

CP Violation in B Decays (and the Search for New Physics)

David London

Université de Montréal

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CP Violation in B Decays

Requires interference of (at least) two amplitudes with different weak (CP-odd) phases. \exists 3 types of CPV observables:

- 1 Indirect CPV: interference of $B^0 \rightarrow f$ and $B^0 \rightarrow \bar{B}^0 \rightarrow f$. Final state f usually (but not always) a CP eigenstate.
- 2 Direct CPV: $\Gamma(B \rightarrow f) \neq \Gamma(\bar{B} \rightarrow \bar{f})$. Nonzero A_{CP} requires that interfering amplitudes have different weak and strong (CP-even) phases. Strong phases not known \implies difficult to use A_{CP} to extract weak-phase info and test for NP. (\exists exceptions, which I'll describe.)
- 3 Triple Products: term of form $\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$ in $|A(B \rightarrow f)|^2$, where f involves (at least) 4 particles. TPs are T-violating, not CPV. Get CPV effect by comparing TPs in process and anti-process. TPs do not require that interfering amplitudes have a strong-phase difference.

α, β, γ

BaBar, Belle: main goal was to measure α, β, γ , search for NP via $\alpha + \beta + \gamma \neq \pi$. Found

- Using $B_d \rightarrow J/\psi K_S$ and related decays, $\beta = (22.14_{-0.67}^{+0.69})^\circ$,
- Using $B_d \rightarrow \pi^+ \pi^-$ and related decays, along with an isospin analysis, $\alpha = (86.4_{-4.3}^{+4.5})^\circ$,
- Using $B^+ \rightarrow DK^+$ (direct CPV), $\gamma = (72.1_{-5.7}^{+5.4})^\circ$,

giving

$$\alpha + \beta + \gamma = (180.6_{-7.2}^{+7.1})^\circ$$

\Rightarrow no sign of NP.

Note: assuming no tree-level NP, only β and α receive NP contributions ($B_d^0 - \bar{B}_d^0$ mixing). But they are of opposite sign, i.e., they cancel in the sum $\Rightarrow \alpha + \beta + \gamma = \pi$ was (almost) guaranteed.

To use this test of NP, need to measure γ using loop-level decays. (Will come back to this.)

Another test of NP: SM predicts

$$\beta(\text{in } b \rightarrow c\bar{c}s) \simeq \beta(\text{in } b \rightarrow s \text{ penguin decays}) .$$

Could be broken if \exists NP in $b \rightarrow s$ penguin. Latest measurements:

$$\begin{aligned} \sin 2\beta(\text{in } b \rightarrow c\bar{c}s) &= 0.699 \pm 0.017 , \\ \sin 2\beta(\text{in } b \rightarrow s \text{ penguin decays}) &= 0.648 \pm 0.038 . \end{aligned}$$

Results agree, no sign of NP.

SM predicts weak phase of B_s^0 - \bar{B}_s^0 mixing to be very small, $O(10^{-2})$.

Measured:

$$\beta_s = 0.01848_{-0.00036}^{+0.00042} \text{ radians} .$$

Consistent with SM.

Direct CPV

If a process has two contributing amplitudes,

$$A = A_1 + A_2 \quad , \quad A_1 = |A_1|e^{i\phi_1}e^{i\delta_1} \quad , \quad A_2 = |A_2|e^{i\phi_2}e^{i\delta_2} \quad ,$$

the direct CP asymmetry is

$$A_{CP} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2) \quad .$$

A nonzero A_{CP} requires both nonzero weak-phase and strong-phase differences.

2-body B decays: many measurements, some nonzero A_{CP} results. E.g., $A_{CP}(B^+ \rightarrow \eta K^+) = -0.37 \pm 0.08$, $A_{CP}(B_s^0 \rightarrow \pi^+ K^-) = 0.213 \pm 0.017$.

In SM, these decays receive contributions from 2 amplitudes (tree + penguin), with different weak phases. But because strong phases cannot be calculated, cannot use measurements to extract information about weak phases and test for NP.

Exception: $B \rightarrow \pi K$ decays. \exists 4 decays: $B^+ \rightarrow \pi^+ K^0$, $B^+ \rightarrow \pi^0 K^+$, $B_d^0 \rightarrow \pi^- K^+$, $B_d^0 \rightarrow \pi^0 K^0$. Amplitudes obey a quadrilateral isospin relation: $\sqrt{2}A^{00} + A^{-+} = \sqrt{2}A^{0+} + A^{+0}$.

9 observables measured: 4 BRs, 4 direct CP asymmetries A_{CP} , and 1 indirect CP asymmetry S_{CP} in $B_d^0 \rightarrow \pi^0 K^0$. \exists a number of contributing amplitudes (diagrams). Keeping leading-order diagrams \implies expect

$$A_{CP}(B^+ \rightarrow \pi^0 K^+) = A_{CP}(B_d^0 \rightarrow \pi^- K^+) \\ \text{Measured: } \quad 0.040 \pm 0.021 \quad \quad -0.082 \pm 0.006 .$$

Differ by 5.5σ . This is the “ $B \rightarrow \pi K$ puzzle.”

Write amplitudes in terms of 3 diagrams: T' , C' , P'_{tc} (neglect small P'_{uc}). With γ , \exists 6 unknown parameters \implies can do a fit. (Note: this is how we can extract info despite unknown strong phases.)

Find (N.B. Beaudry, A. Datta, D.L., A. Rashed and J.-S. Roux, 1709.07142)

- 1 fix $|C'/T'| = 0.2$ (theoretically preferred) and set γ to its measured value: get very poor fit (p value = 0.03).
- 2 fix $|C'/T'| = 0.5$ (theoretically large) and set γ to its measured value: get good fit (p value = 0.43).
- 3 fix $|C'/T'| = 0.5$ and allow γ to vary: get acceptable fit (p value = 0.36). However, best-fit value of $\gamma = (51.2 \pm 5.1)^\circ$ (deviation of 2.7σ from measured value). Note: since penguins are involved, this is a loop-level extraction of γ .

Conclusion: there is still unresolved tension in $B \rightarrow \pi K$ decays.

3-body B decays: $B \rightarrow K\pi\pi$, $K\bar{K}K$, $\pi\pi\pi$, $K\bar{K}\pi$ studied. Inclusive A_{CP} measured. For $K\pi\pi$ and $K\bar{K}K$, also measure A_{CP} in localized areas of Dalitz plot. Although \exists studies with particular theoretical models, and with U-spin symmetry, nobody able to search for NP.

Exception: extraction of loop-level γ from $B_d^0 \rightarrow K^+\pi^0\pi^-$,
 $B_d^0 \rightarrow K_S\pi^+\pi^-$, $B_d^0 \rightarrow K_S K_S K_S$, $B_d^0 \rightarrow K^+ K_S K^-$ and $B^+ \rightarrow K^+\pi^+\pi^-$

(E. Bertholet, E. Ben-Haim, B. Bhattacharya, M. Charles and D.L., 1812.06194):

- Final states related by SU(3). 3 particles \implies 6 symmetry states. Method uses fully-symmetric (FS) state.
- All decays: write FS amplitudes in terms of (3-body) diagrams.
- All decays: Dalitz plots (DPs) measured by BaBar (some time-dependent). From DPs, construct amplitude (isobar method), generate FS DP, get FS observables (BRs, A_{CP} , S_{CP}).
- At each point of DP: perform fit, find best-fit values of theoretical parameters. All parameters will vary throughout the DP, *except* γ .

Consider all DP points: extract loop-level γ with 6-fold ambiguity:

1. $(12.9_{-4.3}^{+8.4} \text{ (stat)} \pm 1.3 \text{ (syst)})^\circ$, 2. $(36.6_{-6.1}^{+6.6} \text{ (stat)} \pm 2.6 \text{ (syst)})^\circ$,
3. $(68.9_{-8.6}^{+8.6} \text{ (stat)} \pm 2.4 \text{ (syst)})^\circ$, 4. $(223.2_{-7.5}^{+10.9} \text{ (stat)} \pm 1.0 \text{ (syst)})^\circ$,
5. $(266.4_{-10.8}^{+9.2} \text{ (stat)} \pm 1.9 \text{ (syst)})^\circ$, 6. $(307.5_{-8.1}^{+6.9} \text{ (stat)} \pm 1.1 \text{ (syst)})^\circ$.

Triple Products

Consider the decay $B \rightarrow f$, with $f \rightarrow 4$ particles. If $A = A_1 + A_2$, with $A_1 = |A_1|e^{i\phi_1}e^{i\delta_1}$ and $A_2 = |A_2|e^{i\phi_2}e^{i\delta_2}$, then $|A|^2$ may contain the term $\epsilon_{\mu\nu\rho\sigma}p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$. This is a triple product (TP), with coefficient

$$\text{Im}(A_1 A_2^*) = |A_1||A_2| \left(\underbrace{\sin(\phi_1 - \phi_2) \cos(\delta_1 - \delta_2)}_{\text{true TP}} + \underbrace{\cos(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}_{\text{fake TP}} \right).$$

TPs are coefficients of P-odd terms in angular distribution \implies
TP(anti-process) = TP(process) \implies true (CPV) TP = TP(process) + TP(anti-process). TPs are sensitive to NP in the decay.

Most common decay is $B \rightarrow V_1(\rightarrow P_1 P'_1) V_2(\rightarrow P_2 P'_2)$. Examples: (i) $B_d \rightarrow \phi K^*$ (Belle) and $B_s^0 \rightarrow \phi\phi$ (LHCb), (ii) $B_s^0 \rightarrow K^*(892)\bar{K}^*(892)$ (LHCb). Both cases: SM predicts no TP (one decay amplitude), experiment finds no TP asymmetry \implies no evidence of NP in (i) $b \rightarrow s\bar{s}s$ or (ii) $b \rightarrow s\bar{d}d$.

B Anomalies and TPs

Another decay: $B \rightarrow K^*(\rightarrow K\pi)\mu^+\mu^-$. Angular distribution contains P'_5 (hint of NP). Many models proposed to explain $b \rightarrow s\mu^+\mu^-$ anomalies. How to distinguish them? One way: different NP models predict different CPV effects: TPs. Angular distribution also contains TP terms. Their (precise) measurement can help to differentiate NP models. (A.K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D.L. and S.U. Sankar, 1703.09247)

There are also hints of NP in $b \rightarrow c\tau\bar{\nu}_\tau$, variety of models proposed to explain data. One way to distinguish NP models is to measure CPV in $B \rightarrow D^*\tau\bar{\nu}$. Specifically, the CPV observables are TPs in $B \rightarrow D^*(\rightarrow D\pi)\tau^-(\rightarrow \pi^-\nu_\tau)\bar{\nu}$. (B. Bhattacharya, A. Datta, S. Kamali and D.L., 1903.02567, 2005.03032)

Conclusions

When we were planning to study CPV in B decays (the 1990s), the hope was that the measurement of indirect CP asymmetries would reveal large NP effects. That did not happen – all measurements seem to be consistent with the SM.

Using CPV measurements, the only hints of NP have appeared (surprisingly) in direct CPV: the extraction of a loop-level value of γ from $B \rightarrow \pi K$ decays and 3-body $B \rightarrow K\pi\pi$ and $B \rightarrow K\bar{K}K$ decays might be different from the tree-level value.

At present, there are (CP-conserving) hints of NP in processes involving $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow c\tau\bar{\nu}_\tau$ decays. To differentiate between proposed models, measurements of CPV TPs in $B \rightarrow K^*(\rightarrow K\pi)\mu^+\mu^-$ and $B \rightarrow D^*(\rightarrow D\pi)\tau^-(\rightarrow \pi^-\nu_\tau)\bar{\nu}$ may be useful.

Of course, Belle II and LHCb will continue to measure CPV in B decays. There may yet be surprises.