Mixing induced $CP$ asymmetry in semileptonic $B$-meson decays at BABAR

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Neutral meson mixing

- In neutral meson systems, particle/antiparticle can couple to each other through weak interaction:
  \[ B_{d,s}^0 \leftrightarrow \bar{B}_{d,s}^0, \ D^0 \leftrightarrow \bar{D}^0, \ K^0 \leftrightarrow \bar{K}^0 \]

- Equation of a decaying particle:
  \[ B(t) = \exp[-imt - (\Gamma/2)t] \]

  \[ i \frac{d}{dt} \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left( \hat{M} - \frac{i}{2} \hat{\Gamma} \right) \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} \]

- Off-diagonal elements \( M_{12}, \Gamma_{12} \) in the matrix are non-trivial (and complex).

- Measurements of various aspects of mixing test the theory of weak interaction.
  - Mixing rate, decay rate difference, \( CP \) violation.

- New physics in the loops could alter these observables.
Mixing induced $CP$ violation

- The eigenstates of the neutral $B$ system are linear combinations of flavor states $|B^0\rangle$ and $|\bar{B}^0\rangle$

$$|B_{L/H}\rangle = \frac{1}{\sqrt{p^2 + q^2}} (p|B^0\rangle \pm q|\bar{B}^0\rangle)$$

- For flavor specific final states: $B^0 \to f$, $\bar{B}^0 \to \bar{f}$; $B^0 \not\to \bar{f}$, $\bar{B}^0 \not\to f$
  - E.g., semileptonic decays: $B^0 \to X\ell^+\nu_\ell$
  - Assume no direct $CPV$: $|\langle f|B^0\rangle| = |\langle \bar{f}|\bar{B}^0\rangle|$  
  - $CP$ violation due to mixing:

$$A_{sl} = \frac{\Gamma(\bar{B}^0(t = 0) \to f) - \Gamma(B^0(t = 0) \to \bar{f})}{\Gamma(\bar{B}^0(t = 0) \to f) + \Gamma(B^0(t = 0) \to \bar{f})} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \simeq -2 \left( \frac{|q|}{p} - 1 \right) \simeq \text{Im} \frac{\Gamma_{12}}{M_{12}}$$

$\bar{B}^0 \to B^0$, then decay to the “wrong sign” final state $f$. $CPV$ if $|q/p| \neq 1$

$$\phi = \text{arg} \left( -\frac{M_{12}}{\Gamma_{12}} \right)$$
Search/constrain new physics

- Standard Model prediction is small:
  
  \[ A_{sl}^s = (1.9 \pm 0.3) \times 10^{-5} \]
  \[ A_{sl}^d = -(4.1 \pm 0.6) \times 10^{-4} \]
  
  [Lenz, Nierste, arXiv:1102.4274 (2011)]

- well below current experimental sensitivity (\( \mathcal{O}(10^{-3}) \)).

- observation of non-zero CPV would indicate new physics.

- Some tension observed in D0 di-muon analysis

- Allowed new physics (model independent) parameter space is still sizable.

  \[ M_{12}^{d,s} = (M_{12}^{d,s})^{SM} \left( 1 + h_{d,s} e^{2i\sigma_{d,s}} \right) \]

  [Ligeti, et al. PRL 105, 131601 (2010)]
Experiment

- In $B$ factories $\Upsilon(4S)$ are produced and decay to a pair of $B$ mesons in a coherent $L=1$ antisymmetric quantum state

\[ |i> = 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] \]

- Once one $B$ decays to a basis state, the other projects to the orthogonal state

Charge of lepton or kaon indicates the flavor of the $B$ at the time of decay.
Experiment

- Reconstruct $B^0 \rightarrow \ell^+ \nu_\ell D^{*-}$ using a partial reconstruction technique.
- Find the flavor of the “tag $B$” using charged kaons in the rest of the event.
- The “wrong-sign” decays (via mixing) are identified by same-sign lepton-kaon combination:
  
  $$A_{sl} = \frac{N(B^0B^0) - N(\bar{B}^0\bar{B}^0)}{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)} = \frac{N(\ell^+K^+) - N(\ell^-K^-)}{N(\ell^+K^+) + N(\ell^-K^-)}$$

- Partial reconstruction gives higher efficiency than exclusive reconstruction, and better purity than inclusive lepton reconstruction.
- Kaon tag has a higher efficiency than lepton tag.
  - Somewhat higher mistag probability
  - Need to take care of interference due to doubly-Cabibbo-suppressed decay
The BABAR detector at PEP II NIM A479, 1 (2002)

Cherenkov Detector
144 quartz bars
11,000 PMTs

Calorimeter
6580 CsI(Tl) crystals

Silicon Vertex Tracker
5 double-sided layers

Drift Chamber
40 layers

Instrumented Flux Return
18–19 layers

e^+ (3.1 GeV)
e^- (9 GeV)

1.5 T solenoid (superconducting)

As of 2008/04/11 00:00

BaBar Recorded Luminosity:
- Y(4S): 531.43 fb
- Y(4s): 432.89 fb
- Y(3s): 30.23 fb
- Y(2s): 14.45 fb
- Off Peak Luminosity: 53.85 fb

Cowan 8

Total ~530 fb^{-1}

~470 M B\bar{B} pairs

Y(4S)

\sigma(e^+e^- \rightarrow \chi)

2m_B
$B \to \ell \nu D^*$ partial reconstruction

- Use only lepton ($e$, $\mu$) and the low momentum $\pi_s$ of the opposite sign from $D^{* -} \to \pi^-_s D^0$, ignoring the remaining products from charm.
- Assume $B$ at rest in $\Upsilon(4S)$ frame.
- Approximate $D^*$ direction using $\pi_s$: $\vec{p}_{D^*} = f(\vec{\pi}_s)$
- Reconstruct $B$ decay vertex using a beamspot constraint:

<table>
<thead>
<tr>
<th>$L &gt; 0.4$</th>
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- Build a likelihood ratio function using lepton and pion momenta, and vertexing probability to reduce background.
$B \to \ell \nu D^*$ partial reconstruction

- Assume only the neutrino is not accounted for, and then calculate the missing neutrino mass
- Good signal
  \[ B^0 \to D^*^- (X) \ell^+ \nu \]
  \[ B^0 \to D^*^- (X) \tau^+ \nu_\tau; \quad \tau^+ \to \ell^+ \nu_\ell \bar{\nu}_\tau \]
  \[ B^0 \to D^*- h^+; \text{ (misidentified)} \]
- Peaking but no $B^0$ flavor info
  - double charm followed by charm semileptonic decay
  - charged $B$.
- Yield:
  \[(5945 \pm 7) \times 10^3\] peaking events

\[ M_{\nu}^2 = (\mathcal{P}_B - \mathcal{P}_{D^*} - \mathcal{P}_\ell)^2 \]
Kaon tag

• Kaons are identified using ionization energy loss in the tracking devices and Cherenkov angles: ~85% efficiency, ~3% pion misidentification.

• Tag-$B$ vertex is identified by intersecting kaon track with the beamspot.

• Define $\Delta t = \frac{z_{\text{reco.}} - z_{\text{tag}}}{\gamma \beta c}$, which should follow $B$ decay distribution (plus some smearing from charm lifetime) for signal events.
Kaon tag

- Kaon can also come from the reco. side, mimicking a mixed event.

Use $\Delta t$ and angular correlation in the PDF to separate the two.
Contributing asymmetries

- Observed asymmetry has contributions from physics and detector.

- Observed asymmetry for same-sign signal events with tag-side kaon reflects \((\ell, \pi_s)\) reconstruction charge asymmetry, kaon-id charge asymmetry, and physics \(A_{sl}\).
  
  \[
  A_{obs;K-tag} = A_{\ell\pi} + A_K + A_{sl}
  \]

- If kaon is from reco. side, then physics \(A_{sl}\) contribution is diluted by the mixing probability \(\chi_d\). (mixed and unmixed are equally likely to be reconstructed.)
  
  \[
  A_{obs;K-rec} = A_{\ell\pi} + A_K + \chi_d A_{sl}
  \]

- Asymmetry before kaon tagging
  
  \[
  A_{obs;rec} = A_{\ell\pi} + \chi_d A_{sl}
  \]

- We have enough observables to determine all three \(A_{\ell\pi}, A_K,\) and \(A_{sl}\) from data simultaneously.
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  - \(A_{obs;K-rec} = A_{\ell\pi} + A_K + \chi_d A_{sl}\)

- Asymmetry before kaon tagging
  - \(A_{obs;rec} \approx A_{\ell\pi} + \chi_d A_{sl}\)

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Contributing asymmetries

- Observed asymmetry has contributions from physics and detector.

- Observed asymmetry for same-sign signal events with tag-side kaon reflects $(\ell, \pi_s)$ reconstruction charge asymmetry, kaon-id charge asymmetry, and physics $A_{sl}$.
  - $A_{\text{obs};K\text{-tag}} \approx A_{\ell\pi} + A_K + A_{sl}$

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- Asymmetry before kaon tagging
  - $A_{\text{obs};rec} \approx A_{\ell\pi} + \chi_d A_{sl}$

- We have enough observables to determine all three $A_{\ell\pi}$, $A_K$, and $A_{sl}$ from data simultaneously.
Without interference from doubly-Cabibbo-suppressed decays (DCSD) on the tag side, the underlying physics would be relatively simple:

\[
\begin{align*}
\mathcal{F}_{\bar{B}^0 B^0}(\Delta t) &= \frac{\Gamma_0 e^{-\Gamma_0 |\Delta t|}}{2} [\cosh(\Delta \Gamma \Delta t/2) + \cos(\Delta m_d \Delta t)] \\
\mathcal{F}_{B^0 \bar{B}^0}(\Delta t) &= \frac{\Gamma_0 e^{-\Gamma_0 |\Delta t|}}{2} [\cosh(\Delta \Gamma \Delta t/2) + \cos(\Delta m_d \Delta t)] \\
\mathcal{F}_{\bar{B}^0 \bar{B}^0}(\Delta t) &= \frac{\Gamma_0 e^{-\Gamma_0 |\Delta t|}}{2} [\cosh(\Delta \Gamma \Delta t/2) - \cos(\Delta m_d \Delta t)] \\
\mathcal{F}_{B^0 B^0}(\Delta t) &= \frac{\Gamma_0 e^{-\Gamma_0 |\Delta t|}}{2} [\cosh(\Delta \Gamma \Delta t/2) - \cos(\Delta m_d \Delta t)]
\end{align*}
\]
Signal physics model

- Including interference from doubly-Cabibbo-suppressed decays (DCSD) on the tag side.

\[
\mathcal{F}_{B^0 \bar{B}^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1 + r'^2)} \left[ \left( 1 + \frac{|q|^2}{|p|^2} r'^2 \right) \cosh(\Delta \Gamma \Delta t / 2) + \left( 1 - \frac{|q|^2}{|p|^2} r'^2 \right) \cos(\Delta m_d \Delta t) \right] - \frac{|q|}{|p|} (b + c) \sin(\Delta m_d \Delta t),
\]

\[
\mathcal{F}_{B^0 \bar{B}^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1 + r'^2)} \left[ \left( 1 + \frac{|p|^2}{|q|^2} r'^2 \right) \cosh(\Delta \Gamma \Delta t / 2) + \left( 1 - \frac{|p|^2}{|q|^2} r'^2 \right) \cos(\Delta m_d \Delta t) \right] + \frac{|p|}{|q|} (b - c) \sin(\Delta m_d \Delta t),
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\]

\[
r' \sim \frac{\mathcal{A}(b \to \bar{u}cd)}{\mathcal{A}(b \to c\bar{u}d)} \sim \mathcal{O}(\%)\]

\[
b = 2r' \sin(2\beta + \gamma) \cos \delta'
\]

\[
c = -2r' \cos(2\beta + \gamma) \sin \delta'
\]
Fitting

- Five variables (Δt, σΔt, cosθℓK, Mν², pK) binned fit to separate signal to background, tag-side kaon from reco-side.

- Also include opposite-sign (unmixed) events ℓ⁺K⁻/ℓ⁻K⁺ to improve resolution and mis-tag parameters, etc.

- More than 100 free parameters:
  - Asl, Aℓπ, AK,
  - reco-side K fraction,
  - wrong tag fractions (charge dependent),
  - Doubly-Cabibbo-suppressed decay parameters,
  - Δt resolution parameters,
  - B lifetime, mixing rate, etc.
Result

\[ A_{s1} = (0.6 \pm 1.6^{+3.6}_{-3.2}) \times 10^{-3} \]

**BABAR Preliminary**
Result summary

- Lifetime and mixing rate consistent with the world average.
- A few per mille reconstruction asymmetry.
- Order of a percent kaon tag asymmetry.
- Fit to MC reproduces the generated value (also checked varying the generated value).

<table>
<thead>
<tr>
<th>Source</th>
<th>Fit to Data</th>
<th>Fit to MC</th>
<th>MC value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peaking Sample Composition</td>
<td>$(0.6 \pm 1.6) \times 10^{-3}$</td>
<td>$(0.4 \pm 0.5) \times 10^{-3}$</td>
<td>0</td>
</tr>
<tr>
<td>Combinatorial Sample Composition</td>
<td>$(3.0 \pm 0.4) \times 10^{-3}$</td>
<td>$(9.7 \pm 0.2) \times 10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta t$ Resolution Model</td>
<td>$(3.1 \pm 0.5) \times 10^{-3}$</td>
<td>$(8.4 \pm 0.3) \times 10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>$K_R$ Fraction</td>
<td>$(13.7 \pm 0.3) \times 10^{-3}$</td>
<td>$(14.7 \pm 0.1) \times 10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>$\tau_B^0$</td>
<td>$1.5535 \pm 0.0019$</td>
<td>$1.5668 \pm 0.0012$</td>
<td>1.540</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>$0.5085 \pm 0.0009$</td>
<td>$0.4826 \pm 0.0006$</td>
<td>0.489</td>
</tr>
</tbody>
</table>

$\Delta_{CP} = 1 - \left| \frac{q}{p} \right| \approx \frac{1}{2} A_{sl}$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma(\Delta_{CP})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peaking Sample Composition</td>
<td>$+1.80 \times 10^{-3}$</td>
</tr>
<tr>
<td>Combinatorial Sample Composition</td>
<td>$-1.17 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta t$ Resolution Model</td>
<td>$+0.60 \times 10^{-3}$</td>
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<tr>
<td>$K_R$ Fraction</td>
<td>$+0.11 \times 10^{-3}$</td>
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<tr>
<td>$K_R$ $\Delta t$ Distribution</td>
<td>$+0.65 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fit Bias</td>
<td>$+0.58 \times 10^{-3}$</td>
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<tr>
<td>$CP$ eigenstate Description</td>
<td>$-0.46 \times 10^{-3}$</td>
</tr>
<tr>
<td>Physical Parameters</td>
<td>$+0.28 \times 10^{-3}$</td>
</tr>
<tr>
<td>Total</td>
<td>$+1.88 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Conclusions

\[ A_{sl} = (0.6 \pm 1.6^{+3.6}_{-3.2}) \times 10^{-3} \]

• Consistent with and more precise than previous \( B \) factories average \((-0.5\pm5.6)\times10^{-3}\).

• Competitive and complementary to similar measurements at hadron colliders.

• Result consistent with the Standard Model, no sign of \( CP \) violation in \( B_d \) mixing.
  ♦ tension still exists in \( B_s \) mixing; \( B \) factories are not able to contribute to that measurement.

\( A_{sl} \) in BABAR Preliminary [accepted by PRL]