Belle CP violation in $b \to sq\bar{q}$ and $u\bar{u}d$ processes

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We report the analysis of time-dependent CP violation in neutral B meson system using a data sample corresponding to $140 fb^{-1}$ collected by Belle detector and KEKB $e^+e^-$ collider. One B meson decaying into CP eigenstate is fully reconstructed and the accompanying B meson flavor is identified by its decay products. The CP violation parameters are determined from the distribution of proper time intervals between the two B decays. Here we cover measurements of CP violation in $b \to u\bar{u}d$ and $b \to sq\bar{q}$ processes.

1 Introduction

In the standard model (SM) of elementary particles, CP violation arises from the Kobayashi-Maskawa (KM) phases in weak interaction quark-mixing matrix. In particular, the SM predicts CP asymmetries in the time-dependent rates for $B^0$ and $\bar{B^0}$ decays to a common CP eigenstate.

We report the time dependent studies of $B^0 \to \pi^+\pi^-$, $B^0 \to \phi K_S$, $B^0 \to K^+K^-K_S^0$, and $B^0 \to \eta'K_S^0$. The $B^0 \to \pi^+\pi^-$ decay is sensitive to the CP-violation parameter $\phi_2$ which is dominated by $b \to u\bar{u}d$ transition. Direct CP violation may also occur in this decay because of interference between $b \to u$ tree ($T$) and $b \to d$ penguin ($P$) amplitudes. For the charmless decays of $B^0 \to \phi K_S$, $B^0 \to K^+K^-K_S^0$, and $B^0 \to \eta'K_S^0$ which is mediated by $b \to sss$, $suu$, and $sdd$ transitions are sensitive to new CP-violation phases from physics beyond the SM.

2 Time-dependent CP violation at Belle

The Belle detector is a large-solid-angle general purpose spectrometer that consists of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counter (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides
1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect $K^0_L$ mesons and identify muons.

The Belle detector collects the data at the KEKB asymmetric-energy $e^+e^-$ collider, in which 8.0 GeV $e^-$ collides with 3.5 GeV $e^+$ at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline ($z$). In the decay chain $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_{CP}f_{\text{tag}}$, where one of the $B$ mesons at time $t_{CP}$ decays to the final state $f_{CP}$ and the accompanying $B$ decays at time $t_{\text{tag}}$ decays to the final state $f_{\text{tag}}$ which distinguishes between $B^0$ and $\bar{B}^0$. The decay rate has a time dependence given by

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{\text{tag}}}}{4\tau_{\text{tag}}} \left\{ 1 + q \cdot \left[ \sin(\Delta m_d \Delta t) + \cos(\Delta m_d \Delta t) \right] \right\},$$

where $\tau_{\text{tag}}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $\Delta t = t_{CP} - t_{\text{tag}}$, and the $b$-flavor charge $q = +1$ (-1) when accompanying $B$ meson is a $B^0$ ($\bar{B}^0$). $S$ and $A$ are mixing-induced and direct $CP$-violation parameters, respectively. Since $B^0$ and $\bar{B}^0$ are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), $\Delta t$ can be determined from the displacement of $z$ between the two $B$ mesons: $\Delta t \simeq (z_{CP} - z_{\text{tag}})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

3 Time-dependent $CP$-violation Analysis

3.1 Event Extraction

For reconstruction of $B^0 \rightarrow \pi^+\pi^-$ candidates, we use the oppositely charged track pairs which are identified as pions to form the $B$ meson. The reconstruction of $B^0 \rightarrow \phi K_S^0$, $B^0 \rightarrow K^+K^-K_S^0$, and $B^0 \rightarrow \eta'K_S^0$ events from the following intermediate meson decay chains: $\eta' \rightarrow \rho^0(\rightarrow \pi^+\pi^-)\gamma$, or $\eta' \rightarrow \pi^+\pi^-\eta(\rightarrow \gamma\gamma)$, $K_S^0 \rightarrow \pi^+\pi^-$, and $\phi \rightarrow K^+K^-$. Candidate $K_S^0 \rightarrow \pi^+\pi^-$ and $\phi \rightarrow K^+K^-$ decays are selected with the same criteria as those used for the previous branching fraction measurement. The $K^+K^-$ pairs are rejected if they are consistent with $D^0 \rightarrow K^+K^-$, $\chi_{c0} \rightarrow K^+K^-$, or $J/\psi \rightarrow K^+K^-$ decays. $D^+ \rightarrow K_S^0K^+$ candidates are also removed. We also applied the same selection criteria for $B^0 \rightarrow \eta'K_S^0$ as our previous analysis. The pion and kaon identification are according to the combined information from ACC and the CDC $dE/dx$ measurements.

Candidate $B$ mesons are reconstructed using the energy difference $\Delta E \equiv E_{B}^{\text{cms}} - E_{\text{beam}}^{\text{cms}}$ and the beam-constraint mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$, where $E_{\text{beam}}^{\text{cms}}$ is the cms beam energy, and $E_{B}^{\text{cms}}$ and $p_B^{\text{cms}}$ are the cms energy and momentum of the $B$ candidate. The signal region for $B^0 \rightarrow \pi^+\pi^-$ is defined as $|\Delta E| < 0.064$ GeV, and 5.271 GeV/c$^2 < M_{\text{bc}} < 5.287$ GeV/c$^2$. The definition for $B^0 \rightarrow \phi K_S^0$, $B^0 \rightarrow K^+K^-K_S^0$, $B^0 \rightarrow \eta' (\rightarrow \rho\gamma)K_S^0$, and $B^0 \rightarrow \eta' (\rightarrow \pi^+\pi^-\eta)K_S^0$ are $|\Delta E| < 0.06$ GeV, $|\Delta E| < 0.04$ GeV, $|\Delta E| < 0.06$ GeV, and $-0.1\text{GeV} < \Delta E < 0.08$ GeV all with $5.27$ GeV/c$^2 < M_{\text{bc}} < 5.29$ GeV/c$^2$.

In order to suppress the $e^+e^- \rightarrow q\bar{q}$ continuum background ($q = u, d, s, c$), we form the signal and background likelihood function, $L_s$ and $L_{BG}$, from the event topology, and apply the likelihood ratio selection on the reconstructed candidates.

3.2 Flavor Tagging

The flavor of the accompanying $B$ meson is identified from inclusive properties of particles that are not associated with the reconstructed $CP$ side decay, the same as Belle $\sin2\phi_1$ measurement. We used two parameters, $q$ and $r$, to represent the tagging information. The first, $q$, is already defined in Eq. 1. The parameter $r$ is and event-by-event, MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six $r$ intervals. The wrong tag fraction for the six
r intervals, $w_l$ ($l = 1, 6$), and difference between $B^0$ and $\bar{B}^0$ decays, $\Delta w_l$ are determined from the data.

### 3.3 Vertex Reconstruction

The decay vertices of $B^0$ meson are reconstructed using tracks that have enough SVD hits. The vertex position for the $f_{CP}$ decay is reconstructed using charged tracks, and the tracks from the $K^0_S$ decays are excluded. The $f_{tag}$ vertex is determined using charged tracks except those used for $f_{CP}$ and tracks that form a $K^0_S$ or a $\Lambda$ candidate. Each vertex position is constrained by the interaction point profile with average transverse $B$ meson decay length smearing.

### 3.4 Event Distribution Function

We got 373, 106, 361, and 421 events in the signal box for $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \phi K_S$, $B^0 \rightarrow K^+K^-K^0_S$, and $B^0 \rightarrow \eta'K^0_S$ decays respectively. We determined event distribution function in the $\Delta E - M_{bc}$ plane for both signal and background to do the signal purity estimation.

Figure 1 shows the $\Delta E$ distribution for the $B^0 \rightarrow \pi^+\pi^-$ candidates are in $M_{bc}$ signal region. The background contains the continuum $q\bar{q}$, $K\pi$, and charmless three-body $B$ decay events. Figure 2 shows the $M_{bc}$ distribution for $B^0 \rightarrow \phi K_S$, $B^0 \rightarrow K^+K^-K^0_S$, and $B^0 \rightarrow \eta'K^0_S$ in $\Delta E$ signal region. The background is dominated by continuum $q\bar{q}$ events.

### 3.5 Maximum-likelihood Fit

The time-dependent $CP$ violation parameters, $S$ and $A$, are determined by performing an unbinned maximum-likelihood fit. The probability density function (PDF) expected for the signal distribution is given by Eq. 1 modified to incorporate the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\text{sig}}$. A small component of broad outliers in the $\Delta z$ distribution is represented by $P_d(\Delta t)$. The
Figure 2: The beam-energy constrained mass distribution for (a) $B^0 \rightarrow \phi K_S$, (b) $B^0 \rightarrow K^+ K^- K_S$, and (c) $B^0 \rightarrow \eta' K_S$ within $\Delta E$ signal region. The dashed curve show the background contributions and the solid curve shows the fit to signal plus background distribution.

likelihood for each event is determined from following PDF:

$$P_i(\Delta t_i; S, A) = (1 - f_{ol}) \int_{-\infty}^{\infty} f_{\text{sig}} P(\Delta t', q, w_l, \Delta w_l) R_{\text{sig}}(\Delta t_i - \Delta t') d(\Delta t') + (f_{\text{bkg}}) P_{\text{bkg}}(\Delta t') R_{\text{bkg}}(\Delta t_i - \Delta t') d(\Delta t'),$$ (2)

where $f_{ol}$ is the outlier fraction and $f_{\text{sig}}$ ($f_{\text{bkg}}$) is the event-by-event signal (background) probability depends on $r$, $\Delta E$ and $M_{bc}$. $P_{\text{bkg}}(\Delta t)$ and $R_{\text{bkg}}$ are the background PDF and resolution function. The only free parameters in the final fit are $S$ and $A$, which are determined by maximizing the likelihood function

$$L = \prod_i P_i(\Delta t_i; S, A),$$ (3)

where the product is over all events.

4 Result

4.1 $B^0 \rightarrow \pi^+ \pi^-$

After the unbinned maximum-likelihood fit we got $S = -1.00 \pm 0.21$ (stat.) $\pm 0.07$ (syst.) and $A = +0.58 \pm 0.15$ (stat.) $\pm 0.07$ (syst.). Figure 3 shows the result. The statistical significance is determined from the Feldman-Cousins frequentist approach. Figure 4 shows the resulting two-dimensional confidence regions in $S$ and $A$ plane. We have 5.2$\sigma$ significance for $CP$ violation.
and 3.2σ significance for direct CP violation. If the source of CP violation is only due to $B - \bar{B}$ mixing or $\Delta B = 2$ transitions so called as super-weak scenarios, then the statistical significance for $(S, A) = (\sin 2\phi_1, 0)$ is 3.3σ.\cite{13, 14}

The range of $\phi_2$ that corresponds to the 95.5% confidence level (CL) for $S$ and $A$ in Figure 4 is $90^\circ \leq \phi_2 \leq 146^\circ$ with $\sin 2\phi_1 = 0$. This result is in agreement with constraints on the unitary triangle from other indirect measurements. The 95.5% CL region for $S$ and $A$ excludes $|P/T| < 0.17$.

### 4.2 $B^0 \to \phi K_S$, $B^0 \to K^+ K^- K_S^0$, and $B^0 \to \eta' K_S^0$

After the unbinned maximum-likelihood fit we got $S = -0.96 \pm 0.50$ (stat.) $\pm 0.11$ (syst.), $A = -0.15 \pm 0.29$ (stat.) $\pm 0.07$ (syst.) for $B^0 \to \phi K_S$ decay, $S = -0.51 \pm 0.26$ (stat.) $\pm 0.05$ (syst.) $\pm 0.00$, $A = -0.17 \pm 0.16$ (stat.) $\pm 0.04$ (syst.) for $B^0 \to K^+ K^- K_S^0$, and $S = +0.43 \pm 0.27$ (stat.) $\pm 0.05$ (syst.), $A = -0.01 \pm 0.16$ (stat.) $\pm 0.04$ (syst.) for $B^0 \to \eta' K_S^0$, while the third error for $K^+ K^- K_S^0$ mode arises from the uncertainty in the fraction of the CP-odd component. Figure 5 shows the result. Based on Feldman-Cousins frequentist approach, we get 3.5σ statistical significance of the observed deviation from the SM in $B^0 \to \phi K_S$.\cite{12}

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Figure 4: Confidence regions for $S$ and $A$.

Figure 5: (a) The asymmetry, in each $\Delta t$ bin for $B^0 \rightarrow \phi K_S$ with $0 < r \leq 0.5$, (b) with $0.5 < r \leq 1.0$, (c) $B^0 \rightarrow K^+ K^- K_S^0$ with $0 < r \leq 0.5$, (d) with $0.5 < r \leq 1.0$, (e) $B^0 \rightarrow \eta' K_S^0$ with $0 < r \leq 0.5$, and (f) with $0.5 < r \leq 1.0$, respectively. In (b) through (g), the solid curves show the result of the unbinned maximum-likelihood fit. The dashed curves show the SM expectation with $\sin^2 \phi_1 = +0.731$ and $|\lambda| = 1$. 
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