Recent results on CP and CPT violation with the BaBar detector

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On behalf on the BaBar Collaboration
European Spallation Source  ESS
and Lund University

Physics of fundamental Symmetries and Interactions PSI 2016
In the 1950’s, it was discovered that the weak interaction violates each one of: time-reversal ("T"), charge ("C"), and parity ("P") fundamental symmetries of Nature.

In 1964 it was discovered that the weak interaction also violated CP in the decay of neutral kaons.

CP symmetry violation is one of the 3 necessary conditions (the “Sakharov conditions”) for matter-antimatter asymmetry of the Universe to develop.

These effects are incorporated in the Standard Model but nobody knows why these symmetry violations occur, nor why they only occur in the weak interaction...

BaBar @ SLAC and Belle @ KEK were constructed to investigate these asymmetries primarily in B and D mesons system.
Even if the weak interaction violated \( C, P, T \) and \( CP \) is believed that \( CPT \) is conserved.

\( CPT \) Invariance is required by every relativistic quantum field theory.

\( CPT \) Theorem states:
- all interactions are invariant under the successive operation of \( C \) (=charge conjugation), \( P \) (=parity operation), and \( T \) (=time reversal).

\[ \Rightarrow \text{Masses, lifetimes, moments, etc. of particles and antiparticles must be identical} \]
A test of CPT symmetry in $\bar{B}^0-B^0$ mixing and in $B^0\rightarrow\bar{c}cK^0$ decays

Measurement of the Unitarity Triangle parameter $\sin(2\beta)$ in $B^0\rightarrow D^0h^0$ decays

First combined BaBar+Belle analysis
The BaBar and Belle detectors

Instrumented Flux Return
Solenoid (1.5T)

Cherenkov Detector
Electromagnetic Calorimeter
Silicon Vertex Tracker
Drift Chamber

[BaBar] [Belle]

<table>
<thead>
<tr>
<th></th>
<th>BELLE</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(5S)</td>
<td>121 fb⁻¹</td>
<td>433 fb⁻¹</td>
</tr>
<tr>
<td>Y(4S)</td>
<td>711 fb⁻¹</td>
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<tr>
<td>Y(3S)</td>
<td>3.0 fb⁻¹</td>
<td>30 fb⁻¹</td>
</tr>
<tr>
<td>Y(2S)</td>
<td>24 fb⁻¹</td>
<td>14 fb⁻¹</td>
</tr>
<tr>
<td>Y(1S)</td>
<td>5.7 fb⁻¹</td>
<td></td>
</tr>
<tr>
<td>Off-resonance</td>
<td>87 fb⁻¹</td>
<td>54 fb⁻¹</td>
</tr>
<tr>
<td>Scan</td>
<td>68 fb⁻¹</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1020 fb⁻¹</td>
<td>531 fb⁻¹</td>
</tr>
</tbody>
</table>

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A test of CPT symmetry in $B^0$-$\bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays

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The discovery of CP violation in 1964 motivated searches for T and CPT violation. Since CPT = CP×T.

Violation of CP means that T or CPT or both are also violated.

Large CP violation in the B⁰ system was discovered in 2001 in the interplay of B⁰ - B̄⁰ mixing and B⁰ → c̅cK⁰ decays.

T violation was discovered only recently.  

In this present analysis, we test CPT symmetry quantitatively in B⁰ - B̄⁰ mixing and in B⁰ → c̅cK⁰ decays.
Transitions in the $B^0 - \bar{B}^0$ system are well described by the quantum-mechanical evolution of a two-state wave function

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

using the Schrödinger equation

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

where the Hamiltonian 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, $|q/p|$, $\text{Re}(z)$, and $\text{Im}(z)$

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

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

$\Delta m$ and $\Delta \Gamma$ are the mass and the width differences of the two mass eigenstates
Previous Measurements

\[ |\frac{q}{p}| = 1 - \frac{2\text{Im}(m_{12}^* \Gamma_{12})}{4|m_{12}|^2 + |\Gamma_{12}|^2}, \]
\[ z = \frac{(m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2}{\Delta m - i\Delta \Gamma/2}, \]

✓ Testing T symmetry means measuring \( |q/p| \).
✓ Testing CPT symmetry means measuring \( \text{Im}(z) \).
✓ Testing CP symmetry means measuring \( |q/p| \) and \( z \).
✓ Present PDG average for \( |q/p| \): \( 1 + (0.8 \pm 0.8) \times 10^{-3} \), no T violation seen.
✓ Present average for \( \text{Im}(z) \): \( -8 \pm 4 \) \times 10^{-3}.
✓ Present average for \( \text{Re}(z) \): \( 19 \pm 40 \) \times 10^{-3}, no CPT violation seen.
A Test of CPT Symmetry in Mixing, and in $B^0$ Decay(I)

- Take advantage of the fact that $B$-mesons are produced as entangled pairs in $Y(4S)$ decays.

- They can be expressed in terms of either flavor-eigenstantes $B^0$ and $\bar{B}^0$, or the states $B_+$ and $B_-$. 

- The stated $B_+$ and $B_-$ are tagged by decays to $J/\psi K_L$ (CP-even) and $J/\psi K_S$ (CP-odd) respectively.

- Flavor eigenstates can be tagged by semileptonic $B$ decays to $l^+X$ and $l^-X$.

- Search for $T$ violation by comparing rates for transitions between flavor and CP states with the rates for the time-reversed processes
A Test of CPT Symmetry in Mixing, and in $B^0$ Decay (II)

- Example decay sequence:

\[
\begin{align*}
B^0 & \to \ell^+ X \\
\bar{B}^0 & \to \ell^- X \\
B^0 & \to J/\psi K_\pi \\
\bar{B}^0 & \to J/\psi K_\pi \\
\end{align*}
\]

\[
\Delta \tau = t_y - t_x > 0
\]

\[
\Delta t = t_{CP} - t_{flav}
\]

<table>
<thead>
<tr>
<th>Reference $(X, Y)$</th>
<th>T-Transformed $(X, Y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to B_+$ (l$^+$, J/ψ $K_{L}$)</td>
<td>$B_+ \to B^0$ (J/ψ $K_S$, l$^+$)</td>
</tr>
<tr>
<td>$B^0 \to B_-$ (l$^+$, J/ψ $K_{S}$)</td>
<td>$B_- \to B^0$ (J/ψ $K_{L}$, l$^+$)</td>
</tr>
<tr>
<td>$\bar{B}^0 \to B_+$ (l$^+$, J/ψ $K_{L}$)</td>
<td>$B_+ \to \bar{B}^0$ (J/ψ $K_S$, l$^+$)</td>
</tr>
<tr>
<td>$\bar{B}^0 \to B_-$ (l$^+$, J/ψ $K_{S}$)</td>
<td>$B_- \to \bar{B}^0$ (J/ψ $K_{L}$, l$^+$)</td>
</tr>
</tbody>
</table>

Reference: Physical Process
$(X,Y)$: Reconstructed Final States

$B_+$ tagged by $J/\psi K_{L}$
$B_-$ tagged by $J/\psi K_{S}$
A Test of CPT Symmetry in Mixing, and in $B^0$ Decay (III)

Analysis performed using the four assumptions:

1. $A = A(B^0 \rightarrow c\bar{c}K^0)$ and $\bar{A}(\bar{B}^0 \rightarrow c\bar{c}K^0)$ have a single weak phase
2. Assume and $B$ does not decay to $c\bar{c}K^0$ and $B^0$ does not decay $c\bar{c}K^0$
3. CP violation in $K^-K^0$ is negligible
4. Assume that $\Delta\Gamma = 0$

We extract the parameter $|\bar{A}/A|$ which relates to CPT violation in decay amplitudes

We also extract the real (Re) and Imaginary (Im) part of $z$ which relate to CPT violation in mixing
Results:

\[ \text{Re}(z) = -0.065 \pm 0.028 \pm 0.014 \]
\[ \text{Im}(z) = 0.010 \pm 0.030 \pm 0.013 \]

The results for \( \text{Im}(Z) \) is not competitive with that from di-lepton decays.

[A Test of CPT Symmetry in Mixing, and in \( B^0 \) Decay](#)

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

All the three results are in agreement with CPT symmetry in \( B^0 \bar{B}^0 \) mixing and in \( B^0 \rightarrow c \bar{c} K^0 \) decays.

The \( \text{Re}(z) \) result deviates from 0 by 2.1 \( \sigma \).

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 \( \pm 0.037 \pm 0.033 \).

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Measurement of the Unitarity Triangle parameter $\sin(2\beta)$ in $B^0 \rightarrow D^{0}h^0$ decays

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CP Violation in the SM: The CKM Matrix

✓ Mass eigenstates are not equal to the weak eigenstates: quark-mixing described by unitary CKM matrix.
✓ Complex matrix elements lead to different amplitudes for quarks and anti-quarks -> CP violation.
✓ The CKM matrix $V_{ij}$ is unitary with 4 independent fundamental parameters

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

✓ Unitarity constraint from 1st and 3rd columns: $\Sigma_i V_{i3}^* V_{ii} = 0$

$\alpha = \pi - \gamma - \beta$

$\gamma \sim \text{arg}[V_{ub}^*]$

$\beta \sim \text{arg}[V_{td}^*]$

$\alpha = \text{arg}\left(\frac{-V_{tb}^*}{V_{ub}^* V_{ud}}\right)$,
$\beta = \text{arg}\left(\frac{-V_{cb}^*}{V_{cd}^* V_{td}}\right)$,
$\gamma = \text{arg}\left(\frac{-V_{ub}^*}{V_{cd}^* V_{cb}}\right)$

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$\sin(2\beta)$ is known at high precision from golden modes (mediated by $c\bar{c}s$); the uncertainty on $\beta$ corresponds to less than 1°.

Motivation for measurement in $B^0 \to D^{(*)0}h^0$?

Some tension exists between direct and indirect estimations of $\beta$.

Possibly related to penguin contributions to the $b \to c\bar{c}s$ process?

Want first joint analysis to have a reasonably solid result expectation, to bootstrap confidence in sound results from the technique.
B^0 \to D^{(*)0}h^0 \text{ decays with } h^0 \in \{\pi^0, \eta^{(')}, \omega\} \text{ are mediated by tree-level amplitudes only.}

Interference between mixing and decay occurs when D^{(*)0} and \overline{D}^{(*)0} decay to a common final state.

No penguin amplitudes, theoretically clean [NPB 659, 321 (2003)]:

These decays are not sensitive to most model of BSM

- Enables testing of, and comparison with, precision measurements from b \to c\bar{c}s.
- Can provide an alternative Standard Model reference for \sin(2\beta).
- Belle2 and LHCb will be able to provide further precision in this set of channels.
Time-dependent rate of neutral B meson decaying to a CP eigenstates is:

\[ g(\Delta t) = e^{-|\Delta t|/\tau_{B^0}} \frac{1}{4\tau_{B^0}} \left\{ 1 + q S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t) \right\} \]

\( q = +1 (-1) \Rightarrow \) tagging B is a \( B^0 (\bar{B}^0) \)

\( C \) = direct CP violation
\( \Delta m_d \) is the \( B^0 - \bar{B}^0 \) mixing frequency
\( \Delta t \) = time interval between the decays of the two B mesons

Signal yield determined by unbinned maximum likelihood to the \( M_{bc} \)

\[ M_{bc} = \sqrt{(E_{\text{beam}}^* / c^2)^2 - (p_B^* / c)^2} \]

Signal yield = \( 508 \pm 31 \) events

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CP violation measurement performed by maximizing:

\[
\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{B\bar{B}} + \sum_j \ln \mathcal{P}_j^{Belle},
\]

\[-\eta f \mathcal{S} = +0.66 \pm 0.10 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \]
\[C = -0.02 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \]

These results agree with 0.2 \(\sigma\) with the world average
\[\sin 2\beta = 0.68 \pm 0.02\] from \(b \rightarrow c\bar{c} s\)
Excludes the hypothesis of no mixing-induced CPV in $B^0 \rightarrow D^{(*)0} h^0$ at a confidence level of $1 - (6.6 \times 10^{-8})$, corresponding to a significance of 5.4$\sigma$. 
Conclusions

✓ We have presented a measurement of a test of CPT symmetry in $B^0 - \bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays.

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✓ Measurement of the Unitarity Triangle parameter $\sin(2\beta)$ in $B^0 \rightarrow D^0 h^0$ decays.

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✓ BaBar and Belle continues to produce leading results on several different test of fundamental symmetries.
Thanks for your attention