G. Denig,[30] M. Fritsch,[30] W. Gradl,[30] K. Griessinger,[30] A. Hafner,[30] K. R. Schubert,[30] R. J. Barlow,[31,‡] G. D. Lafferty,[31] R. Cenci,[32] A. Jawahery,[32] D. A. Roberts,[32] R. Cowan,[33] R. Cheaib,[34] S. H. Robertson,[34] B. Dey,[35a] N. Neri,[35a] F. Palombo,[35a,35b] L. Cremaldi,[36] R. Godang,[36,§] D. J. Summers,[36] P. Taras,[37] G. De Nardo,[38] C. Sciacca,[38] G. Raven,[39] C. P. Jessop,[40] J. M. LoSecco,[40] K. Honscheid,[41] R. Kass,[41] A. Gaz,[42a] M. Margoni,[42a,42b] M. Posocco,[42a] M. Rotondo,[42a] G. Simi,[42a,42b] F. Simonetto,[42a,42b] R. Stroili,[42a,42b] S. Akar,[43] E. Ben-Haim,[43] M. Bomben,[43] G. R. Bonneaud,[43] G. Calderini,[43] J. Chauveau,[43] G. Marchiori,[43] J. Ocariz,[43] M. Biasini,[44a,44b] E. Manoni,[44a] A. Rossi,[44a] G. Batignani,[45a,45b] S. Bettarini,[45a,45b] M. Carpinelli,[45a,45b,¶] G. Casarosa,[45a,45b] M. Chrzaszcz,[45a] F. Forti,[45a,45b] M. A. Giorgi,[45a,45b] A. Lusiani,[45a,45c] B. Oberhof,[45a,45b] E. Paoloni,[45a,45b] M. Rama,[45a] G. Rizzo,[45a,45b] J. J. Walsh,[45a] A. J. S. Smith,[46] F. Anulli,[47a] R. Faccini,[47a,47b] F. Ferrarotto,[47a] F. Ferroni,[47a,47b] A. Pilloni,[47a,47b] G. Piredda,[47a] C. Bünger,[48] S. Dittrich,[48] O. Grünberg,[48] M. Heß,[48] T. Leddig,[48] C. Voß,[48] R. Waldi,[48] T. Adye,[49] F. F. Wilson,[49] S. Emery,[50] G. Vasseur,[50] D. Aston,[51] C. Cartaro,[51] M. R. Convery,[51] J. Dorfan,[51] W. Dunwoodie,[51] M. Ebert,[51] R. C. Field,[51] B. G. Fulsom,[51] M. T. Graham,[51] C. Hast,[51] W. R. Innes,[51] P. Kim,[51] D. W. G. S. Leith,[51] S. Luitz,[51] V. Luth,[51] D. B. MacFarlane,[51] D. R. Muller,[51] H. Neal,[51] B. N. Ratcliff,[51] A. Roodman,[51] M. K. Sullivan,[51] J. Va'vra,[51] W. J. Wisniewski,[51] M. V. Purohit,[52] J. R. Wilson,[52] A. Randle-Conde,[53] S. J. Sekula,[53] M. Bellis,[54] P. R. Burchat,[54] E. M. T. Puccio,[54] M. S. Alam,[55] J. A. Ernst,[55] R. Gorodeisky,[56] N. Guttman,[56] D. R. Peimer,[56] A. Soffer,[56] S. M. Spanier,[57] J. L. Ritchie,[58] R. F. Schwitters,[58] J. M. Izen,[59] X. C. Lou,[59] F. Bianchi,[60a,60b] F. De Mori,[60a,60b] A. Filippi,[60a] D. Gamba,[60a,60b] L. Lanceri,[61] L. Vitale,[61] F. Martinez-Vidal,[62] A. Oyanguren,[62] J. Albert,[63] A. Beaulieu,[63] F. U. Bernlochner,[63] G. J. King,[63] R. Kowalewski,[63] T. Lueck,[63] I. M. Nugent,[63] J. M. Roney,[63] N. Tasneem,[63] T. J. Gershon,[64] P. F. Harrison,[64] T. E. Latham,[64] R. Prepost,[65] and S. L. Wu[65]

(*BaBar* Collaboration)

[1]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France*
[2]*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3]*INFN Sezione di Bari and Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy*
[4]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[7]*University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[8a]*Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia*
[8b]*Novosibirsk State University, Novosibirsk 630090, Russia*
[8c]*Novosibirsk State Technical University, Novosibirsk 630092, Russia*
[9]*University of California at Irvine, Irvine, California 92697, USA*
[10]*University of California at Riverside, Riverside, California 92521, USA*
[11]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[12]*California Institute of Technology, Pasadena, California 91125, USA*
[13]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[14]*University of Colorado, Boulder, Colorado 80309, USA*
[15]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France*
[16a]*INFN Sezione di Ferrara, I-44122 Ferrara, Italy*
[16b]*Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, I-44122 Ferrara, Italy*
[17]*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
[18]*INFN Sezione di Genova, I-16146 Genova, Italy*

[19]*Indian Institute of Technology Guwahati, Guwahati, Assam 781 039, India*
[20]*University of Iowa, Iowa City, Iowa 52242, USA*
[21]*Iowa State University, Ames, Iowa 50011, USA*
[22]*Physics Department, Jazan University, Jazan 22822, Saudi Arabia*
[23]*Johns Hopkins University, Baltimore, Maryland 21218, USA*
[24]*Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, F-91898 Orsay Cedex, France*
[25]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[26]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[27]*Queen Mary, University of London, London E1 4NS, United Kingdom*
[28]*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
[29]*University of Louisville, Louisville, Kentucky 40292, USA*
[30]*Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany*
[31]*University of Manchester, Manchester M13 9PL, United Kingdom*
[32]*University of Maryland, College Park, Maryland 20742, USA*
[33]*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
[34]*McGill University, Montréal, Québec H3A 2T8, Canada*
[35a]*INFN Sezione di Milano, I-20133 Milano, Italy*
[35b]*Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy*
[36]*University of Mississippi, University, Mississippi 38677, USA*
[37]*Université de Montréal, Physique des Particules, Montréal, Québec H3C 3J7, Canada*
[38]*INFN Sezione di Napoli and Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy*
[39]*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, Netherlands*
[40]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[41]*Ohio State University, Columbus, Ohio 43210, USA*
[42a]*INFN Sezione di Padova, I-35131 Padova, Italy*
[42b]*Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy*
[43]*Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France*
[44a]*INFN Sezione di Perugia, I-06123 Perugia, Italy*
[44b]*Dipartimento di Fisica, Università di Perugia, I-06123 Perugia, Italy*
[45a]*INFN Sezione di Pisa, I-56127 Pisa, Italy*
[45b]*Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy*
[45c]*Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy*
[46]*Princeton University, Princeton, New Jersey 08544, USA*
[47a]*INFN Sezione di Roma, I-00185 Roma, Italy*
[47b]*Dipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy*
[48]*Universität Rostock, D-18051 Rostock, Germany*
[49]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[50]*CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
[51]*SLAC National Accelerator Laboratory, Stanford, California 94309, USA*
[52]*University of South Carolina, Columbia, South Carolina 29208, USA*
[53]*Southern Methodist University, Dallas, Texas 75275, USA*
[54]*Stanford University, Stanford, California 94305, USA*
[55]*State University of New York, Albany, New York 12222, USA*
[56]*Tel Aviv University, School of Physics and Astronomy, Tel Aviv 69978, Israel*
[57]*University of Tennessee, Knoxville, Tennessee 37996, USA*
[58]*University of Texas at Austin, Austin, Texas 78712, USA*
[59]*University of Texas at Dallas, Richardson, Texas 75083, USA*
[60a]*INFN Sezione di Torino, I-10125 Torino, Italy*
[60b]*Dipartimento di Fisica, Università di Torino, I-10125 Torino, Italy*
[61]*INFN Sezione di Trieste and Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
[62]*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*
[63]*University of Victoria, Victoria, British Columbia V8W 3P6, Canada*

[64]*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*
[65]*University of Wisconsin, Madison, Wisconsin 53706, USA*
(Received 16 May 2016; published 18 July 2016)

Using the eight time dependences $e^{-\Gamma t}(1+C_i\cos\Delta mt+S_i\sin\Delta mt)$ for the decays $\Upsilon(4S)\to B^0\bar{B}^0\to f_j f_k$, with the decay into a flavor-specific state $f_j=\ell^\pm X$ before or after the decay into a CP eigenstate $f_k=c\bar{c}K_{S,L}$, as measured by the *BABAR* experiment, we determine the three CPT-sensitive parameters $\mathrm{Re}(\mathsf{z})$ and $\mathrm{Im}(\mathsf{z})$ in B^0-$\bar{B}^0$ mixing and $|\bar{A}/A|$ in $B^0\to c\bar{c}K^0$ decays. We find $\mathrm{Im}(\mathsf{z})=0.010\pm0.030\pm0.013$, $\mathrm{Re}(\mathsf{z})=-0.065\pm0.028\pm0.014$, and $|\bar{A}/A|=0.999\pm0.023\pm0.017$, in agreement with CPT symmetry.

DOI: 10.1103/PhysRevD.94.011101

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 5σ 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 $B^0\to c\bar{c}K^0$ 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 $B^0\to c\bar{c}K^0$ decays.

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

$$\Psi=\psi_1|B^0\rangle+\psi_2|\bar{B}^0\rangle, \tag{1}$$

using the Schrödinger equation

$$\dot{\Psi}=-\mathrm{i}\mathcal{H}\Psi, \tag{2}$$

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

$$|q/p|=1-\frac{2\mathrm{Im}(m_{12}^*\Gamma_{12})}{4|m_{12}|^2+|\Gamma_{12}|^2},$$
$$\mathsf{z}=\frac{(m_{11}-m_{22})-\mathrm{i}(\Gamma_{11}-\Gamma_{22})/2}{\Delta m-\mathrm{i}\Delta\Gamma/2}, \tag{3}$$

where $\Delta m=m(B_H)-m(B_L)\approx2|m_{12}|$ 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 ($H=$ heavy, $L=$ light) of the Hamiltonian,

$$B_H=(p\sqrt{1+\mathsf{z}}B^0-q\sqrt{1-\mathsf{z}}\bar{B}^0)/\sqrt{2},$$
$$B_L=(p\sqrt{1-\mathsf{z}}B^0+q\sqrt{1+\mathsf{z}}\bar{B}^0)/\sqrt{2}. \tag{4}$$

Note that we use the convention with $+q$ for the light and $-q$ for the heavy eigenstate. If $|q/p|\neq1$, the evolution violates the discrete symmetries CP and T. If $\mathsf{z}\neq0$, 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, $r\mathsf{z}$, and higher.

The T-sensitive mixing parameter $|q/p|$ has been determined in several experiments, the present world average [7] being $|q/p|=1+(0.8\pm0.8)\times10^{-3}$. The CPT-sensitive parameter $\mathrm{Im}(\mathsf{z})$ has been determined by analyzing the time dependence of dilepton events in the decay $\Upsilon(4S)\to B^0\bar{B}^0\to(\ell^+\nu X)(\ell^-\bar{\nu}X)$; the *BABAR* result [8] is $\mathrm{Im}(\mathsf{z})=(-13.9\pm7.3\pm3.2)\times10^{-3}$. Since $\Delta\Gamma$ is very small, dilepton events are only sensitive to the product $\mathrm{Re}(\mathsf{z})\Delta\Gamma$. Therefore, $\mathrm{Re}(\mathsf{z})$ has so far only been determined by analyzing the time dependence of the decays $\Upsilon(4S)\to B^0\bar{B}^0$ with one B meson decaying into $\ell\nu X$ and the other one into $c\bar{c}K$. With $88\times10^6 B\bar{B}$ events, *BABAR* measured $\mathrm{Re}(\mathsf{z})=(19\pm48\pm47)\times10^{-3}$ in 2004 [9], while Belle used $535\times10^6 B\bar{B}$ events to measure $\mathrm{Re}(\mathsf{z})=(19\pm37\pm33)\times10^{-3}$ in 2012 [10].

In our present analysis, we use the final data set of the *BABAR* experiment [11,12] with $470\times10^6 B\bar{B}$ events for a new determination of $\mathrm{Re}(\mathsf{z})$ and $\mathrm{Im}(\mathsf{z})$. As in Refs. [9,10], this is based on $c\bar{c}K$ decays with amplitudes A for $B^0\to c\bar{c}K^0$ and $\bar{A}$ for $\bar{B}^0\to c\bar{c}\bar{K}^0$, 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 $c\bar{c}K^0$;

[*] Present address: Wuhan University, Wuhan 43072, China.
[†] Present address: Università di Bologna and INFN Sezione di Bologna, I-47921 Rimini, Italy.
[‡] Present address: University of Huddersfield, Huddersfield HD1 3DH, United Kingdom.
[§] Present address: University of South Alabama, Mobile, Alabama 36688, USA.
[¶] Also at Università di Sassari, I-07100 Sassari, Italy.

(2) CP violation in K^0-$\bar{K}^0$ mixing is negligible, i.e., $K_S^0 = (K^0 + \bar{K}^0)/\sqrt{2}$, $K_L^0 = (K^0 - \bar{K}^0)/\sqrt{2}$.

The CPT-sensitive parameters are determined from the measured time dependences of the four decay rates $B^0, \bar{B}^0 \to c\bar{c}K_S^0, K_L^0$. In $\Upsilon(4S)$ decays, B^0 and $\bar{B}^0$ mesons are produced in the entangled state $(B^0\bar{B}^0 - \bar{B}^0 B^0)/\sqrt{2}$. 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 $B_2 \to f_2$ 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

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

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

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

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

$$R(B_j \to B_i) - R(\bar{B}_i \to B_j). \tag{7}$$

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

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

$i = 1\ldots8$, were fitted to the four time-dependent rates where the ℓX decay precedes the $c\bar{c}K$ decay, and to the four rates where the order of the decays is inverted. The rate ansatz in Eq. (8) requires $\Delta\Gamma = 0$. 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 $\Delta\tau$, equal to $t_{c\bar{c}K} - t_{\ell X}$ if the ℓX decay occurred first, and equal to $t_{\ell X} - t_{c\bar{c}K}$ with $c\bar{c}K$ as the first decay. After the 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 $\mathsf{z} = 0$, but no results for $\mathrm{Re}(\mathsf{z})$ and $\mathrm{Im}(\mathsf{z})$ 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_+ and B_-. We are therefore able to determine the decay parameter $|\bar{A}/A|$ in addition to the mixing parameters $\mathrm{Re}(\mathsf{z})$ and $\mathrm{Im}(\mathsf{z})$. 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 $\bar{A}$ have a single weak phase,

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

II. B-MESON DECAY RATES

The time-dependent rates of the decays $B^0, \bar{B}^0 \to c\bar{c}K$ 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 $A_f = A(B^0 \to f)$ and $\bar{A}_f = A(\bar{B}^0 \to f)$, using $\lambda_f = q\bar{A}_f/(pA_f)$ and approximating $\sqrt{1 - \mathsf{z}^2} = 1$, the rates are given by

$$\begin{aligned} R(B^0 \to f) &= \frac{|A_f|^2 \mathrm{e}^{-\Gamma t}}{4} |(1 - \mathsf{z} + \lambda_f)\mathrm{e}^{\mathrm{i}\Delta m t}\mathrm{e}^{\Delta\Gamma t/4} + (1 + \mathsf{z} - \lambda_f)\mathrm{e}^{-\Delta\Gamma t/4}|^2, \\ R(\bar{B}^0 \to f) &= \frac{|\bar{A}_f|^2 \mathrm{e}^{-\Gamma t}}{4} |(1 + \mathsf{z} + 1/\lambda_f)\mathrm{e}^{\mathrm{i}\Delta m t}\mathrm{e}^{\Delta\Gamma t/4} + (1 - \mathsf{z} - 1/\lambda_f)\mathrm{e}^{-\Delta\Gamma t/4}|^2. \end{aligned} \tag{9}$$

For the CP eigenstates $c\bar{c}K_L^0(CP = +1)$ and $c\bar{c}K_S^0(CP = -1)$ with $A_{S(L)} = A[B^0 \to c\bar{c}K_{S(L)}^0]$ and $\bar{A}_{S(L)} = A[\bar{B}^0 \to c\bar{c}K_{S(L)}^0]$, assumptions (1) and (2) give $A_S = A_L = A/\sqrt{2}$ and $\bar{A}_S = -\bar{A}_L = \bar{A}/\sqrt{2}$. 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

$$
\begin{aligned}
S_1 &= S(\ell^- X, c\bar{c}K_L)\\
&= \frac{2\mathrm{Im}(\lambda)}{1+|\lambda|^2} - \mathrm{Re}(\mathsf{z})\mathrm{Re}(\lambda)\mathrm{Im}(\lambda) + \mathrm{Im}(\mathsf{z})[\mathrm{Re}(\lambda)]^2,\\
C_1 &= +\frac{1-|\lambda|^2}{2} - \mathrm{Re}(\lambda)\mathrm{Re}(\mathsf{z}) - \mathrm{Im}(\lambda)\mathrm{Im}(\mathsf{z}),\\
S_2 &= S(\ell^+ X, c\bar{c}K_L)\\
&= -\frac{2\mathrm{Im}(\lambda)}{1+|\lambda|^2} - \mathrm{Re}(\mathsf{z})\mathrm{Re}(\lambda)\mathrm{Im}(\lambda) - \mathrm{Im}(\mathsf{z})[\mathrm{Re}(\lambda)]^2,\\
C_2 &= -\frac{1-|\lambda|^2}{2} + \mathrm{Re}(\lambda)\mathrm{Re}(\mathsf{z}) - \mathrm{Im}(\lambda)\mathrm{Im}(\mathsf{z}),\\
S_3 &= S(\ell^- X, c\bar{c}K_S)\\
&= -\frac{2\mathrm{Im}(\lambda)}{1+|\lambda|^2} - \mathrm{Re}(\mathsf{z})\mathrm{Re}(\lambda)\mathrm{Im}(\lambda) + \mathrm{Im}(\mathsf{z})[\mathrm{Re}(\lambda)]^2,\\
C_3 &= +\frac{1-|\lambda|^2}{2} + \mathrm{Re}(\lambda)\mathrm{Re}(\mathsf{z}) + \mathrm{Im}(\lambda)\mathrm{Im}(\mathsf{z}),\\
S_4 &= S(\ell^+ X, c\bar{c}K_S)\\
&= \frac{2\mathrm{Im}(\lambda)}{1+|\lambda|^2} - \mathrm{Re}(\mathsf{z})\mathrm{Re}(\lambda)\mathrm{Im}(\lambda) - \mathrm{Im}(\mathsf{z})[\mathrm{Re}(\lambda)]^2,\\
C_4 &= -\frac{1-|\lambda|^2}{2} - \mathrm{Re}(\lambda)\mathrm{Re}(\mathsf{z}) + \mathrm{Im}(\lambda)\mathrm{Im}(\mathsf{z}).
\end{aligned} \tag{10}
$$

The four other rates $R_5(t)\cdots R_8(t)$ with $c\bar{c}K$ as the first decay and $t_{\ell X} - t_{c\bar{c}K} = t$ follow from the same two-decay-time expression [16,17] as the rates $R_1 \ldots R_4$ with $t_{c\bar{c}K} - t_{\ell X} = t$. Therefore, the rates $R_5(c\bar{c}K_L, \ell^- X)$, $R_6(c\bar{c}K_L, \ell^+ X)$, $R_7(c\bar{c}K_S, \ell^- X)$, and $R_8(c\bar{c}K_S, \ell^+ X)$ are given by Eq. (8) with the coefficients

$$
S_i = -S_{i-4}, C_i = +C_{i-4} \quad \text{for } i = 5, 6, 7, \text{ and } 8. \tag{11}
$$

The S_i and C_i results from our 2012 analysis, including uncertainties and correlation matrices, have been published as Supplemental Material [18] of Ref. [6] in Tables II–IV. For completeness, we include in Table I the results and the uncertainties.

TABLE I. Input values from the Supplemental Material [18] of Ref. [6]. The second column gives the two decays with their sequence in decay time.

i	decay pairs	S_i	σ_{stat}	σ_{sys}	C_i	σ_{stat}	σ_{sys}
1	$\ell^- X, c\bar{c}K_L$	0.51	0.17	0.11	−0.01	0.13	0.08
2	$\ell^+ X, c\bar{c}K_L$	−0.69	0.11	0.04	−0.02	0.11	0.08
3	$\ell^- X, c\bar{c}K_S$	−0.76	0.06	0.04	0.08	0.06	0.06
4	$\ell^+ X, c\bar{c}K_S$	0.55	0.09	0.06	0.01	0.07	0.05
5	$c\bar{c}K_L, \ell^- X$	−0.83	0.11	0.06	0.11	0.12	0.08
6	$c\bar{c}K_L, \ell^+ X$	0.70	0.19	0.12	0.16	0.13	0.06
7	$c\bar{c}K_S, \ell^- X$	0.67	0.10	0.08	0.03	0.07	0.04
8	$c\bar{c}K_S, \ell^+ X$	−0.66	0.06	0.04	−0.05	0.06	0.03

III. FIT RESULTS

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

$$
y = M_1 p, \tag{12}
$$

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

$$
\chi^2 = (M_1 p - \hat{y})^T G (M_1 p - \hat{y}), \tag{13}
$$

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

$$
G = [C_{\text{stat}}(y) + C_{\text{sys}}(y)]^{-1}, \tag{14}
$$

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

$$
\hat{p} = \mathcal{M}_1 \hat{y} \quad \text{with} \quad \mathcal{M}_1 = (M_1^T G M_1)^{-1} M_1^T G, \tag{15}
$$

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

$$
\begin{aligned}
C_{\text{stat}}(p) &= \mathcal{M}_1 C_{\text{stat}}(y) \mathcal{M}_1^T,\\
C_{\text{sys}}(p) &= \mathcal{M}_1 C_{\text{sys}}(y) \mathcal{M}_1^T,
\end{aligned} \tag{16}
$$

with the property

$$
C_{\text{stat}}(p) + C_{\text{sys}}(p) = (M_1^T G M_1)^{-1}. \tag{17}
$$

This first-step fit yields

$$
\begin{aligned}
p_1 &= 0.001 \pm 0.023 \pm 0.017,\\
p_2 &= 0.689 \pm 0.030 \pm 0.015.
\end{aligned} \tag{18}
$$

This leads to

$$
\begin{aligned}
|\lambda| &= 1 - p_1 = 0.999 \pm 0.023 \pm 0.017,\\
\mathrm{Im}(\lambda) &= (1-p_1)p_2 = 0.689 \pm 0.034 \pm 0.019,\\
\mathrm{Re}(\lambda) &= -(1-p_1)\sqrt{1-p_2^2}\\
&= -0.723 \pm 0.043 \pm 0.028,
\end{aligned} \tag{19}
$$

where the negative sign of $\mathrm{Re}(\lambda)$ is motivated by four measurements [19–22]. The results of all four favor $\cos 2\beta > 0$, and in Ref. [22] $\cos 2\beta < 0$ is excluded with 4.5σ significance.

In the second step, we fix the two λ values according to the p_1 and p_2 results of the first step, i.e. to the central values in Eqs. (19). Equations (12) to (17) are then applied again, replacing M_1 with the new relations matrix M_2. This gives the same results for p_1 and p_2 as in Eq. (18), and

$$p_3 = \mathrm{Im}(\mathsf{z}) = 0.010 \pm 0.030 \pm 0.013,$$
$$p_4 = \mathrm{Re}(\mathsf{z}) = -0.065 \pm 0.028 \pm 0.014, \qquad (20)$$

with a χ^2 value of 6.9 for 12 degrees of freedom.

The $\mathrm{Re}(\mathsf{z})$ result deviates from 0 by 2.1σ. The result for $|\lambda|$ can be easily converted into $|\bar{A}/A|$ by using the world average of measurements for $|q/p|$. With $|q/p| = 1.0008 \pm 0.0008$ [7], we obtain

$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017, \qquad (21)$$

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 $C_{\mathrm{stat}}(p) + C_{\mathrm{sys}}(p) = (M^T G M)^{-1}$, where M relates y and p after convergence of the fit. The statistical correlation coefficients are $\rho[|\bar{A}/A|, \mathrm{Im}(\mathsf{z})] = 0.03$, $\rho[|\bar{A}/A|, \mathrm{Re}(\mathsf{z})] = 0.44$, and $\rho[\mathrm{Re}(\mathsf{z}), \mathrm{Im}(\mathsf{z})] = 0.03$. The systematic correlation coefficients are $\rho[|\bar{A}/A|, \mathrm{Im}(\mathsf{z})] = 0.03$, $\rho[|\bar{A}/A|, \mathrm{Re}(\mathsf{z})] = 0.48$, and $\rho[\mathrm{Re}(\mathsf{z}), \mathrm{Im}(\mathsf{z})] = -0.15$.

IV. ESTIMATING THE INFLUENCE OF $\Delta\Gamma$

Using an accept/reject algorithm, we have performed two "toy simulations," each with $\sim 2 \times 10^6$ events, i.e. t values sampled from the distributions

$$e^{-\Gamma t}[1 + \mathrm{Re}(\lambda)\sinh(\Delta\Gamma t/2) + \mathrm{Im}(\lambda)\sin(\Delta m t)], \qquad (22)$$

with $\Delta\Gamma = 0$ for one simulation and $\Delta\Gamma = 0.01\Gamma$ for the other one, corresponding to one standard deviation from the present world average [7]. For both simulations we use $\mathrm{Im}(\lambda) = 0.67$ and $\mathrm{Re}(\lambda) = -0.74$ and sample t values between 0 and $+5/\Gamma$. We then fit the two samples, binned in intervals of $\Delta t = 0.25/\Gamma$, to the expressions

$$N e^{-\Gamma t}[1 + C\cos(\Delta m t) + S\sin(\Delta m t)], \qquad (23)$$

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 $470 \times 10^6 B\bar{B}$ events from *BABAR*, we determine

$$\mathrm{Im}(\mathsf{z}) = 0.010 \pm 0.030 \pm 0.013,$$
$$\mathrm{Re}(\mathsf{z}) = -0.065 \pm 0.028 \pm 0.014,$$
$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017,$$

where the first uncertainties are statistical and the second uncertainties are systematic. All three results are compatible with CPT symmetry in B^0-$\bar{B}^0$ mixing and in $B \to c\bar{c}K$ decays. The uncertainties on $\mathrm{Re}(\mathsf{z})$ are comparable with those obtained by Belle in 2012 [10] with $535 \times 10^6 B\bar{B}$ events, $\mathrm{Re}(\mathsf{z}) = -0.019 \pm 0.037 \pm 0.033$. The uncertainties on $\mathrm{Im}(\mathsf{z})$ are considerably larger, as expected, than those obtained by *BABAR* in 2006 [8] with dilepton decays from $232 \times 10^6 B\bar{B}$ events, $\mathrm{Im}(\mathsf{z}) = -0.014 \pm 0.007 \pm 0.003$. The result of the present analysis for $\mathrm{Re}(\mathsf{z})$, $-0.065 \pm 0.028 \pm 0.014$, supersedes the *BABAR* result of 2004 [9].

ACKNOWLEDGMENTS

We thank H.-J. Gerber (ETH Zurich) and T. Ruf (CERN) for very useful discussions on T and CPT symmetry. We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (Netherlands), NFR (Norway), MES (Russia), MINECO (Spain), STFC (United Kingdom), and BSF (USA-Israel). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation (USA).

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
[2] K. R. Schubert, B. Wolff, J. C. Chollet, J.-M. Gaillard, M. R. Jane, T. J. Ratcliffe, and J.-P. Repellin, Phys. Lett. B **31**, 662 (1970).
[3] J. S. Bell and J. Steinberger, *Proc. Int. Conf. Elem. Part., Oxford 1965* (Rutherford Lab, Appleton, 1966), p. 195.
[4] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **87**, 091801 (2001).
[5] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001).
[6] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **109**, 211801 (2012).
[7] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014) and 2015 update.
[8] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **96**, 251802 (2006).
[9] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **70**, 012007 (2004), inserting $\mathrm{Re}(\lambda) = -0.73$.
[10] T. Higuchi *et al.* (Belle Collaboration), Phys. Rev. D **85**, 071105 (2012).
[11] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).
[12] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **729**, 615 (2013).
[13] In addition to prompt charged leptons from inclusive semileptonic decays $\ell^{\pm}\nu X$, Ref. [6] used charged kaons, charged pions from D^* decays and high-momentum charged particles in the flavor-specific samples $\ell^{\pm}X$.
[14] C. P. Enz and R. R. Lewis, Helv. Phys. Acta **38**, 860 (1965).
[15] T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. **106**, 340 (1957).
[16] T. B. Day, Phys. Rev. **121**, 1204 (1961).
[17] H. Lipkin, Phys. Rev. **176**, 1715 (1968).
[18] J. P. Lees *et al.* (*BABAR* Collaboration), see Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.109.211801.
[19] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **71**, 032005 (2005).
[20] R. Itoh *et al.* (Belle Collaboration), Phys. Rev. Lett. **95**, 091601 (2005).
[21] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 231802 (2007).
[22] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 161802 (2007).