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CP violation: Recent Results from BABAR
Presented at SUSY2014

Roger Barlow
representing the BaBar collaboration

Huddersfield University

25th July 2014
A brief history of CP violation in particle physics

**Discovery 1964**
Small effect (0.3%) for s quark: $K_L^0 \rightarrow \pi^+\pi^-$

Nothing much happened for almost 40 years: $K_L^0 \rightarrow \ell^\pm\pi^\mp\nu$, $K_L^0 \rightarrow \pi^0\pi^0$

**Seen in B mesons (b quark): BaBar and Belle**

PRL 81 091801, 2001, Nobel prize 2008
Large effects (several %). Many measurements.
Mainstream $\Upsilon(4S) \rightarrow B^0\bar{B}^0$
1st decays to CP eigenstate, 2nd tagged as $b$ or $\bar{b}$
Plot decay time dependences.

**Reported in D mesons (c quark)**

1 For Kobayashi and Maskawa
Overview

Talk covers 7 non-mainstream beauty results and 3 charm results

Caused by complex weak phase in:

Mixing
Indirect CP violation
Violation of CP quantum number conservation

Decays
Direct CP violation
E.g. asymmetry in $B^0 \rightarrow K^+\pi^- / \bar{B}^0 \rightarrow K^-\pi^+$ is 9.8 ± 1.2%

Interference between mixing and decays
Different time dependence
Results from $471 \times 10^6 \Upsilon(4S)$ decays produced with speed $0.5c$ in the lab
Luminosity $1.2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$  
Currents 2-3 amps
Technical triumph. Design goals greatly exceeded.
The BABAR detector

Precision vertex chamber, charged particle tracking, PID using DIRC, precision EM calorimeter, muon detector.
Direct CP violation in $B^{\pm} \rightarrow K^{*^{\pm}(892)}\pi^{0}$

new result - preliminary

Select $B^{\pm} \rightarrow K_{s}^{0}\pi^{\pm}\pi^{0}$. BR $(45.9 \pm 2.6 \pm 3.0 \pm 8.6) \times 10^{-6}$

First measurement!

Final error uncertainty due to signal model

Overall $A_{CP} = \frac{N^{+}-N^{-}}{N^{++}+N^{--}} = 0.07 \pm 0.05 \pm 0.03 \pm 0.04$

Fit Dalitz plot using isobar model: $K^{*^{0}(892)}\pi^{+}$, $K^{*^{+}(892)}\pi^{0}$, $K_{s}^{0}\rho^{+}$, etc

$A_{CP} = -0.52 \pm 0.14 \pm 0.04 \pm 0.04$ : Significant at 3.4σ

Difference between $B^{+} \rightarrow K^{*^{+}}\pi^{0}$ and $B^{-} \rightarrow K^{*^{-}}\pi^{0}$
Direct CP violation in $B^\pm \rightarrow K(\ast)^\pm D(\ast)^0$: global fit to $\gamma$

Phys Rev D 87 052015 (2013)

Interference between 2 diagrams in final states accessible through $D$ or $\bar{D}$

GGSZ: $K\pi\pi$ etc
GL: $K^+K^-$ etc
ADS: $K^+\pi^-$ doubly-Cabibbo-suppressed states

$\gamma = (69^{+17}_{-16})^\circ$

Significant at $5.9\sigma$
$B^0 \rightarrow \pi^+\pi^-\pi^0$: fit to $\alpha$


Dalitz plot: fit $\rho^\pm\pi^\mp$ and $\rho^0\pi^0$.

Transform to square plot to include efficiencies.

Time dependent fit

$\propto 1 + C \cos(\Delta_m t) + S \sin(\Delta_m t)$

$C$ terms are direct CP,
$S$ terms are interference

Results interpretable in terms of CKM angle $\alpha$
10 different exclusive $X_s$ modes ($K^+, K^+\pi^0, K^+\pi^-, K^+\pi^--\pi^0, K^+\pi^-\pi^+, K^0_S, K^0_S\pi^0, K^0_S\pi^+, K^0_S\pi^+\pi^0, K^0_S\pi^+\pi^-\pi^0$)
Extrapolation gives branching ratio
$(6.73^{+0.70+0.34}_{-0.64-0.25} \pm 0.50) \times 10^{-6}$
for $m_{\ell\ell}^2 > 0.1$

$A_{CP} = 0.04 \pm 0.11 \pm 0.01$

blue=electrons, black=muons, red=average
Use charged $B$ mesons and self-tagging neutral $B$ meson decays
Sum over exclusive $X_s$ states
Reconstruct 38 ($\times 2$) different final states - use 16 with good statistics.

$$A_{CP} = \frac{\Gamma(B^-/B^0) - \Gamma(B^+/B^0)}{\Gamma(B^-/B^0) + \Gamma(B^+/B^0)}$$

$A_{CP} = (1.7 \pm 1.9 \pm 1.0)\%$

consistent with SM prediction

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<th>Final State</th>
<th>#</th>
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<td>$B^+ \rightarrow K^+ \eta \gamma$</td>
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<td>38</td>
<td>$B^0 \rightarrow K^+ K^- K_S \pi^0 \gamma$</td>
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\[ B^0 \rightarrow D^*+ D^*- \] Time dependent asymmetry


One \( D^* \) reconstructed fully from \( D^0 \pi \) with \( D^0 \rightarrow K\pi, K\pi\pi, K\pi\pi\pi, K_S^0 \pi\pi \)

Second reconstructed partially: combine first with slow pion and requiring missing mass consistent with \( M_D \).

Flavour of other \( B^0 \) from identified kaon or lepton.

\[ C = 0.15 \pm 0.09 \pm 0.04 \quad S = -0.34 \pm 0.12 \pm 0.05 \]

Consistent with \( \sin 2\beta \) determined from \( B^0 \rightarrow \text{charmonium} \).
CP violation in mixing: $B^0 \rightarrow D^{*-} X \ell \nu_{\ell}$ and a kaon tag

Reminder: CPV in mixing not seen by BaBar: dilepton asymmetry ( PRL 96 251802 (2006) )

$$A_{CP} = (1.6 \pm 5.4 \pm 3.8) \times 10^{-3}$$

Consistent with SM($\approx 0$). Means the DØ result must be due to $B_s$ decays.

Partial reconstruction technique for $D^*$
Tag the other $B$ through kaon
(avoid lepton identification systematics)

$$A_{CP} = \frac{N(B^0 B^0) - N(B^0 \bar{B}^0)}{N(B^0 B^0) + N(B^0 \bar{B}^0)} = (0.6 \pm 1.7^{+3.8}_{-3.2}) \times 10^{-3}$$
Charm: \( D^0 \to K^+ K^-, K^\pm \pi^\mp, \pi^+ \pi^- \)


Compare lifetimes to CP even \( K^+ K^- \) and \( \pi^+ \pi^- \) with CP mixed \( K^\pm \pi^\mp \)

Rate \( \Gamma^+ \) for \( D^0 \to CP_{even} \),
\( \bar{\Gamma}^+ \) for \( \bar{D}^0 \to CP_{even} \),
\( \Gamma \) for \( D^0 \to CP_{mixed} \)

\[
y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1 = (0.72 \pm 0.18 \pm 0.12)\% \\
\Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma} = (0.09 \pm 0.26 \pm 0.06)\%
\]

So 3.3\( \sigma \) evidence for mixing, no evidence for CP violation.
Evaluate charge asymmetry:

\[ A_{CP} = (0.37 \pm 0.30 \pm 0.15)\% \]

Also no sign in any of the subregions (low \( M_{K\pi} \), \( K^* \), \( \phi \), high \( M_{K\pi} \)) or in isobar-model fits (\( KK^* \), \( \pi\phi \), etc)
Charm: $D^\pm \rightarrow K^0_S K^\pm$, $D_s^\pm \rightarrow K^0_S K^\pm$, $D_s^\pm \rightarrow K^0_S \pi^\pm$


Detector charge bias determined from data

$A_{CP}(D^\pm \rightarrow K^0_S K^\pm) = (0.13 \pm 0.36 \pm 0.25)\%$

$A_{CP}(D^\pm_s \rightarrow K^0_S K^\pm) = (-0.05 \pm 0.23 \pm 0.24)\%$

$A_{CP}(D^\pm_s \rightarrow K^0_S \pi^\pm) = (0.6 \pm 2.0 \pm 0.3)\%$

All consistent with zero and small SM prediction (0.33 %).
Conclusions

Measurements of CP violation in B mesons continue
No sign of CP violation in charm
No sign of charge asymmetry as reported by DØ
Results give consistent values of CKM matrix $\alpha, \beta, \gamma$ angles.
Powerful constraints on New Physics models