$D^0$ Mixing and $CP$ Violation from Belle

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Introduction

- Review of Charm Mixing and $CP$ Violation Formalism

- Charm Mixing Results (WS, time-dep., ...)

- $CP$ Violation in Time-integrated Decays ($K_S h^\pm$, $K_S P^0$, ...)

- Conclusion
KEKB and Belle Detector

Largest integrated luminosity in the world, ~1020 fb\(^{-1}\)

Electron-positron beam, proceeds through:

\[
\begin{align*}
e^+e^- & \rightarrow \Upsilon(4S) \rightarrow \bar{b}b \\
e^+e^- & \rightarrow \gamma \rightarrow c\bar{c}
\end{align*}
\]

\[\sigma(b\bar{b}) = 1.1 \text{ nb}\]
\[\sigma(c\bar{c}) = 1.3 \text{ nb}\]

\~1.3 \times 10^9 \text{ } c\bar{c} \text{ pairs}

B-factories serve as good charm factories!

Luminosity at B factories

> 1 ab\(^{-1}\)
On resonance:
\- \Upsilon(5S): 121 fb\(^{-1}\)
\- \Upsilon(4S): 711 fb\(^{-1}\)
\- \Upsilon(3S): 3 fb\(^{-1}\)
\- \Upsilon(2S): 24 fb\(^{-1}\)
\- \Upsilon(1S): 6 fb\(^{-1}\)

Off reson./scan:
\~100 fb\(^{-1}\)

\~550 fb\(^{-1}\)
On resonance:
\- \Upsilon(4S): 433 fb\(^{-1}\)
\- \Upsilon(3S): 30 fb\(^{-1}\)
\- \Upsilon(2S): 14 fb\(^{-1}\)

Off resonance:
\~54 fb\(^{-1}\)
Mixing Formalism

Evolution of $D^0 - \bar{D}^0$ system described by time-dependent Schrödinger equation

$$i \frac{\partial}{\partial t} \left( \frac{D^0(t)}{\bar{D}^0(t)} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \frac{D^0(t)}{\bar{D}^0(t)} \right)$$

Mixing occurs when flavor eigenstates ($D^0$, $\bar{D}^0$) produced in decays are not the same as mass eigenstates ($D_1$, $D_2$).

Mixing often expressed in terms of mass and width differences of eigenstates:

$$\Delta M = M_1 - M_2$$
$$\Delta \Gamma = \Gamma_1 - \Gamma_2$$

and mixing parameters:

$$x = \frac{\Delta M}{\Gamma}$$
$$y = \frac{\Delta \Gamma}{2 \Gamma}$$

Time-dependent expression for $D^0$ decay rate is given by:

$$|D^0(t)\rangle = \left| D^0 \right\rangle \cosh \left( \frac{ix + y \Gamma t}{2} \right) - \frac{q}{p} |\bar{D}^0\rangle \sinh \left( \frac{ix + y \Gamma t}{2} \right) e^{-\frac{m}{2}t}$$
Contributions to $x$ and $y$

**Standard Model predictions for $x$ and $y**

Mixing strongly suppressed in charmed mesons by CKM and GIM mechanism, calculable short-distance effects give:

$$|x|, |y| < 10^{-5}$$


**Contributions from $SU(3)$ breaking and hadronic intermediate states give:**

$$x, y < 10^{-2}$$

Golowich,Hewett,Pakvasa,Petrov arXiv:0705.3650v2

Difficult to calculate, BUT measurements of $x$ and $y$ can still provide useful constraints on New Physics models

**Long distance**

$$\begin{align*}
D^0 & \xleftarrow{\text{W}} \ L \rightarrow \bar{c} \\
\bar{D}^0 & \xleftarrow{\text{W}} \ \bar{u} \\
D^0 & \xleftarrow{\text{KK, } \pi \pi \ldots} \ \bar{D}^0
\end{align*}$$
**CP Violation in Charm**

- CP violation arises as a single complex phase \( \eta \) in the CKM mixing matrix
- CP violation in SM is CKM suppressed, \( \sim O(10^{-3}) \)
- Observation of \( O(1\%) \) CP violation would be a sign for New Physics

**CP-violating effects are classified by three parameters:**

\[
A_{CP}^f = \frac{\Gamma(D \rightarrow f) - \Gamma(D \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(D \rightarrow \bar{f})} \approx a_d^f + a_m^f + a_i^f
\]

1) CP violation in decay:

\[ |A_f| \neq |\bar{A}_f| \]

2) CP violation in mixing:

\[ |q/p| \neq 1 \]

3) CP violation in interference:

\[ \phi \neq 0 \text{ or } \pi \quad \phi = \arg \left( \frac{q}{p} A_f \right) \]

**Common experimental observables**

\[
A_{\Gamma} = \frac{\tau(D \rightarrow f_{CP}) - \tau(D \rightarrow \bar{f}_{CP})}{\tau(D \rightarrow f_{CP}) + \tau(D \rightarrow \bar{f}_{CP})} \quad A_{CP}^f = \frac{N(D \rightarrow f) - N(D \rightarrow \bar{f})}{N(D \rightarrow f) + N(D \rightarrow \bar{f})}
\]
Decays to $CP$ Eigenstates

Measurement of lifetime difference between $D^0 \rightarrow K^- \pi^+$ ($CP$-mixed) and $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$ ($CP$-even) decays (tagged and untagged samples)

\[ \Gamma(D^0 \rightarrow K^- \pi^+) \propto e^{-t/\tau_{D^0}} \]

\[ \Gamma(D^0 \rightarrow K^+ K^-, \pi^+ \pi^-) \propto e^{-(1+y_{CP})t/\tau_{D^0}} \]

In terms of mixing parameters:

\[ y_{CP} = -1 + \frac{\tau_{K^+ \pi^-}}{\tau_{K^+ K^-, \pi^+ \pi^-}} = \frac{1}{2} \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) y \cos \phi - \frac{1}{2} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) x \sin \phi \]

\[ A_\Gamma = \frac{\tau(D^0 \rightarrow f_{CP}) - \tau(D^0 \rightarrow f_{CP})}{\tau(D^0 \rightarrow f_{CP}) + \tau(D^0 \rightarrow f_{CP})} = \frac{1}{2} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) y \cos \phi - \frac{1}{2} \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) x \sin \phi \]

Limit no $CP$ violation, $y_{CP} = y$ and $A_\Gamma = 0$
Reconstructing $D$ Mesons

Tagging the flavor of neutral D meson

Reconstruct decay chain:

$D^{*+} \rightarrow D^0 \pi^+$

- Flavor of $D^0$ is tagged by slow pion
- Background suppression using mass difference

Proper decay time determination

Beam point is used to constrain vertex fit:

$D$ mesons from $b \rightarrow c$ are eliminated with $p^0_{\text{cms}} > 2.5 \text{ GeV/c2}$

Uncertainty $\sigma_t$ typically between $1/6 \tau_D$ and $1/2 \tau_D$
Proper decay time was fitted for each sample

\[540 \text{ fb}^{-1}, \sim 130K \, K^+K^- \text{ events,} \sim 57K \, \pi^+\pi^- \text{ events}\]

Staric et al. (Belle), PRL98, 211803 (2007)

\[\chi^2 (\text{ndf}) \quad 0.97 (97)\]

\[\chi^2 (\text{ndf}) \quad 1.14 (97)\]

\[\chi^2 (\text{ndf}) \quad 1.14 (95)\]

\[y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%\]

Measured to 3.2σ significance, first evidence of mixing

\[A_\Gamma = (0.01 \pm 0.30 \pm 0.15)\%\]

No CPV observed to .4% sensitivity
**D-Mixing in $D^0 \rightarrow K_S K^+ K^-$**

Measure lifetime differences between $\text{CP}$-even and $\text{CP}$-odd eigenstates

Zupanc et al. (Belle), Phys.Rev.D80:052006 (2009)

\[ \sqrt{s_0} = m_{K^+K^-} \text{ dependent CP mixture} \]
\[ \rightarrow \text{ON region: mainly } \text{CP-odd} (\phi(1020)) \]
\[ \rightarrow \text{OFF region: mainly } \text{CP-even} (a_0(980)^0) \]

\[ \frac{d^2N(s_0,t)}{ds_0 dt} \propto a_1(s_0) e^{-(1+y_{\text{CP}})t/\tau_{D^0}} + a_2(s_0) e^{-(1-y_{\text{CP}})t/\tau_{D^0}} \]

**Effective lifetimes in ON and OFF regions**

$F_{\text{ON}}$ and $F_{\text{OFF}}$ regions fit with 8-resonance Dalitz model

72K signal events in ON region, 62K in OFF

$y_{\text{CP}} = (0.11 \pm 0.61 \pm 0.52)\%$

Consistent with previous measurement of $y_{\text{CP}}$
Mixing in WS Decay $D^0 \rightarrow K^+\pi^-$

Right sign (RS) charge combination

$$D^{*+} \rightarrow D^0(K^-\pi^+)%$$

$$\Gamma_{RS} \propto e^{-t/\tau_{D^0}}$$

Wrong sign (WS) charge combination

$$D^{*+} \rightarrow D^0(K^+\pi^-)%$$

→ DCS or mixing

WS rate include DCS, interference, and mixing

$$\Gamma_{WS} \propto \left [ R_D + y' \sqrt{R_D} (\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right ] e^{-\Gamma t}$$

$R_D = \text{DCS/CF rate}$

$x' = x \cos \delta + y \sin \delta$

$y' = y \cos \delta - x \sin \delta$

($\delta$ = strong phase)
**Mixing in WS Decay $D^0 \rightarrow K^+\pi^-$**

Belle [400 fb$^{-1}$]

Zhang et al. (Belle), Phys.Rev.Lett.96, 151801 (2006)

$D^0$ and $\bar{D}^0$ samples fit separately:

$$(R_D^+, x'^+2, y'^+)_{D^0} \iff (R_{\bar{D}}^-, x'^{-2}, y'^-)_{\bar{D}^0}$$

CPV in decay $\Rightarrow A_D = \frac{R_D^+-R_D^-}{R_D^++R_D^-}$; $R_D$ (DCS/CF rate)

CPV in mixing $\Rightarrow A_M = \frac{R_M^+-R_M^-}{R_M^++R_M^-}$; $R_M = \frac{x^2+y^2}{2}$ (mixing rate)

$A_D = (23 \pm 47) \times 10^{-3}$

$A_M = 0.67 \pm 1.2$

$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$

$x^2 = (0.18^{+21}_{-23}) \times 10^{-3}$

No-mixing point (0,0) corresponds to C.L. 3.9%
Mixing in Time-dependent Dalitz Analyses

Dalitz plots provide unique environment for determining strong phases between $D^0$ and $\bar{D}^0$ decays in self-conjugate final states. Contributions include:

- **CF:** $D^0 \rightarrow K^*\pi^+$
- **DCS:** $D^0 \rightarrow K^*\pi^-$
- **CP:** $D^0 \rightarrow K_{S}\rho^0$

Decay model is parameterized using Dalitz variables:

$$D^0: \mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2) + a_{nr} e^{i\phi_{nr}}$$

$$\bar{D}^0: \bar{\mathcal{A}}(m_-^2, m_+^2) = \sum_r \bar{a}_r e^{i\bar{\phi}_r} \bar{\mathcal{A}}_r(m_-^2, m_+^2) + a_{nr} e^{i\phi_{nr}}$$

The time-dep. decay rate allows simultaneous determination of $x$ and $y$ ($\mathcal{A}_{1,2} = \frac{1}{2}(\mathcal{A} \pm \bar{\mathcal{A}})$)

$$\Gamma(m_-^2, m_+^2, t) = e^{-\Gamma t} (|\mathcal{A}_1|^2 e^{-y\Gamma t} + |\mathcal{A}_2|^2 e^{y\Gamma t} + 2\mathcal{R}[\mathcal{A}_1\mathcal{A}_2^*] \cos(x\Gamma t) + 2\mathcal{I}[\mathcal{A}_1\mathcal{A}_2^*] \sin(x\Gamma t))$$
Mixing in Time-dependent $D^0 \rightarrow K_s \pi^+ \pi^-$


Assuming no CP violation:

\[
\begin{align*}
    x &= (0.80 \pm 0.29^{+0.13}_{-0.16})\% \\
    y &= (0.33 \pm 0.24^{+0.10}_{-0.14})\%
\end{align*}
\]

Allowing for CPV

\[
\begin{align*}
    |q/p| &= 0.86 \pm 0.30 \pm 0.09 \\
    \phi &= -0.24 \pm 0.30 \pm 0.09
\end{align*}
\]

No CP violation observed
**CP Violation in Time-integrated Decays**

Standard Model predicts O(0.1%) direct CP violation in Singly Cabibbo-Suppressed (SCS) decays


Examples: \( D^+ \rightarrow K_S \pi^+ \), \( D^+ \rightarrow K_S K^+ \)

Must distinguish possible CP asymmetry from reconstruction asymmetries, such as detector effects and production asymmetry

\[
A_{CP}^{D \rightarrow X^0 h^+} = \frac{\Gamma(D \rightarrow X^0 h^+) - \Gamma(\bar{D} \rightarrow X^0 h^-)}{\Gamma(D \rightarrow X^0 h^+) + \Gamma(\bar{D} \rightarrow X^0 h^-)}
\]

\[
A_{rec}^{D \rightarrow X^0 h^+} = A_{CP}^{D \rightarrow X^0 h^+} + A_{other}, \quad A_{other} \in \{A_{FB}^D, A_{\xi}^{h^+}\}
\]

\( A_{CP} \) = CP asymmetry, independent of kinematics
\( A_{FB} \) = Production asymmetry, due to \( \gamma^*/Z \) interference
\( A_{\xi} \) = Reconstruction efficiency asymmetry (\( p^{lab}, \cos \theta^{lab} \))

Deviations in \( A_{CP} \) greater than 0.1% could signify New Physics

Includes (-0.332 ± 0.006)% CP violation due to neutral kaon
**CP Violation in** \( D^+ \to K_S \pi^+ \)

Ko et al. (2010), PRL 104, 181602

673 fb\(^{-1}\) Measured in bins of \((p_{\text{lab}}, \cos \theta_{\text{lab}}, \cos \theta_{D^*})\)

1) For \( D^+ \to K_S \pi^+ \) measure

\[ A_{\text{rec}} = A_{FB} + A_{\varepsilon} \pi^+ + A_{CP} \]

2) For \( D_S^+ \to \phi \pi^+ \) measure

\[ A_{\text{rec}} = A_{FB} + A_{\varepsilon} \pi^+ \]

3) Subtract measured asymmetries

\[ A_{CP}(D^+ \to K_S \pi^+) = (-0.71 \pm 0.19 \pm 0.20)\% \]

Results consistent with -0.33% due to neutral kaon
**CP Violation in $D_{(s)}^+ \rightarrow K_S K^+$**

\[ A_{CP}(D^+ \rightarrow K_S K^+) = (-0.16 \pm 0.58 \pm 0.25)\% \]

\[ A_{CP}(D_S^+ \rightarrow K_S K^+) = (0.12 \pm 0.36 \pm 0.22)\% \]

Consistent with -0.33% due to neutral kaon

Most precise measurement of SCS/CF:

\[ R(D^+) = 0.1899 \pm 0.0011 \pm 0.0022 \]

\[ R(D_S^+) = 0.0803 \pm 0.0024 \pm 0.0019 \]

Dashed line: leading-order prediction for $A_{FB}$
CP Violation in $D^0 \rightarrow K_S P^0$

Events reconstructed from tagged $D^*$ sample

$A_{CP}(D^0 \rightarrow K_S \pi^0) = (-0.28 \pm 0.19 \pm 0.10)\%$

$A_{CP}(D^0 \rightarrow K_S \eta) = (-0.54 \pm 0.51 \pm 0.13)\%$

$A_{CP}(D^0 \rightarrow K_S \eta') = (-0.90 \pm 0.67 \pm 0.15)\%$*

*World’s first measurement

Results consistent with -0.33% due to neutral kaon

791 fb$^{-1}$
$\Delta A_{CP}$ between $D^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$

Event reconstruction as follows:

$\phi \rightarrow K^+ K^-$ and $m(K^+ K^-)$ within $m_{\phi}^{PDG} \pm 16$ MeV/$c^2$

$\Delta A_{CP}$ defined as $A_{CP}(D^+ \rightarrow \phi \pi^+) - A_{CP}(D_s^+ \rightarrow \phi \pi^+)$

$\Delta A_{CP} = (0.62 \pm 0.30 \pm 0.15)\%$

No significant difference found in production asymmetry of $D^+$ and $D_s^+$

PRELIMINARY

850 fb$^{-1}$
Prospects with Belle’s Full Data Set

• Belle now has about $\sim 1$ ab$^{-1}$ for mixing measurements

• Updating previous mixing analyses and working on new measurements

• Expect significant improvement in sensitivity to mixing and $CP$ violation

• Additionally, expect 20-40% increase in signal yields due to new reprocessing

• E.g. signal yield for $D^0 \rightarrow K_S\pi^+\pi^-$ analysis increased from 534K events to $\sim 1.25M$

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**Belle @ 540 fb$^{-1}$, PRL. 99, 131803 (2007)**

- $x = (8.0 \pm 2.9^{+1.3}_{-1.4}) \times 10^{-3}$, $y = (3.3 \pm 2.4^{+1.0}_{-1.4}) \times 10^{-3}$
- 2.2 standard deviation from no-mixing hypothesis

**Babar @ 468.5 fb$^{-1}$, PRL. 105, 081803 (2010)**

<table>
<thead>
<tr>
<th>Fit type</th>
<th>$x/10^{-3}$</th>
<th>$y/10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>$1.6 \pm 2.3 \pm 1.2 \pm 0.8$</td>
<td>$5.7 \pm 2.0 \pm 1.3 \pm 0.7$</td>
</tr>
<tr>
<td>$K^0_S\pi^+\pi^-$</td>
<td>$2.6 \pm 2.4$</td>
<td>$6.0 \pm 2.1$</td>
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<tr>
<td>$K^0_SK^+K^-$</td>
<td>$-13.6 \pm 9.2$</td>
<td>$4.4 \pm 5.7$</td>
</tr>
</tbody>
</table>

- 1.9 standard deviation from no-mixing hypothesis
Conclusion

• Wide program of $D$-mixing and $CP$ violation underway at Belle

• Measurements have provided compelling evidence for $D^0$-$D^0$ mixing

• No evidence of $CP$ violation to 0.3% level of sensitivity

• First $A_{CP}$ measure measurements for $D^0 \rightarrow K_S \eta$ and $D^0 \rightarrow K_S \eta'$

• Expect significant improvement with full dataset, new analyses underway

• Best $D$-mixing and $CP$ violation measurements to come?
Backup