Recent Results on CP Lifetime differences of Neutral D mesons

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Part I: Charm Mixing and $y_{CP}$
  Basic mixing phenomenology

Part II: The FOCUS analysis
  Summary of PLB485(2000), 62

Part II: The BELLE analysis
  Preliminary results on 11/fb.

Part III: The CLEO analysis
  Preliminary results from II.V

Part IV: Conclusion
Mixing review...

- Neutral charm mesons:
  \[ D^0 = c\bar{u}, \overline{D}^0 = \bar{c}u \]

- If \( H_{12}, H_{21} \neq 0 \), they are not eigenstates.

\[ i \frac{\partial}{\partial t} \begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix} \]

where \( H_{ij} = M_{ij} - i \Gamma_{ij}/2 \).

- If CP is conserved,

\[ D_{1,2} = (D^0 \pm \overline{D}^0)/\sqrt{2} \]

with mass and lifetime as

\[ M_{1,2} = M \pm \Re[H_{12}H_{21}]^{1/2} = M \pm 1/2 \Delta M \]

\[ \Gamma_{1,2} = \Gamma \mp 2\Im[H_{12}H_{21}]^{1/2} = \Gamma \mp \Delta \Gamma \]

- For charm mesons, experimental limits state that \( \Delta M, \Delta \Gamma \ll \Gamma \).

\[ x = \frac{\Delta M}{\Gamma}, y = \frac{\Delta \Gamma}{2\Gamma} \]

- Methods to see x or y:
  - mixing (wrong sign final decays): E791, CLEO
  - comparing lifetime of CP eigenstates: E791, FOCUS

See hep-ph/0005181, etc. for more generalized treatment of mixing parameters.
Mixing Mechanisms

• For $\Delta M$: Virtual intermediate states (short distance int.)

• For $\Delta \Gamma$: Long range, eg, mutual intermediate states

- Dominant Standard model shown.
- Other Standard model contributions (CP violation)
- New Physics?

PDG 2000 reports:

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>$d\bar{s}$</td>
<td>0.474±0.001</td>
</tr>
<tr>
<td>$B$</td>
<td>$d\bar{b}$</td>
<td>0.730 ±0.029</td>
</tr>
<tr>
<td>$B_S$</td>
<td>$s\bar{b}$</td>
<td>$x&gt;15.7$</td>
</tr>
<tr>
<td>$D$</td>
<td>$c\bar{u}$</td>
<td>$x&lt;0.03$</td>
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</table>
Theoretical “guidance”

From compilation of H.N. Nelson hep-ex/9908021

Triangles are SM x
Squares are SM y
Circles are NSM x

Predictions encompass 15 orders magnitude for $R_{\text{mix}}$

(but only 7 orders of x or y!)
Methods to see $x, y$

- In hadronic $D^0$ decays, wrong sign final: mixing, double Cabibbo suppressed or interference (strong phase $\delta$). $\rightarrow D^0$ charge tagged by $D^{*+}$
- Time evolution study finds $x', y'$.

\[
\begin{align*}
K^-\pi^+ & \quad \text{CF} \quad D^0 \quad \text{mixing} \quad D^0 \quad \text{DCS} \quad K^+\pi^- \\
\frac{dN_{ws}}{dt} & \approx e^{-\Gamma t} \left\{ \left( \frac{x^2 + y^2}{2} \right) \frac{\Gamma^2 t^2}{2} + D_{DCS}^2 \right\} \\
D_{DCS} & \equiv CLEO y' (\sigma \approx 1.7\%) \\
D_{DCS} & = 0 \text{ in semileptonic decays. } \rightarrow \text{Cleaner analysis but less sensitivity.}
\end{align*}
\]

- Direct comparison of CP final state lifetime finds $y_{CP}$.

\[
\begin{align*}
D^0 & \rightarrow K^+K^- (CP +) \rightarrow \Gamma_2 \\
D^0 & \rightarrow K^-\pi^+ (CP +: CP - = 1:1) \\
\rightarrow \Gamma (K^-\pi^+) & \approx (\Gamma_1 + \Gamma_2)/2 \\
y_{CP} & = \frac{\tau(D \rightarrow K\pi)}{\tau(D \rightarrow KK)} - 1
\end{align*}
\]

- If we select 16532 $D^0 \rightarrow K^+K^-$ FOCUS events (S/N=2.3).

\[
\begin{align*}
\sigma_y & \approx \frac{\sigma(\tau(KK))}{\tau(KK)} \approx \frac{1}{\sqrt{N^*}} \approx 1.2\%
\end{align*}
\]
Successor to E687. Designed to study charm particles produced by ~200 GeV photons using a fixed target spectrometer with updated Vertexing, Cerenkov, EM Calorimeters, and Muon id capabilities. Member groups from USA, Italy, Brazil, Mexico, Korea.

FCP01, D0 CP lifetime diff.
Detector Performance related to lifetime study

- Segmented target:
  - 62% of charm decay in air.
  - small absorption correction.
- Extremely good proper time resolution: $\sigma(\tau)/\tau(D^0) = 8\%$ (30fs)
  - No resolution convolution systematics/error inflation → Binned likelihood method.

- Vertex algorithm is driven by D candidates:
  - The Fit variable (reduced proper time $t' = t - N\sigma$) acceptance is flat.
- Excellent (and flexible) Cerenkov identification:
  - Minimized systematics on particle ID misidentification.

![Graph of Decays vs Z (cm)](image)
Selection of $D \to K\pi, KK$

- Important: Get a sample with a flat efficiency over $t'$

- Common base cuts: detachment ($l/\sigma > 5$), Kaon ID ($W\pi \cdot W_K > 4$)

- Tagged sample:
  \[
  |M(D^*) - M(D)| < 145.4 \text{ MeV}
  \]

- Or inclusive sample:
  More Cerenkov cuts: pion ID ($W^*-W\pi > -2$), Kaon ID 2 ($W_P - W_K > -2$)

Mom sym: $|\alpha| < 0.7$ where $\alpha \equiv \frac{p_1 - p_2}{p_1 + p_2}$

Primary vertex in target (PIT)

Resolution: $\sigma < 60 \text{ fs}$ where $\sigma \equiv \frac{\sigma}{\gamma \beta c}$

$D \to K\pi$: 119738 selected

$D \to KK$: 10331 selected
D→KK signal for several cleanups

$\frac{l}{\sigma} > 5$
$W\pi - W_K > 1$

$Y=16532$
$S/N=2.3$

K$\pi$
reflection

$\frac{l}{\sigma} > 9$
$W\pi - W_K > 1$

$Y=11528$
$S/N=4.3$

$\frac{l}{\sigma} > 5$
$W\pi - W_K > 4$

$Y=10331$
$S/N=2.7$

$\frac{l}{\sigma} > 9$
$W\pi - W_K > 4$

$Y=7151$
$S/N=5.7$

3/5/01  FCP01, D0 CP lifetime diff.
Fit technique: non-parametric background

- Binned likelihood: $20 \times 200$ fs
- Acceptance/absorption $f(t')$ correction by MC ~ nearly 1!!
- $\mu_i$: expected in each $t'$ bin
- $b_i$: background from sidebands
- Fit $\tau (K\pi)$, $B (K\pi)$ (but see next page)

$$\mu_i = (N_s - B) \frac{f(t'_{i}) \exp(-t'_{i}/\tau)}{\sum_i f(t'_{i}) e^{-t'_{i}/\tau}} + B \frac{b_i}{\sum_i b_i}$$

$$w = -2 \left( \sum_i \ln \left( \frac{\mu_i^n e^{-\mu_i}}{n_i!} \right) \right) - 2 \ln \frac{(2B)^{(N_1+N_2)} e^{-(2B)}}{(N_1 + N_2)!}$$

- option: w or w/o B-tie term.
...Fitting technique

- The KK sample has some Kπ reflection at its side; B2 = Kπ + nominal → one more player in fitting.
  - Subtract Kπ reflection by a mass fit.
    - The reflection mass shape from MC.
    - The subtraction level by the mass fit.
    - Time evolution of the reflection from \( \tau (K\pi) \)

- Background under KK signal ≅ B1 + (B2 - Kπ reflection)
  - Simultaneous time evolution fit of both Kπ and KK histos.
  - 4 variables in the time fit: \( \tau (K\pi), y_{CP}, B (K\pi), B (KK) \)
Fitted: Time evolutions

• Background subtracted and $f(t')$ corrected time evolution of $K\pi$ and $KK$ events in the final fit.

• Before background subtraction happens…. 
$y_{cp}$: Results and Systematics

$y_{CP} = 3.42 \pm 1.39 \pm 0.74\%$

Sample standard deviation of fit variants is $\pm0.63$.

$\tau(K\pi) = 409.2 \pm 1.3 \pm ??\ fs$

Sample standard deviation of fit variants $\pm0.3$.

Absolute lifetime systematics not ready until we analyze $K3\pi$, etc.
BELLE D0 LIFETIME STUDY

- 12 GeV @ Y(4s), 11/fb preliminary.
- Searching y_{CP} using D^0 \rightarrow K\pi, KK decay channels.
- Part of D lifetime analysis package (D^0, D_s, D^+, two/three body decay with charged K/\pi.)
- Basic cuts to select D mesons:
  - P^*(D) > 2.5 GeV to cut off b\bar{b} background.
  - CDC (dE/dx), TOF, ACC for (Kaon/pion) PID.
  - Decay angle cut of D0 decay particles.
  - D* tag optional for D^0 \rightarrow K\pi channel.

\[ \tau = \frac{L \cdot m(D)}{p(D) \cdot c} \]

- D decay vertex in 3D
- Extrapolate to IP.
- \( \sigma(\tau) \sim 150 \, \mu m \sim 0.36 \, \tau(D) \)
BELLE : Lifetime Fit

• Unbinned Maximum Likelihood Fit

\[
L(t_i, \sigma_i^S, f_{SIG}^i) = f_{SIG}^i \cdot \int_0^\infty dt' \frac{1}{\tau_{SIG}} e^{-t'/\tau_{SIG}} R_{SIG}(t_i - t', \sigma_i^S) \\
+ (1 - f_{SIG}^i) \int_0^\infty dt' [f_{BG} \cdot \frac{1}{\tau_{BG}} e^{-t'/\tau_{BG}} + (1 - f_{BG}) \cdot \delta(t') ] R_{BG}(t_i - t', \sigma_i^S)
\]

\[
R(x, \sigma_x) = (1 - f_{tail}) \frac{1}{\sqrt{2\pi} \sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} + f_{tail} \frac{1}{\sqrt{2\pi} \sigma_x} e^{-\frac{x^2}{2\sigma_{tail}^2}}
\]

• \(f_{SIG}\): event by event, from D mass fit. \(\sigma_i\): event by event, from Kalman filter.

• Fit parameters: \(\tau_{SIG}, \tau_{BG}, f_{cBG}, S, S_{tail}, f_{tail}, (S, S_{tail}, f_{tail})_{BG}\)

3/5/01 FCP01, D0 CP lifetime diff. 15
BELLE : D0 → Kπ

σ = 5.4MeV

90601±387 events
M = 1865.0MeV

τ_{SIG} = 414.5±1.7fs (stat)
(PDG 2K: 412.6±2.8fs)
BELLE : D0→ KK

σ = 6.5MeV

7451 ± 118 events

M = 1865.0MeV

τSIG = 409.8±6.3fs(stat)
BELLE : $y_{CP}$ Fit Result

• From combined fit, $y_{CP} = 1.16^{+1.67}_{-1.65} \%$, $\tau(D^0) = 414.5 \pm 1.7$ fs (preliminary, statistical error only.)

• Combined fit $y_{CP}$ result comparable to separately measured $\{\tau(K\pi), \tau(KK)\}$ result, i.e., $\tau(K\pi)/\tau(KK) - 1$.

• Consistent with previous results from other experiments.

• Systematics study going on. Will publish.

• Future plan: Wrong sign (DCSD and mixing) event search.
CLEO D0 LIFETIME STUDY

- 10.6 GeV, 9.0/fb preliminary.
- \(D^0 \rightarrow K\pi, KK, \pi\pi\) decay channels. Compare lifetimes with the \(K\pi\) channel.
- \(D^*\) tag required \((\sigma(Q) \sim 190\pm2\) KeV, \(Q \equiv M^* - M - m_\pi\))
- Reconstruct D0 proper time \((\sigma(\tau) \sim 0.35\) \(\tau(D)\)).

20272 ± 178 events
\(M = 1865.14\) MeV
\(K\pi\)

2463 ± 65 events
\(KK\)

930 ± 37 events
\(\pi\pi\)
CLEO: Lifetime Fit

• Unbinned maximum likelihood fit to proper time distribution.

• Fitting method optimized for lifetime difference, not for $\tau(D^0)$.

• Resolution: Measured proper time error $\pm$ two gaussians for mismeasured.

• Fit parameters: $N_{\text{sig}}$, $\tau(D^0)$, $B_g$ fraction, $B_g$ non-zero lifetime fraction, $\tau$(background), mismeasured fraction, $\sigma$(mismeasured).

$\tau(D^0) = 404.6\pm3.6\text{fs (stat)}$

$\tau(D^0) = 411\pm12\text{fs(stat)}$

$\tau(D^0) = 401\pm17\text{fs(stat)}$
CLEO: $y_{CP}$ Fit Result

- $y_{KK} = -0.019 \pm 0.029$ (stat) $\pm 0.016$ (syst).
- $y_{\pi\pi} = 0.005 \pm 0.043$ (stat) $\pm 0.018$ (syst).
- Average of the above: $y_{CP} = -0.011 \pm 0.025$ (stat) $\pm 0.014$ (syst), preliminary.
- Consistent with the other measurements.
- Dominant systematic errors: Statistical uncertainty in MC lifetime study (9fs), background description (8fs), proper time resolution model (5fs), fit procedure (5fs).
D^0 Lifetime Update

<table>
<thead>
<tr>
<th>Exp</th>
<th>D^0 lifetime (fs)</th>
</tr>
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<tbody>
<tr>
<td>PDG2K</td>
<td>412.6 ± 2.8</td>
</tr>
<tr>
<td>E791</td>
<td>413 ± 3 ± 4</td>
</tr>
<tr>
<td>CLEO</td>
<td>408.5 ± 4.1 ± 3.5</td>
</tr>
<tr>
<td>FOCUS</td>
<td>409.2 ± 1.3 ± x*</td>
</tr>
<tr>
<td>SELEX Prelim.</td>
<td>409 ± 6 ± 4</td>
</tr>
<tr>
<td>BELLE Prelim.</td>
<td>414.5 ± 1.7 ± x*</td>
</tr>
<tr>
<td>Average of recent values</td>
<td>411.1 ± 1.0</td>
</tr>
</tbody>
</table>

χ²=6.6 for 4
Conclusion: BELLE, CLEO, E791 and FOCUS

The comparison to CLEO mixing analysis is valid only if one assumes a small strong phase difference $\delta$.

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<tr>
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<th>Belie</th>
<th>CLEO prel</th>
<th>E791</th>
<th>FOCUS</th>
<th>CLEO</th>
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<tbody>
<tr>
<td>Average $y_{CP}$</td>
<td>$1.8 \pm 1.0 %$</td>
<td>$1.16^{+1.67}_{-1.65} %$</td>
<td>$0.8 \pm 2.9 \pm 1 %$</td>
<td>$3.42 \pm 1.39 \pm 0.74 %$</td>
<td>$-1.1 \pm 2.5 \pm 1.4 %$</td>
</tr>
</tbody>
</table>

$\chi^2 = 2.3$ for 3
Phase ambiguity

What if $\delta = 40^\circ$, the estimated maximum of the model of Falk, Nir & Petrov (99)? We see some overlap...

CLEO and FOCUS would be more consistent if $\delta > 90^\circ$...

*Bergmann, Grossman et al*(00).
Sensitivity of FOCUS semileptonic

- FOCUS on-going mixing analysis in a semileptonic channel.
  - A blind analysis; haven’t looked at the WS signal yet.
  - Cuts not optimized yet.
- “Sensitivity”
  - Limit we would get if WS signal is consistent with zero.
  - $95\%$ CL: $r_{\text{mix}} < 0.149\%$