UNIVERSITY OF Cincinnati

Tests of CPT Symmetry in $B^0\bar{B}^0$ Mixing and $B^0 \rightarrow c\bar{c}K^0$ Decays

Michael D. Sokoloff
University of Cincinnati
on behalf of the BaBar Collaboration

Using 8 measurements for the time dependences of the decays $\Upsilon(4S) \rightarrow B^0\overline{B}^0 \rightarrow f_j f_k$ with the decay into a flavor-specific state $f_j = \ell^{\pm}X$ before or after the decay into a CP eigenstate $f_k = c\bar{c}K_{S,L}$, we determine three CPT – sensitive parameters and find them consistent with CPT symmetry.

Is the assumption of CPT-symmetry valid?

The theory of time-dependent oscillations in the neutral kaon system began with an assertion by Gell-Mann and Pais in 1955 [1]: "**It is generally accepted that the microscopic laws of physics are invariant to the operation of charge conjugation (CC); we shall take the rigorous validity of this postulate for granted**."
At that time, the discovery that weak interactions violate CC symmetry almost maximally was two years in the future.

Nonetheless, the essential insights from their seminal paper hold true: that **neutral kaons are produced in strong interactions in two "opposite" flavors**, as particle and antiparticle; that **the eigenstates of the strong interaction** in which flavor is **produced and the eigenstates of the weak interaction** by which neutral kaons decay **differ**; that the weak eigenstates are (approximately) equal admixtures of flavor eigenstates; that **the lifetimes of the weak neutral eigenstates** could **differ substantially**, and that the **"mass difference is surely tiny."** Their prediction that a longer-lived neutral kaon would be observed to decay into three pions was confirmed by Lande, Lederman and Chinowsky [2] in 1957.

[1] M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387-1389, (1955).
[2] K. Lande, L. M. Lederman, and W. Chinowsky, Phys. Rev. 105, 1925-1927, (1957).

Some Relevant History

1953 - 57 Dalitz, Lee and Yang, Wu et al, Lederman et al:

P symmetry is broken in K^+ and in ^{60}Co decays and in the decay chain $\pi^+ \to \mu^+ \to e^+$

1964 Christenson, Cronin, Fitch and Turlay:

CP symmetry is broken in $K^0 \to \pi^+ \pi^-$ decays at late decay times

1966 - 69 Gourdin, Casella, Okun, Kabir, Wolfenstein ...

Is CPT symmetry valid in Lorentz-invariant QFT, but broken in Nature?

1970 Schubert et al (PLB 31, 662) using Bell-Steinberger unitarity:

$K^0 \bar{K}^0$ mixing is CPT-symmetric ($\delta = 0$) and breaks T symmetry (Re $\varepsilon \neq 0$ with ~5 σ)

2013 Most recent update of Bell-Steinberger unitarity in $K^0 \bar{K}^0$ mixing by the PDG:

Re ε = (161.1 ± 0.5) 10^{-5}, Im δ = (-0.7 ± 1.4) 10^{-5}, Re δ = (0.2 ± 0.2) 10^{-3}

How much can we learn from the 10 times heavier B mesons?

$M^0\bar{M}^0$ Mixing

$$|\Psi\rangle = \psi_1 |M^0\rangle + \psi_2 |\bar{M}^0\rangle, \quad i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \left[\begin{pmatrix} m_{11} & m_{12} \\ m_{12}^* & m_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

This simplest evolution equation for a two-state system (simple = linear = weak)

has 7 real parameters: m_{11}, m_{22}, Γ_{11}, Γ_{22}, $|m_{12}|$, $|\Gamma_{12}|$, and $\Phi(\Gamma_{12}/m_{12})$.

Two solutions have exponential decay laws, they contain **7 real observables**

$$M^0_\alpha(t) = \left[(1+\varepsilon+\delta)\cdot M^0 + (1-\varepsilon-\delta)\cdot \bar{M}^0\right]\cdot e^{-\Gamma_\alpha t/2 - i m_\alpha t} / \sqrt{2}$$

$$M^0_\beta(t) = \left[(1+\varepsilon-\delta)\cdot M^0 - (1-\varepsilon+\delta)\cdot \bar{M}^0\right]\cdot e^{-\Gamma_\beta t/2 - i m_\beta t} / \sqrt{2}$$

m_α, m_β, Γ_α, Γ_β,

Re ε, Re δ, Im δ.

unambiguously related to the 7 parameters of the evolution:

$$\mathrm{Re}\,\varepsilon \approx \frac{\mathrm{Im}(\Gamma_{12}/m_{12})}{4+|\Gamma_{12}/m_{12}|^2}, \quad \delta = \frac{(m_{22}-m_{11}) - \mathrm{i}(\Gamma_{22}-\Gamma_{11})/2}{2(m_\alpha - m_\beta) - \mathrm{i}(\Gamma_\alpha - \Gamma_\beta)}.$$

T symmetry ➔ Re $\varepsilon = 0$,

CPT ➔ $\delta = 0$, CP ➔ Re $\varepsilon = \delta = 0$.

Sign of δ for $M^0 = K^0$:

α = heavy = long-living,

β = light = short-living.

for $M^0 = B^0$:

α = heavy, β = light.

BABAR, Belle: $z = -2\delta$

Notations for $B^0\bar{B}^0$ Mixing

$$|\Psi\rangle = \psi_1 |B^0\rangle + \psi_2 |\bar{B}^0\rangle, \quad i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1 \\ \psi_2\end{pmatrix} = \left[\begin{pmatrix} m_{11} & m_{12} \\ m_{12}^* & m_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}\psi_1 \\ \psi_2\end{pmatrix}$$

$$B_H^0(t) = N_H\left[p\sqrt{1+z}\cdot B^0 - q\sqrt{1-z}\cdot \bar{B}^0\right]\cdot \mathrm{e}^{-\Gamma_H t/2 - \mathrm{i}m_H t}, \qquad |q/p| = 1 - 2\,\mathrm{Re}(\varepsilon),$$

$$B_L^0(t) = N_L\left[p\sqrt{1-z}\cdot B^0 + q\sqrt{1+z}\cdot \bar{B}^0\right]\cdot \mathrm{e}^{-\Gamma_L t/2 - \mathrm{i}m_L t}, \qquad z = -2\delta.$$ up to z^2

$N_H = N_L = 1/\sqrt{2}$ in lowest order of z and r = 1 - |q/p|, neglecting r^2, z^2, r z ...

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

$$\Delta m = m_H - m_L, \quad \Delta\Gamma = \Gamma_H - \Gamma_L.$$

Symmetries in $B^0 \bar{B}^0$ Mixing (1)

Testing T symmetry means measuring |q/p|,

Testing CPT symmetry means measuring z,

Testing CP symmetry means measuring |q/p| **and** z.

Present PDG average for |q/p|: 1 + (0.8 ± 0.8) 10^{-3}, **no T violation seen.**

Present average for Im(z): (- 8 ± 4) 10^{-3},

Present average for Re(z): (19 ± 40) 10^{-3}, **no CPT violation seen.**

With $\Delta m = m_H - m_L$

and $\Delta\Gamma = \Gamma_H - \Gamma_L$

and $|\Delta\Gamma| \ll \Gamma$:

$$
\begin{aligned}
P(B^0 \to B^0) &= \frac{1}{2} e^{-\Gamma t} [1 + \cos(\Delta m\, t) - \mathrm{Re(z)} \Delta\Gamma t + 2\, \mathrm{Im(z)} \sin(\Delta m\, t)], \\
P(\overline{B}^0 \to \overline{B}^0) &= \frac{1}{2} e^{-\Gamma t} [1 + \cos(\Delta m\, t) + \mathrm{Re(z)} \Delta\Gamma t - 2\, \mathrm{Im(z)} \sin(\Delta m\, t)], \\
P(B^0 \to \overline{B}^0) &= \frac{1}{2} e^{-\Gamma t} [1 - \cos(\Delta m\, t)] \cdot \left|\frac{q}{p}\right|^2, \\
P(\overline{B}^0 \to B^0) &= \frac{1}{2} e^{-\Gamma t} [1 - \cos(\Delta m\, t)] \cdot \left|\frac{p}{q}\right|^2.
\end{aligned}
$$

Symmetries in $B^0 \bar{B}^0$ Mixing (2)

All present z measurements have been performed by BABAR and Belle

Method: $e^+ e^- \to \Upsilon(4S) \to$ **$(B^0 \bar{B}^0 - \bar{B}^0 B^0)$**$/\sqrt{2} \to f_1(t_1)\, f_2(t_2 \geq t_1)$ with **$t = t_2 - t_1$**

At t = 0, the surviving state B_2 is defined by f_1 and evolves as $B_2(t)$.

With $f_1 = \ell^+ X$ ($\ell^- X$), $B_1 = B^0$ ($\bar{B}^0$) and $B_2(t=0) = \bar{B}^0$ (B^0).

Control: At t=0, there are only decay pairs $\ell^+\ell^-$, no pairs $\ell^+\ell^+$ and $\ell^-\ell^-$.

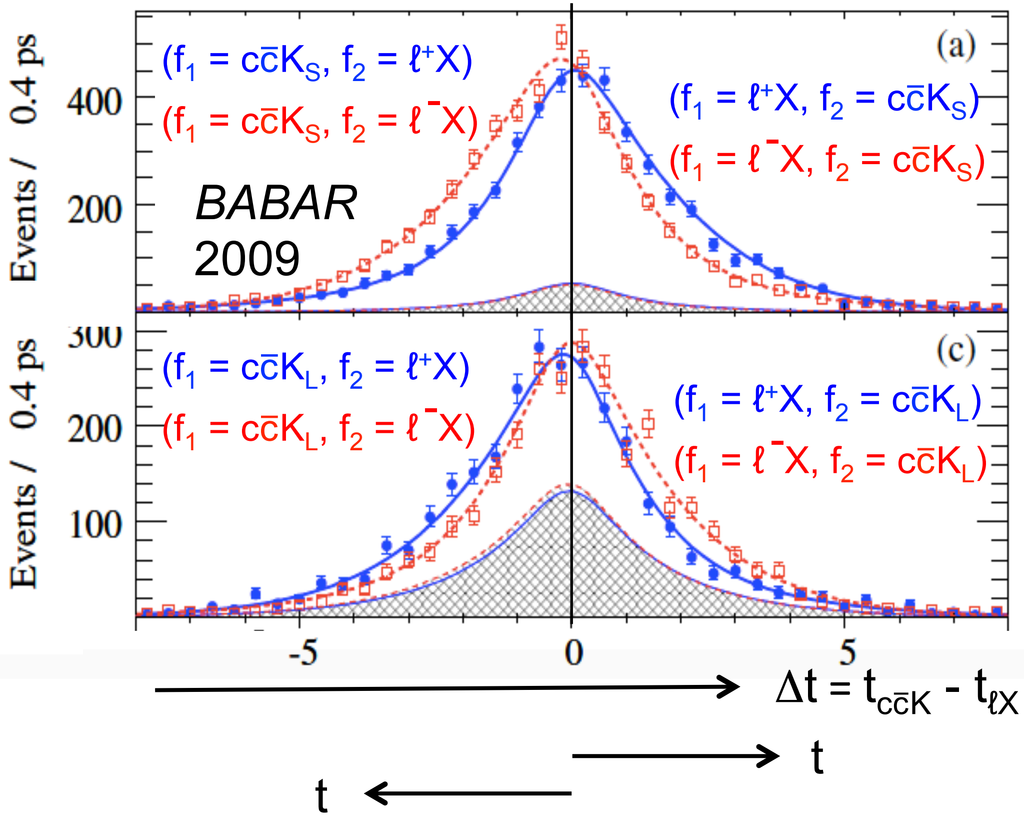
$\ell^+\ell^+$ and $\ell^-\ell^-$ evolve with t > 0. Rate difference ➔ $P(\bar{B}^0 \to B^0) - P(B^0 \to \bar{B}^0)$ ➔ **|q/p|.**

$\ell^+\ell^-$ and $\ell^-\ell^+$ ($f_1 = \ell^+ X$, $f_2 = \ell^- X$) and ($f_1 = \ell^- X$, $f_2 = \ell^+ X$) ➔ $P(\bar{B}^0 \to \bar{B}^0) - P(B^0 \to B^0)$ ➔ **z**.

$$
\begin{aligned}
P(B^0 \to B^0) &= \frac{1}{2} e^{-\Gamma t} [1 + \cos(\Delta m\, t) - \mathrm{Re(z)} \Delta\Gamma t + 2\, \mathrm{Im(z)} \sin(\Delta m\, t)], \\
P(\overline{B}^0 \to \overline{B}^0) &= \frac{1}{2} e^{-\Gamma t} [1 + \cos(\Delta m\, t) + \mathrm{Re(z)} \Delta\Gamma t - 2\, \mathrm{Im(z)} \sin(\Delta m\, t)], \\
P(B^0 \to \overline{B}^0) &= \frac{1}{2} e^{-\Gamma t} [1 - \cos(\Delta m\, t)] \cdot \left|\frac{q}{p}\right|^2, \\
P(\overline{B}^0 \to B^0) &= \frac{1}{2} e^{-\Gamma t} [1 - \cos(\Delta m\, t)] \cdot \left|\frac{p}{q}\right|^2.
\end{aligned}
$$

Since $\Delta\Gamma$ is unknown, the t dependence of $\ell^+\ell^-$ and $\ell^-\ell^+$ pairs determines only Im(z) and not Re(z).

$B^0 \to c\,\bar{c}\,K^0$ Decays for the Determination of Re(z)



With $c\bar{c}\,K^0 = J/\psi\,K^0_S$, $\psi(2S)\,K^0_S$, $\chi_{c1}\,K^0_S$ (CP = -1), $J/\psi\,K^0_L$(CP = +1) and 470 M $B\bar{B}$ events, BABAR in **PRD 79,072009 (2009)** measured these 8 t-dependent rates, but fitted only CP-violating differences of them.

In **PRL 109, 211801 (2012)**, separate rates **$N_i\,[1 + C_i\cos(\Delta mt) + S_i\sin(\Delta mt)]$** were fitted, and the 8 C_i and 8 S_i were used to demonstrate T violation in $B^0 \to c\,\bar{c}\,K^0$ decays.

In the same analysis, they were also used for a qualitative test of CPT symmetry i $B^0\,\bar{B}^0$ mixing. The result was compatible with z = 0, but no value for z was given.

The present analysis of 2012 data determines z, using the C_i and S_i results of BABAR 2012.

Symmetries in the Interplay of $B^0\bar{B}^0$ Mixing and $B^0 \to c\bar{c}K^0$ Decays

Introducing $A = \langle c\bar{c}\,K^o | D | B^o \rangle$, $\bar{A} = \langle c\bar{c}\,\bar{K}^o | D | \bar{B}^o \rangle$ and assuming that

(1) A and $\bar{A}$ have a single weak phase,

(2) $\langle c\bar{c}\,\bar{K}^o | D | B^o \rangle = \langle c\bar{c}\,K^o | D | \bar{B}^o \rangle = 0$, $\Delta S = \Delta B$ rule,

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

CP, T, CPT symmetries are completely described by 5 parameters:

|q/p|, Re(z), Im(z), |Ā/A| and **Im(qĀ/pA).**

T symmetry requires **Im(qĀ/pA) = 0** [Enz Lewis, Helv.Phys.Acta 38, 860 (1965)]

and **|q/p| = 1.**

CPT symmetry requires **|Ā/A| = 1** [Lee Oehme Yang, PR 106, 340 (1957)]

and **Re(z) = Im(z) = 0**.

CP symmetry requires all 5 conditions.

Time-dependent Decay Rates (1)

$$A_S = \langle c\bar{c}K_S|D|B^o\rangle, \bar{A}_S = \langle c\bar{c}K_S|D|\bar{B}^o\rangle, \quad A_L = \langle c\bar{c}K_L|D|B^o\rangle, \bar{A}_L = \langle c\bar{c}K_L|D|\bar{B}^o\rangle$$

With assumptions (2) and (3), **$A_S = A_L = A/\sqrt{2}$** and **$\bar{A}_S = -\bar{A}_L = \bar{A}/\sqrt{2}$** , and using

$\lambda_{S(L)} = \dfrac{q\bar{A}_{S(L)}}{pA_{S(L)}}$ we have **$\lambda_S = -\lambda_L = \lambda$**. Approximating $\sqrt{1-z^2} = 1$, rates are given by

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

$$R(\bar{B}^0 \to f) = \frac{|\bar{A}_f|^2 e^{-\Gamma t}}{4}\left|(1 + z + 1/\lambda_f)\, e^{i\Delta m t}\, e^{\Delta\Gamma t/4} + (1 - z - 1/\lambda_f)\, e^{-\Delta\Gamma t/4}\right|^2.$$

For **$f = c\bar{c}K_S$** we have **$\lambda_f = \lambda$**, for **$c\bar{c}K_L$** we have **$\lambda_f = -\lambda$**.

Setting $\Delta\Gamma = 0$ and keeping only first-order terms in the small quantities

$|\lambda| - 1$, z and $|q/p| - 1$, this leads to expressions

$R_i(t) = N_i\,[1 + C_i\cos(\Delta m t) + S_i\sin(\Delta m t)]$ with coefficients S_i and C_i (next page).

In $\Upsilon(4S)$ decays, the 4 rates for $B^0, \bar{B}^0 \to c\bar{c}K_S, K_L$ are measured as **$R_i(f_1,f_2)$** with **$f_1 = \ell^- X, \ell^+ X$** as the first decay and **$f_2 = c\bar{c}K_S, K_L$** as the second decay.

Time-dependent Decay Rates (2)

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

The two-decay-time formula for the two decays from $B^0\bar{B}^0$ pairs in Υ(4S) decays (a consequence of entanglement) relates the 4 rates with $c\bar{c}K$ first and ℓX second,

$R_5(c\bar{c}K_L, \ell^- X)$, $R_6(c\bar{c}K_L, \ell^+ X)$, $R_7(c\bar{c}K_S, \ell^- X)$ and $R_8(c\bar{c}K_S, \ell^+ X)$ to the first four by the exchange $t_2 - t_1 = t \rightarrow t_1 - t_2 = -t$, resulting in $\mathbf{C_i = C_{i-4}}$, $\mathbf{S_i = -S_{i-4}}$ for i = 5 ... 8.

Time-dependent Decay Rates (2)

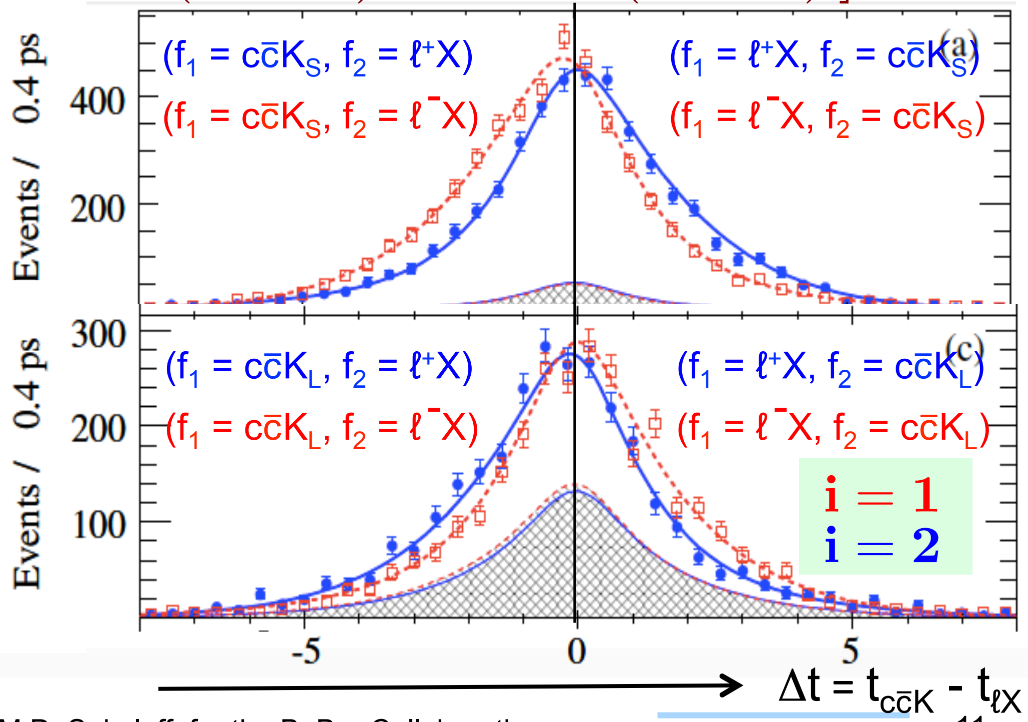
$$S_1 = S(\ell^- X, c\bar{c}K_L) = \frac{2\,\mathrm{Im}\,(\lambda)}{1+|\lambda|^2} - \mathrm{Re}\,(\mathbf{z})\mathrm{Re}\,(\lambda)\mathrm{Im}\,(\lambda) + \mathrm{Im}\,(\mathbf{z})[\mathrm{Re}\,(\lambda)]^2 \; ,$$

$$C_1 = +\frac{1-|\lambda|^2}{2} - \mathrm{Re}\,(\lambda)\,\mathrm{Re}\,(\mathbf{z}) - \mathrm{Im}\,(\lambda)\,\mathrm{Im}\,(\mathbf{z})\, ,$$

$$S_2 = S(\ell^+ X, c\bar{c}K_L) = -\frac{2\,\mathrm{Im}\,(\lambda)}{1+|\lambda|^2} - \mathrm{Re}\,(\mathbf{z})\mathrm{Re}\,(\lambda)\mathrm{Im}\,(\lambda) - \mathrm{Im}\,(\mathbf{z})[\mathrm{Re}\,(\lambda)]^2 \; ,$$

$$C_2 = -\frac{1-|\lambda|^2}{2} + \mathrm{Re}\,(\lambda)\,\mathrm{Re}\,(\mathbf{z}) - \mathrm{Im}\,(\lambda)\,\mathrm{Im}\,(\mathbf{z})\, ,$$

$$\mathbf{R_i(t) = N_i\,[1 + C_i\,\cos(\Delta m\,t) + S_i\,\sin(\Delta m\,t)\,]}$$



Determination of CPT Parameters (Fit Input and Fit Procedure)

Here the S_i and C_i results in BABAR-2012 from the 8 rates

$N_i\,[1 + C_i \cos(\Delta m t) + S_i \sin(\Delta m t)]$

In the present analysis we use them and their published correlaions for determining **Re(z), Im(z) and $|\bar{A}/A|$ in a χ^2 fit.**

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

The relations between the 16 observables $y_i = S_1 \ldots C_8$ and the 4 parameters **$p_1 = (1 - |\lambda|^2)/2$, $p_2 = 2\,\mathrm{Im}(\lambda)/(1 + |\lambda|^2)$, $p_3 = \mathrm{Im}(z)$** and **$p_4 = \mathrm{Re}(z)$** are approximately Linear, y = M p. This allows a multi-step χ^2 fit with matrix algebra using Mathematica. The fit converges already in the second step ➔

Determination of CPT Symmetry Parameters (Fit Output)

The fit has a χ^2 value of 6.9 for 12 d.o.f. and results in

$$|\lambda| = 0.999 \pm 0.023 \pm 0.017,$$

$$\mathrm{Im}(\lambda) = 0.689 \pm 0.034 \pm 0.019, \quad \mathrm{Re}(\lambda) = -0.723 \pm 0.043 \pm 0.028,$$

$$\mathrm{Im}(z) = 0.010 \pm 0.030 \pm 0.013, \quad \mathrm{Re}(z) = -0.065 \pm 0.028 \pm 0.014,$$

Re(z) deviates from zero by 2.1 σ. The result for $|\lambda| = |q/p| \cdot |\bar{A}/A|$ gives

$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017.$$

by using the PDG average $|q/p| = 1.0008 \pm 0.0008$. The results for $|\lambda|$ and Im(λ) leave the sign of Re(λ) undetermined. Re(λ) < 0 is chosen since 4 measurements of BABAR and Belle determine $\cos 2\beta > 0$.

The matrix-algebra fit allows to determine statistical and systematic uncertainties of the fit parameters separately. The stat. and sys. correlation coefficients between Re(z) and Im(z) are 0.03 and -0.15, between $|\bar{A}/A|$ and Re(z) 0.44 and 0.48, between $|\bar{A}/A|$ and Im(z) 0.03 and 0.03.

Given the present PDG average for $\Delta\Gamma$, $(0.1 \pm 1.0)\,10^{-2}$, **Setting $\Delta\Gamma = 0$ has a negligible influence on the results of this analysis**.

Summary

Using 470 M $B\bar{B}$ events from BABAR, i.e. our final data sample, and starting from the measured time dependences of decays $B^0, \bar{B}^0 \rightarrow c\bar{c}K^0_{S,L}$, we determine

$$\mathrm{Im}(z) = 0.010 \pm 0.030 \pm 0.013,$$

$$\mathrm{Re}(z) = -0.065 \pm 0.028 \pm 0.014,$$

$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017,$$

in agreement with CPT symmetry in $B^0\bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays.

Published as **PRD 94, 011101(R) (2016)**.

The result for Im(z) is not competitive with that from di-lepton decays.

For Re(z), it replaces an older BABAR result from 88 M $B\bar{B}$ events, and it has uncertainties comparable with **Belle** from 535 M $B\bar{B}$ events, **$-0.019 \pm 0.037 \pm 0.033$**.

To our knowledge, the $|\bar{A}/A|$ result is the first one obtained without requiring $z = 0$.

Back-up Material Follows

Estimating the Influence of $\Delta\Gamma$

The present PDG average for $\Delta\Gamma$ is $(0.1\pm 1.0)\,10^{-2}$.

The S_i and C_i values in BABAR-2012, and consequently the final results here, have been obtained with $\Delta\Gamma = \Gamma_H - \Gamma_L = 0$. The influence of this approximation has been studied with a Monte-Carlo simulation.

Using "accept/reject", we generate "events", i.e. Δt values from two distributions,

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

in $[-5/\Gamma, 5/\Gamma]$, one with $\Delta\Gamma = 0$ and one with $\Delta\Gamma = 0.01\,\Gamma$, each with 2 M Δt values, setting $\mathrm{Re}(\lambda) = -0.74$, $\mathrm{Im}(\lambda) = 0.67$. We fit the two samples, binned in intervals of $0.25/\Gamma$, to the expressions

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

with free N, C, S. The fit results agree between the two samples within 0.002 for C and 0.008 for S, less than 1/10 of the systematic errors.

Setting $\Delta\Gamma = 0$ has a negligible influence on the results of this analysis.