Measurements of CKM angles at Belle

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In this review recent studies on $CP$ violation and related hadronic $B$ decays by the Belle experiment, in particular measurements of CKM angles $\phi_1$ and $\phi_2$ are reported.
1. Introduction

In the standard model (SM) of electroweak interaction, charge-parity (CP) violation arises from an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The Belle and BaBar experiments have established CP violating effects in the $B$ meson system. Both experiments use their measurements of the mixing-induced CP violation in $b \rightarrow c \bar{c} s$ transitions to precisely determine the parameter $\sin(2\phi_1)$, where $\phi_1$ is defined as $\arg[-V_{cb}V_{ub}^*/V_{td}V_{tb}^*]$, with $V_{ij}$ is the CKM matrix element of quarks $i, j$. In this proceeding an overview of recent measurements of the CKM angles $\phi_1$ and $\phi_2$ ($\arg[-V_{ub}V_{cb}^*/V_{cd}V_{td}^*]$) is presented. Unless stated otherwise, all measurements presented here are based on Belle’s final dataset of $772 \times 10^6 \bar{B}B$ pairs.

2. First observation of CP violation in $\bar{B}^0 \rightarrow D^{(*) \pm} h^0$ decays with Belle + BaBar data

The decay $\bar{B}^0 \rightarrow D^{(*)} h^0$, where $h^0$ is a light, unflavored neutral meson ($h^0 \in \pi^0, \eta, \omega$), is dominated by a $b \rightarrow c \bar{u} d$ color-suppressed tree diagram in the SM. The final state $D^{(*)} h^0$ is a CP eigenstate if the neutral $D$ meson decays to a CP eigenstate as well (i.e., $D_{CP}^0 \rightarrow K_S^0 \pi^0$, $D_{CP}^0 \rightarrow K_S^0 \omega$ (CP = −1) or $D_{CP}^0 \rightarrow K^+ K^−$ (CP = +1) and $D_{CP}^0 \rightarrow D_{CP}^0 \pi^0$). Therefore, a time-dependent CP asymmetry measurement is applicable in the same way as used in the $b \rightarrow c \bar{c} s$ decays, but with a small correction from the $b \rightarrow u \bar{c} d$ process. This $b \rightarrow u \bar{c} d$ amplitude is suppressed by $V_{ub} V_{cd}^*/V_{ub} V_{cd} \approx 0.02$ relative to the leading amplitude. Neglecting the suppressed amplitude, the time evolution of $\bar{B}^0 \rightarrow D^{(*)} h^0$ decays is governed by $\phi_1$ [2].

Due to the limited available statistics, previous measurements performed separately by the BaBar and Belle collaborations were not able to establish CP violation in these or related decays [3]. This motivated a joint analysis using the combined full dataset of Belle and BaBar experiments [4]. Using a fit to the beam-energy constrained mass $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - p_B^2}$, where $E_{\text{beam}}$ is the beam energy and $p_B$ is the reconstructed $B$ meson momentum in the center-of-mass system, we extract 508 ± 31 signal events in the BaBar data of 431 million $B\bar{B}$ events and 757 ± 44 signal events in the Belle data of 772 million $B\bar{B}$ events, as shown in Fig. 1. The dominant source of background originates from $e^+ e^- \rightarrow p\bar{q}$ ($q \in u, d, s, c$) continuum events. To suppress this background, we use a multivariate analyzer based on a neural network. The neural network uses the so-called event shape variables to discriminate continuum events, which tend to be jetlike, from spherical $B\bar{B}$ events.

The time-dependent CP violation measurement is performed using established Belle and BaBar techniques for the vertex reconstruction, the flavor-tagging, and the modeling of $\Delta t$ resolution effects, where $\Delta t$ is the proper time interval between the decays of the two $B$ mesons produced in an $\Upsilon(4S)$ decay. Combined analysis is performed by maximizing a joint log-likelihood function

$$\ln L = \sum_i \ln \mathcal{L}_i^{\text{Belle}} + \mathcal{L}_i^{\text{BaBar}}.$$ (2.1)

The experiment-dependent probability density function (PDF) $\mathcal{P}^{\text{exp}}$ is defined as

$$\mathcal{P}^{\text{exp}} = \sum_k f_k \int \left[ P_k(\Delta') h_k^{\text{exp}}(\Delta - \Delta') \right] d\Delta',$$ (2.2)

where $f_k$ is the number of events in the $k$-th bin of the $\Delta'$ variable.
Figure 1: $M_{bc}$ distributions (data points with error bars) and fit projections (solid lines) of $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$ decays for (a) BaBar and (b) Belle. The dashed (dotted) lines represent projections of the signal (background) fit components.

where the index $k$ represents the signal and background PDF components. The symbol $P_k$ denotes the PDF describing the proper time interval of the particular physical process and $R_k^{\text{Exp}}$ refers to the corresponding resolution function. The fractions $f_k$ are evaluated on an event-by-event basis as a function of $M_{bc}$. While the background model is determined from the $M_{bc}$ sideband and hence is experiment-dependent, the signal model is expressed as

$$P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \left[ 1 + q (S \sin(\Delta m \Delta t) - A \cos(\Delta m \Delta t)) \right],$$

(2.3)

where the $B^0$ meson lifetime is represented by $\tau_{B^0}$, $B^0 - \bar{B}^0$ mixing frequency by $\Delta m$ and $q$ is event- and experiment-dependent tagging quality parameter. In the SM, the coefficients, $S = -\eta_f \sin(2\phi_1)$ and $A = 0$, where $\eta_f$ is the CP eigenvalue of the final state. $S$ and $A$ quantify mixing-induced and direct CP violation, respectively. The combined fit gives

$$-\eta_f S = +0.66 \pm 0.10 \text{ (stat.)} \pm 0.06 \text{ (syst.)}, \quad A = -0.02 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)}.$$  

(2.4)

These results correspond to the first observation of CP violation in $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$ decays with a significance of 5.4 standard deviations and are in agreement with the value of $\phi_1$ measured from $b \rightarrow c\bar{c}s$ transitions.

3. Measurement of $\phi_1$ in $B^0 \rightarrow \bar{D}^{(*)}h^0$ with time-dependent binned Dalitz plot analysis

In this analysis, we present a model-independent measurement of the angle $\phi_1$ in $b \rightarrow c\bar{c}d$ transitions governing $B^0 \rightarrow D^{(*)}h^0$ decays, with subsequent decay $B^0 \rightarrow K^0_s \pi^+\pi^-$ is not a CP eigenstate [5]. From a fit to $M_{bc}$ and $\Delta E = E_{B} - E_{\text{beam}}$, where $E_{B}$ is the reconstructed $B$ mesons energy in the center-of-mass system, we extract total 962 ± 41 signal events, of which 464 ± 26 events are from $B^0 \rightarrow \bar{D}^0 \pi^0$ mode (Fig. 2), with a signal fraction (72.1 ± 4.1)% and 182 ± 18 events from $B^0 \rightarrow \bar{D}^0 \omega$ with a fraction of (58.4 ± 5.7)%). The signal fraction of other decay modes ranges between 44% and 70%.
CKM angles at Belle

Bilas Pal

Figure 2: $M_{bc}$ and $\Delta E$ distributions of $B^0 \to \bar{D}^0 \pi^0$ decays.

Our measurement of $\phi_1$ is based on the binned Dalitz distribution approach. This idea was proposed in Ref. [6] to measure the angle $\phi_3$. Events are divided into 16 bins on the Dalitz plot plane and the number of events in bin $i$ ($i = -8, ..., -1, +1, ..., +8$) is modeled as

$$P_i(\Delta t, \phi_1) = he^{-|\Delta t|/\tau_{B^0}} \left[ 1 + q \frac{K_i - K_{i-1}}{K_i + K_{i-1}} \cos(\Delta m \Delta t) \right. \right.$$  

$$+ 2q \xi h \left( -1 \right)^L \sqrt{K_i K_{i-1}} \sin(\Delta m \Delta t) \left( S_i \cos(2\phi_1) + C_i \sin(2\phi_1) \right) \left. \right], \quad (3.1)$$

where $h$ is the normalization constant, $\xi h \phi$ is the CP eigenvalue of $h^0$ meson, $L$ is the relative angular momentum in the $D^{(*)0}h^0$ system, $K_i$ is the integrated squared amplitude, and $S_i$ and $C_i$ represent the weighted averages of the sine and cosine of the phase difference between $\bar{D}^0$ and $D^0$ decay amplitudes over the $i$th Dalitz plot bin. The parameters $K_i$ can be measured with a set of flavor-tagged neutral $D$ mesons such as $D^{*+} \to D^0 \pi^+$ or $B^+ \to \bar{D}^0 \pi^+$ decays, by measuring signal yield in each Dalitz plot bin. The measurement of the phase parameters $S_i$ and $C_i$ is more complicated and can be done with coherent decays of $D^0\bar{D}^0$ pairs [7]. We obtain

$$\sin(2\phi_1) = 0.43 \pm 0.27 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$$

$$\cos(2\phi_1) = 1.06 \pm 0.33 \text{ (stat.)} \pm 0.21 \text{ (syst.)}$$

$$\phi_1 = 11.7^\circ \pm 7.8^\circ \text{ (stat.)} \pm 2.1^\circ \text{ (syst.).} \quad (3.2)$$

The value $\sin(2\phi_1) = 0.691 \pm 0.017$ measured in $b \to c\bar{c}s$ transitions determines the absolute value of $\cos(2\phi_1)$, leading two possible solutions in the $0^\circ \leq \phi_1 \leq 180^\circ$ range. Our measurement is inconsistent with the negative solution, corresponding to the value $\phi_1 = 68.1^\circ$ at the level of 5.1 standard deviations, but in agreement with the positive solution, corresponding to the value $\phi_1 = 21.9^\circ$ at 1.3 standard deviations.

4. First observation of the decay $B^0 \to \psi(2S)\pi^0$

Although decays mediated via $b \to c\bar{c}s$ transitions allow us to access the $\phi_1$ at first order (tree), its value is prone to distortion from suppressed higher-order loop-induced (penguin) amplitudes containing different weak phases. The related $b \to c\bar{d}$ induced decays can be used to quantify the
shift in $\phi_1$ caused by these loop contributions and may provide useful information about the penguin pollution [8]. Since the dominant $b \to c\bar{c}d$ tree amplitude is also suppressed, $B^0 \to J/\psi\pi^0$ is the only mode measured so far, providing $\sin(2\phi_1) = 0.65 \pm 0.21$ (stat.) $\pm 0.05$ (syst.) by Belle [9], which is consistent with $\sin(2\phi_1)$ from $b \to c\bar{c}s$. The possible next mode, $B^0 \to \psi(2S)\pi^0$ was not observed previously.

The decay mode $B^0 \to \psi(2S)\pi^0$ is reconstructed with $\psi(2S) \to \ell^+\ell^- (\ell = e, \mu)$ or $\psi(2S) \to J/\psi(\to \ell^+\ell^-)\pi^+\pi^-$ [10]. The major background contribution originates from $b \to c\bar{c}q$ decays other than the signal. The background arises from $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum events is not so problematic and is suppressed by applying a loose requirement on the ratio of second-to zeroth-order Fox-Wolfram moments. The signal is extracted from a fit to $M_{bc}'$ and $\Delta E$, where $M_{bc}'$ is the modified beam-constrained mass to take into account the worse energy resolution of $\pi^0$ than rest of the particles. The fit gives $85 \pm 12$ signal events with a significance of 7.2 standard deviations. The branching fraction is measured to be

$$\mathcal{B}(B^0 \to \psi(2S)\pi^0) = [1.17 \pm 0.17 \text{ (stat.)} \pm 0.08 \text{ (syst.)}] \times 10^{-5}. \quad (4.1)$$

This measurement constitutes the first observation of this decay and it will contribute to the future time-dependent $CP$ asymmetry measurement of the $b \to c\bar{c}d$ process.

5. Study of $B^0 \to \rho^+\rho^-$ decays

In order to access $\phi_2$, charmless decay modes that are mediated via $b \to u\bar{d}d$ transitions are necessary. Examples are the decays $B \to \pi\pi, \rho\pi, \rho\rho$. At tree level, one expects $A = 0$ and $S = \sin(2\phi_2)$. Possible penguin contributions can give rise of direct $CP$ violation, $A \neq 0$ and also pollute the measurement of $\phi_2$, $S = \sqrt{1-A^2}\sin(2\phi_2^{\text{eff}})$, where the observed $\phi_2^{\text{eff}} = \phi_2 - \Delta\phi_2$ is shifted by $\Delta\phi_2$ due to different weak and strong phases from additional non-leading contributions. This inconvenience can be overcome by estimating $\Delta\phi_2$ using either an isospin analysis [11] or $SU(3)$ flavor symmetry [12]. In this analysis, we present a measurement of the branching fraction and the longitudinal polarization fraction of $B^0 \to \rho^+\rho^-$ decays, as well as the time-dependent $CP$ violating parameters [13].

In addition to combinatorial background, the presence of multiple background components with the same four-pion final state as $B^0 \to \rho^+\rho^-$ make this decay quite difficult to isolate and interferences between the various four-pion modes need to be considered. A multi-dimensional maximum likelihood fit is performed. The fit uses the variables $\Delta E, M_{bc}$, the masses and helicity angles (angle between one of the daughter of $\rho^\pm$ meson and the $B$ flight direction in the corresponding rest frame of the $\rho^\pm$) of the two reconstructed $\rho^\pm$ mesons to separate longitudinally polarized states from transversely polarized states, a fisher discriminant to separate the jet-like continuum events from the spherical $B\bar{B}$ decays and the $\Delta t$ distribution for the two flavors of $B_{\text{tag}}$. We obtain the branching fraction

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = [28.3 \pm 1.5 \text{ (stat.)} \pm 1.5 \text{ (syst.)}] \times 10^{-6}, \quad (5.1)$$

the fraction of longitudinal polarization

$$f_L = 0.988 \pm 0.012 \text{ (stat.)} \pm 0.023 \text{ (syst.)}, \quad (5.2)$$
and the $CP$ violating parameters

$$S = -0.13 \pm 0.15 \text{ (stat.)} \pm 0.05 \text{ (syst.)}, \quad A = 0.00 \pm 0.10 \text{ (stat.)} \pm 0.06 \text{ (syst.)}. \quad (5.3)$$

These results together with the other Belle measurements [14] are used to perform an isospin analysis to constrain the CKM angle $\phi_2$ and obtain two solutions with $\phi_2 = (93.7 \pm 10.6)^\circ$ being most compatible with other SM based fits to the data. The size of the penguin pollution is consistent with zero: $\Delta \phi_2 = (0.0 \pm 9.6)^\circ$. Figure 3 shows the $\phi_2$ can from the isospin analysis.

![Figure 3: Probability scan of $\phi_2$ in the $B \to \rho\rho$ system. The horizontal line shows the 68% confidence level.](image)

6. Summary

The first observation of $CP$ violation in $\bar{B}^0 \to D^{(*)}_CP h^0$ decays from a combined analysis of Belle and BaBar dataset is presented. The result is consistent with the value of $\sin(2\phi_1)$ measured in the $b \to c\bar{c}s$ process. Using a similar process, $B^0 \to D^{(*)}_CP h^0$ with $D^0 \to K^0 \pi^+ \pi^-$, a model-independent time-dependent Dalitz plot analysis is performed and excludes the second $\phi_1$ solution by 5.1 standard deviations. Observation of $B^0 \to \psi(2S)\pi^0$ is presented, which will contribute to the $\phi_1$ measurement in future. And finally $\phi_2$ measurement from $B \to \rho\rho$ decays is presented.

Acknowledgements

The author thanks the workshop organizers for hosting a fruitful and stimulating workshop and providing excellent hospitality. This research is supported by the U.S. Department of Energy.

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