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Time-dependent CP violation in B decays at Belle

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Using the full data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider, we present three recent measurements of time-dependent CP violation in B decays, and a measurement of branching fraction of the $B^0 \to \rho^0\rho^0$ decay. We studied $B \to \omega K$ decays and measured the values of CP violation parameters in $B^0 \to \omega K^0_S$ to be $A_{\omega K^0_S} = 0.36 \pm 0.19(stat) \pm 0.05(syst)$ and $S_{\omega K^0_S} = +0.91 \pm 0.32(stat) \pm 0.05(syst)$, which gives the first evidence of CP violation in this decay. In addition, we measured the direct CP violation in $B^+ \to \omega K^+$ to be $A_{CP}(B^+ \to \omega K^+) = 0.03 \pm 0.04(stat) \pm 0.01(syst)$, and two branching fractions $B(B^0 \to \omega K^0) = (4.5 \pm 0.4(stat) \pm 0.3(syst)) \times 10^{-6}$ and $B(B^+ \to \omega K^+) = (6.8 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-6}$ (preliminary). From the measurement of CP violation parameters in the $B^0 \to \eta' K^0$ decay we obtain $S_{\eta' K^0} = 0.68 \pm 0.07(stat) \pm 0.03(syst)$ and $A_{\eta' K^0} = +0.03 \pm 0.05(stat) \pm 0.03(syst)$ (preliminary), which are the world's most precise values to date. Measuring CP violating parameters in the $B^0 \to \pi^+\pi^-$ decay gives $A_{\pi^+\pi^-} = +0.33 \pm 0.06(stat) \pm 0.03(syst)$ and $S_{\pi^+\pi^-} = -0.64 \pm 0.08(stat) \pm 0.03(syst)$. This result is used in an isospin analysis to constrain the ϕ_2 angle of the unitarity triangle, with which we rule out the region $23.8^\circ < \phi_2 < 66.8^\circ$ at the 1σ confidence level. The measured branching fraction of the $B^0 \to \rho^0\rho^0$ decay is $B(B^0 \to \rho^0\rho^0) = (1.02 \pm 0.30(stat) \pm 0.15(syst)) \times 10^{-6}$, with the fraction of longitudially polarized ρ^0 mesons being $f_L = 0.21^{+0.18}_{-0.22} \pm 0.13$. From the same measurement we obtain also the first evidence of the $B^0 \to f_0\rho^0$ decay, by measuring $B(B^0 \to f_0\rho^0) \times B(f_0 \to \pi^+\pi^-) = (0.86 \pm 0.27(stat) \pm 0.14(syst)) \times 10^{-6}$. Using this result in an isospin analysis we obtain $\phi_2 = (91.0 \pm 7.2)^\circ$.

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1. Introduction

Measuring the parameters of the unitarity triangle (UT) provides a major test of the Standard Model (SM), in particular of the Cabibbo-Kobayashi-Maskawa (CKM) description of flavor changing currents and CP violation. Angles of the UT related to $B_{u,d}$ decays can be determined by measuring CP asymmetries in various B meson decays, and this was the main motivation for construction of two so-called B factory experiments, Belle and BaBar. In the previous decade both experiments have confirmed the complex phase of the CKM matrix as the main source of CP violation.

In these proceedings we present two recent measurements related to the ϕ_1 angle of the UT, mainly motivated by their sensitivity to possible New Physics contributions, and two measurements of the ϕ_2 angle. All measurements are based on the data sample containing 772 millions $B\bar{B}$ pairs collected by the Belle experiment [2] , during its full data taking period (1999-2010).

Angles ϕ_1 and ϕ_2 can be determined by measuring time-dependent asymmetry between decays of B^0 and $\bar{B}^0$ mesons into a common CP eigenstate f_{CP} [1]. At the Belle experiment pairs of B mesons are produced in asymmetric energy collisions of electrons and positrons, through the $\Upsilon(4S) \to B_{tag}B_{CP} \to f_{tag}f_{CP}$ process. Since a B meson pair is in a quantum coherent state, a decay of B_{tag} into a flavor specific final state f_{tag} at t_{tag}, determines the flavor of B_{CP} at t_{tag}. In this case the CP asymmetry is given by[1]

$$a_{CP}(\Delta t) = \frac{\Gamma(B^0(\Delta t) \to f_{CP}) - \Gamma(\bar{B}^0(\Delta t) \to f_{CP})}{\Gamma(B^0(\Delta t) \to f_{CP}) + \Gamma(\bar{B}^0(\Delta t) \to f_{CP})} = A_f \cos\Delta M \Delta t + S_f \sin\Delta M \Delta t, \tag{1.1}$$

where Δt is the time difference between decays of B_{tag} and B_{CP}, ΔM is the mass difference between the two B^0 mass eigenstates (B_L and B_H), and A_f and S_f are the so-called CP violation parameters, which can be within the SM related with the UT angles.

2. Measurement of branching fractions and CP violation parameters in $B \to \omega K$ decays

The $B^0 \to \omega K_S^0$ decays are sensitive to the $\phi_1 = \arg(-V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)$ interior angle of the UT. The decay proceeds dominantly by the $b \to s\bar{q}q$ penguin diagram, and within the SM we expect $A_{\omega K_S^0} = 0$ and $S_{\omega K_S^0} = \sin 2\phi_1$, neglecting other contributing CKM-suppressed amplitudes with a different weak phase. However, the contribution of these CKM-suppressed amplitudes may not be negligible, resulting in a non-zero $A_{\omega K_S^0}$ and in a deviation of $S_{\omega K_S^0}$ from $\sin 2\phi_1$. Several theoretical methods were used to estimate the effect of these amplitudes, indicating the expected value of $S_{\omega K_S^0}$ slightly higher than $\sin 2\phi_1$ [3]. However, current experimental measurements indicate the opposite [4, 5, 6], which might be a consequence of a contribution of new heavy particles in the loop of the penguin diagram [7].

In this measurement, we have also measured the direct CP violating parameter A_{CP} in the $B^+ \to \omega K^+$ decay, defined as

$$A_{CP} = \frac{\Gamma(B^- \to \omega K^-) - \Gamma(B^+ \to \omega K^+)}{\Gamma(B^- \to \omega K^-) + \Gamma(B^+ \to \omega K^+)}, \tag{2.1}$$

[1] Here $B^0(t)$ ($\bar{B}^0(t)$) denote states that were at $t = 0$ pure B^0 ($\bar{B}^0$) states, but later get mixed due to $B^0 - \bar{B}^0$ mixing.

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where again a deviation from the expected asymmetry could be an indication of New Physics. Furthermore, the measurement of the branching fractions provides an important test of the QCD factorization (QCDF) and perturbative QCD (pQCD) approaches.

To obtain the two branching fractions and CP violation parameters we perform a seven-dimensional unbinned extended maximum likelihood fit to $M_{bc}, \Delta E$ (two kinematic variables of the reconstructed B meson), $R_{s/b}$ (event topology variable), $m_{3\pi}$ (invariant mass of the reconstructed ω), $H_{3\pi}$ (helicity angle), Δt and q (where $q = +1$ ($q = -1$) for $B_{tag} = B^0$ ($\bar{B}^0$)). The fit is performed simultaneously to $B^0 \to \omega K_S^0$ and $B^+ \to \omega K^+$ data samples, sharing common calibration factors. Following this, the model shape is fixed and the $A_{CP}(B^+ \to \omega K^+)$ parameter is obtained from two further fits to extract the number of B^+ and B^- events. The preliminary results are:

$$
\begin{aligned}
B(B^0 \to \omega K^0) &= (4.5 \pm 0.4(stat) \pm 0.3(syst)) \times 10^{-6}, \\
B(B^+ \to \omega K^+) &= (6.8 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-6}, \\
A_{\omega K_S^0} &= 0.36 \pm 0.19(stat) \pm 0.05(syst), \\
S_{\omega K_S^0} &= +0.91 \pm 0.32(stat) \pm 0.05(syst), \\
A_{CP}(B^+ \to \omega K^+) &= 0.03 \pm 0.04(stat) \pm 0.01(syst),
\end{aligned}
\tag{2.2}
$$

where the first uncertainty is statistical and the second is systematic. The latter is dominated by uncertainties of the Δt resolution function parameters for $A_{\omega K_S^0}$ and $S_{K_S^0}$, and by parameters of the background PDF shape for the branching fractions. The comparison of data distributions and the fitted PDF is shown in figure 1. The results given in (2.2) are the world's most precise measurements of the branching fractions and CP violation parameters in $B \to \omega K$ decays. The observed values of $A_{\omega K_S^0}$ and $S_{\omega K_S^0}$ differ from zero with a significance of 3.1 standard deviations, which gives the first evidence of CP violation in the $B^0 \to \omega K_S^0$ decay.

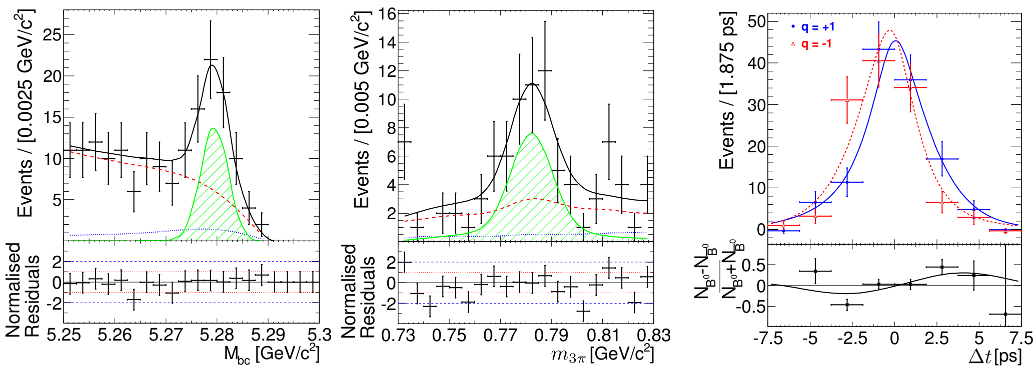

Figure 1: Left two: Distribution of reconstructed events in M_{bc} and $m_{3\pi}$ (black points) along with the fitted PDF (the full line). The dashed line shows contribution of the $q\bar{q}$ background (from $e^+e^- \to q\bar{q}$ ($q = u,d,s,c$) events), the dotted line of the $B\bar{B}$ background. **Right:** Distributions of reconstructed events in Δt (events with $q = +1$ (blue points) and $q = -1$ (red points)) along with the corresponding $q = +1$ and $q = -1$ parts of the fitted PDF; bottom plot shows the asymmetry in data distributions and in the fitted PDF.

3. Measurement of CP violation parameters in $B^0 \to \eta' K^0$ decay

The $B^0 \to \eta' K^0$ decay is another decay that proceeds dominantly through the $b \to s\bar{q}q$ transition, for which within the SM we expect $A_{\eta' K^0} = 0$ and $S_{\eta' K^0} = -\xi_f \sin 2\phi$ (where $\xi_f = -1$ $(+1)$ for $B \to \eta' K^0_S$ $(B \to \eta' K^0_L)$). Theoretically this is the cleanest mode to measure CP violation parameters in a $b \to s\bar{q}q$ process, as the contributions from the CKM suppressed diagrams are expected to be $\lesssim 0.02$ for both $S_{\eta K^0}$ and $A_{\eta' K^0}$ [3].

In the first part of the analysis, event reconstruction and signal fraction estimation, we study separately $B^0 \to \eta' K^0_S$ and $B^0 \to \eta' K^0_L$ events. To obtain the fraction of signal events we study the distribution of events in $M_{bc}, \Delta E$ and $R_{s/b}$ for K^0_S events, and the distribution in p_B^{cms} (B candidate momentum in the center-of-mass system), r (quality of the B candidate flavor information) and $R_{s/b}$ for K^0_L events. Altogether we reconstruct 2503 ± 63 $B^0 \to \eta' K^0_S$ signal events, and 1041 ± 41 $B^0 \to \eta' K^0_L$ signal events, where the uncertainties are statistical only. Following this, we perform an unbinned maximum likelihood fit to extract the values of CP violation parameters from the measured $\Delta t, q$ distribution of events. Our preliminary results are

$$\begin{aligned} S_{\eta' K^0} &= 0.68 \pm 0.07(stat) \pm 0.03(syst), \\ A_{\eta' K^0} &= +0.03 \pm 0.05(stat) \pm 0.03(syst), \end{aligned} \tag{3.1}$$

where the first uncertainty is statistical and the second is systematic. The main contribution to the latter comes from the uncertainties in the Δt resolution function parameters for $S_{\eta' K^0}$, and from the tag-side interference effect for $A_{\eta' K^0}$. The comparison of data distribution and the fitted PDF is shown in figure 2. The measured values of $S_{\eta' K^0}$ and $A_{\eta' K^0}$ are the world's most precise values of CP violation parameters in this particular decay, as well as among all $b \to s\bar{q}q$ transition dominated decays. They are consistent with previous measurements [8, 9] and with the SM prediction.

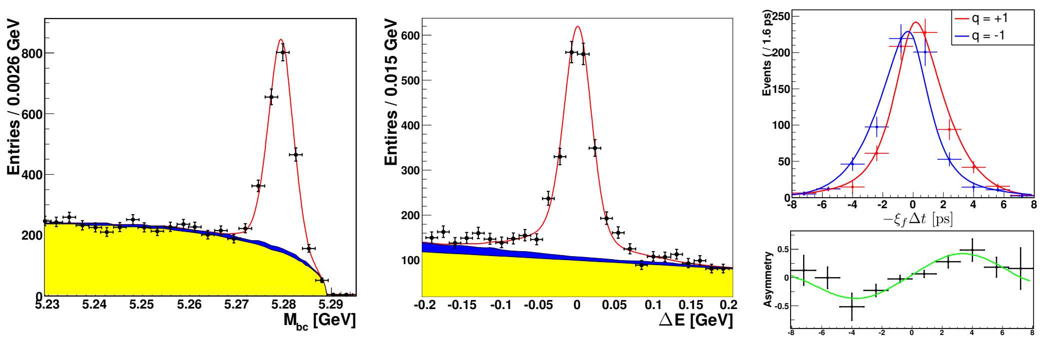

Figure 2: Left two: Distribution of reconstructed $B^0 \to \eta' K^0_S$ events in M_{bc} and ΔE (black points) along with the fitted PDF (the red). The yellow area shows contribution of the $q\bar{q}$ background, and the blue area of the $B\bar{B}$ background. **Right:** Distribution of the reconstructed events in Δt (events with $q = +1$ (red points) and $q = -1$ (blue points)) along with the corresponding $q = +1$ and $q = -1$ parts of the fitted PDF; bottom plot shows the asymmetry in data distributions and in the fitted PDF.

4. Measurements of ϕ_2 angle in $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^0\rho^0$ decays

Decays $B \to \pi^+\pi^-$ and $B \to \rho^0\rho^0$ are sensitive to $\phi_1 = \arg(-V_{td}V^*_{tb})/(V_{ud}V^*_{ub})$. At the tree level we expect $A_f = 0$ and $S_f = \sin 2\phi_2$. However, penguin contributions can give rise to direct CP violation, $A_f \neq 0$, and also pollute the measurement of ϕ_2. Despite this, it is still possible to obtain the value of ϕ_2 with a $SU(2)$ isospin analysis, by considering the set of three $B \to hh$ decays ($h = \pi$ or $h = \rho$), related via isospin symmetry [10]. Belle recently updated measurements of CP violation parameters in the $B^0 \to \pi^+\pi^-$ decay and of branching fraction of the $B^0 \to \rho^0\rho^0$ decay to the full data sample, and the values obtained were used to provide new constraints on ϕ_2.

4.1 The $B^0 \to \pi^+\pi^-$ decay

To obtain the values of $S_{\pi^+\pi^-}$ and $A_{\pi^+\pi^-}$ a seven-dimensional fit to $L^+_{K\pi}, L^-_{K\pi}$ (π, K separation likelihood function), $M_{bc}, \Delta E, R_{s/b}, \Delta t$ and q is performed. The main background contribution comes from $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events. In total we reconstruct 2964 ± 88 signal events, and the following values of CP violation parameters are obtained [11]

$$
\begin{aligned}
A_{\pi^+\pi^-} &= +0.33 \pm 0.06(stat) \pm 0.03(syst), \\
S_{\pi^+\pi^-} &= -0.64 \pm 0.08(stat) \pm 0.03(syst),
\end{aligned}
\tag{4.1}
$$

where the first uncertainty is statistical and the second is systematic. The comparison of data distribution in Δt with the fitted PDF is shown in figure 3. The values given in (4.1) are the world's most precise values of CP violation parameters in this decay. Using these values, and input from other Belle measurements (branching fractions of $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ [14] and $B^0 \to \pi^0\pi^0$ [15] decays), an isospin analysis is performed to constrain ϕ_2. Obtained difference 1-CL (confidence level) is plotted in figure 3, for a range of ϕ_2. The region $23.8° < \phi_2 < 66.8°$ is ruled out at the 1σ level, including systematic uncertainties.

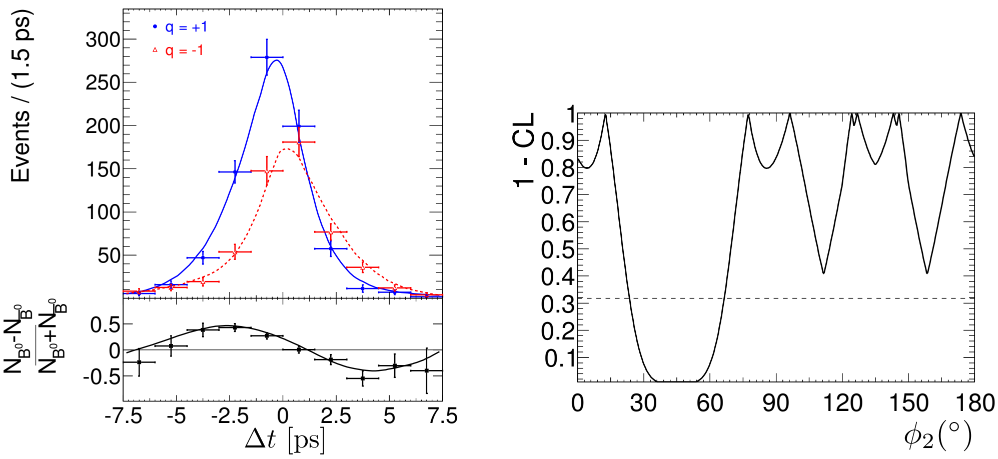

Figure 3: Left: Distribution of reconstructed events in Δt (events with $q = +1$ (red points) and $q = -1$ (blue points)) along with the corresponding $q = +1$ and $q = -1$ parts of the fitted PDF. **Right:** Difference 1-CL, plotted for a range of ϕ_2. The dashed line indicate the 1σ exclusion level.

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4.2 The $B^0 \to \rho^0\rho^0$ decay

Measuring the branching fraction of the $B^0 \to \rho^0\rho^0$ decay is quite challenging due to its low value and the presence of other, largely unknown, four-pion final states. In addition, due to two vector particles in the final state, a helicity analysis is needed in order to separate the longitudinal and transverse polarization amplitudes, with even and odd CP eigenvalues respectively.

We perform an unbinned maximum likelihood fit to a six-dimensional distribution of reconstructed candidates in $m^1_{\pi^+\pi^-}, m^2_{\pi^+\pi^-}$ (invariant masses of reconstructed $\rho^0 s$), $\cos\theta^1_{hel}, \cos\theta^2_{hel}$ (helicity angles), and $R_{s/b}$. The results are [12]

$$B(B^0 \to \rho^0\rho^0) = (1.02 \pm 0.30(stat) \pm 0.15(syst)) \times 10^{-6},$$
$$f_L = 0.21^{+0.18}_{-0.22}(stat) \pm 0.13(syst), \quad (4.2)$$

where B is a branching fraction and f_L is a fraction of longitudinally polarized ρ^0 mesons. The branching fraction is measured with a significance of 3.4 standard deviations. In addition, we measured

$$B(B^0 \to f_0\rho^0) \times B(f_0 \to \pi^+\pi^-) = (0.86 \pm 0.27(stat) \pm 0.15(syst)) \times 10^{-6}, \quad (4.3)$$

with a significance of 3.0 standard deviations, which gives the first evidence of the $B^0 \to f_0\rho^0$ decay.

Using the values of $B(B^0 \to \rho^0\rho^0)$ and f_L, along with the world average values [6] of $B(B^0 \to \rho^+\rho^-)$, f_L^{+-}, $A_{\rho^+\rho^-}$, $S_{\rho^+\rho^-}$, $B(B^+ \to \rho^+\rho^0)$ and CP violation parameters $A_{\rho^0\rho^0}, S_{\rho^0\rho^0}$ from BaBar measurement [13], an isospin analysis is performed to constrain ϕ_2. We obtain $\phi_2 = (91.0 \pm 7.2)^\circ$, at a 1σ confidence level.

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