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CP violation: Recent results from BaBar

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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 $B^0 \rightarrow K^+\pi^- / \overline{B^0} \rightarrow K^-\pi^+$ is $9.8 \pm 1.2\%$

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 $3.4\sigma$

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

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 $m^2_{\ell\ell} > 0.1$

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

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 ($x2$) different final states - use 16 with good statistics.

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

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

consistent with SM prediction

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<th>Final State</th>
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<td>$B^+ \rightarrow K_S\pi^+\gamma$</td>
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<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 $D^0 \rightarrow K\pi, K\pi\pi, K\pi\pi\pi, K^0_S\pi\pi$
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 $\sin2\beta$ determined from $B^0 \rightarrow$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
(avoiding lepton identification systematics)

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


Compare lifetimes to CP even $K^+ K^-$ and $\pi^+ \pi^-$ with CP mixed $K^{\pm} \pi^{\mp}$

Rate $\Gamma^+$ for $D^0 \rightarrow CP_{even}$,
$\bar{\Gamma}^+$ for $\bar{D}^0 \rightarrow CP_{even}$,
$\Gamma$ for $D^0 \rightarrow CP_{mixed}$

$\gamma_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1 = (0.72 \pm 0.18 \pm 0.12)\%$

$\Delta \gamma = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma} = (0.09 \pm 0.26 \pm 0.06)\%$

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: $D^\pm \rightarrow K_S^0 K^\pm$, $D_S^\pm \rightarrow K_S^0 K^\pm$, $D_S^\pm \rightarrow K_S^0 \pi^\pm$


Detector charge bias determined from data

$A_{CP}(D^\pm \rightarrow K_S^0 K^\pm) = (0.13 \pm 0.36 \pm 0.25)\%$
$A_{CP}(D_S^\pm \rightarrow K_S^0 K^\pm) = (-0.05 \pm 0.23 \pm 0.24)\%$
$A_{CP}(D_S^\pm \rightarrow K_S^0 \pi^\pm) = (0.6 \pm 2.0 \pm 0.3)\%$

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