Measurements of $\phi_1(\beta)$ in B decays to charm and charmonium at Belle

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Abstract. We present a measurement of the time-dependent CP violation parameters for $B^0 \rightarrow D^*+D^*-K^0_S$ and $B^0 \rightarrow J/\psi K^0_S$ decays obtained from the distribution of proper time intervals between the two $B$ decays. These results are obtained from a data sample of $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ collider. For $B^0 \rightarrow D^*+D^*-K^0_S$, we find no evidence for direct or mixing-induced CP violation, and in a fit sensitive to $\cos 2\phi_1$, no conclusion can be drawn regarding its sign with current statistics. For $B^0 \rightarrow J/\psi\pi^0$, we find no evidence for direct CP violation and measure mixing-induced CP violation consistent with Standard Model expectations, with a $2.4\sigma$ significance.

1. Introduction

CP violation in the Standard Model is due to a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1, 2]. Time-dependent CP parameters can be extracted from the time-dependent rate asymmetry [3],

$$\frac{\Gamma(t) - \Gamma(t)}{\Gamma(t) + \Gamma(t)} = A_{CP} \cos(\Delta m_d t) + S_{CP} \sin(\Delta m_d t). \quad (1)$$

$\Gamma(t)$ is the decay rate at proper time, $t$, after production while $\bar{\Gamma}(t)$ represents the charge conjugate rate. $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $A_{CP}$ is the direct CP violating component and $S_{CP}$ measures mixing-induced CP violation. Interference between $b \rightarrow c$ decays and $B^0 - \bar{B}^0$ mixing allows us to measure the CKM angle, $\phi_1$.

This measurement of CP violating parameters is based on $449 \times 10^6$ $B\bar{B}$ pairs for $B^0 \rightarrow D^{\ast^+}D^{*-}K^0_S$ and $535 \times 10^6$ $B\bar{B}$ pairs for $B^0 \rightarrow J/\psi\pi^0$, collected with the Belle detector [4] at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [5]. Operating with a peak luminosity that exceeds $1.6 \times 10^{34}$ cm$^{-2}$s$^{-1}$, the collider produces the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a Lorentz boost of $\beta\gamma = 0.425$, opposite to the positron beamline direction, $z$. Since the $B^0$ and $\bar{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ Center-of-Mass System (CMS), the difference in decay time between the $B\bar{B}$ pair, $\Delta t$, can be determined from the displacement in $z$ between the final state decay vertices, $\Delta t \approx (z_{CP} - z_{Tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$. The subscripts, CP and Tag, denote the reconstructed final state, $B_{CP}$, and the final state from which the flavor is identified, $B_{Tag}$.
2. $B^0 \rightarrow D^{*+} D^{-} K_S^0$

Following Ref [6], $S_{CP} = D \sin 2\phi_1$ as $CP$ contamination from penguins and final state interactions are expected to be small. The factor, $D$, is the dilution of the $CP$ asymmetry and may arise from two sources. The contribution from different waves in the amplitude of $B^0 \rightarrow D^{*+} D^{-} K_S^0$ influences the $CP$ mixture and polarization of the final state. Furthermore, if an intermediate $D^{*+} K_S^0$ resonance exists, additional dilution of the $CP$ asymmetry occurs as the decay becomes self-tagging.

If resonant structure were to exist, $\cos 2\phi_1$ may also be extracted from a 3-parameter fit, assuming no direct $CP$ violation, from the time-dependent rate asymmetry [6],

$$\frac{\Gamma(t) - \Gamma(-t)}{\Gamma(t) + \Gamma(-t)} = \eta_c \frac{J_c}{J_0} \cos (\Delta m_d t) - \frac{2J_{s1}}{J_0} \sin 2\phi_1 + \frac{2J_{s2}}{J_0} \cos 2\phi_1 \sin (\Delta m_d t), \quad (2)$$

in the half-Dalitz space, $s^- \leq s^+$ or $s^- > s^+$. The Dalitz variables are defined as $s^\pm \equiv m^2 (D^{*\pm} K_S^0)$ and $\eta_c = +1 (-1)$ if $s^- \leq s^+$ ($s^- > s^+$). $J_c$, $J_0$, $J_{s1}$ and $J_{s2}$ are integrals over the half-Dalitz space, $s^- > s^+$, of $|a|^2 + |b|^2$, $|a|^2 - |b|^2$, the real component, $\Re (\bar{a}a^*)$ and the imaginary component, $\Im (\bar{a}a^*)$, respectively, where $a (\bar{a})$ are the decay amplitudes of $B^0 (\bar{B}^0) \rightarrow D^{*+} D^{-} K_S^0$. Note that $J_{s2}$ is non-zero only if $B^0 \rightarrow D^{*+} D^{-} K_S^0$ has a resonant component: in this case, $J_c$ may be large.

We then determine the $CP$ asymmetry parameters of $B^0 \rightarrow D^{*+} D^{-} K_S^0$ from a 2-parameter fit,

$$A_{CP} = -0.01^{+0.28}_{-0.28} \text{ (stat)} \pm 0.09 \text{ (syst)}, \quad (3)$$

$$D \sin 2\phi_1 = 0.06^{+0.45}_{-0.44} \text{ (stat)} \pm 0.06 \text{ (syst)},$$

and a 3-parameter fit,

$$J_c/J_0 = 0.60^{+0.25}_{-0.28} \text{ (stat)} \pm 0.08 \text{ (syst)},$$

$$2J_{s1}/J_0 \sin 2\phi_1 = -0.17^{+0.42}_{-0.42} \text{ (stat)} \pm 0.09 \text{ (syst)}$$

$$2J_{s2}/J_0 \cos 2\phi_1 = -0.23^{+0.41}_{-0.41} \text{ (stat)} \pm 0.13 \text{ (syst)}, \quad (4)$$

where the corresponding fit curves are shown in Figure 1.

![Figure 1](image-url)

Figure 1. (a),(c) and (d) show the background subtracted $\Delta t$ distribution in the Dalitz integrated, $s^- \leq s^+$, and $s^- > s^+$ regions respectively. The solid curve represents $B^0$ tagged candidates and the dashed curve represents $\bar{B}^0$ tagged candidates. (b),(e) and (f) show the corresponding $B^0 - \bar{B}^0$ raw asymmetry in each region.
3. $B^0 \to J/\psi\pi^0$

At the quark level, the $B^0 \to J/\psi\pi^0$ decay proceeds via a $b \to c\bar{c}d$ transition. In this decay, the tree amplitude is CKM-suppressed. Since the tree amplitude has the same weak phase as the $b \to c\bar{c}s$ transition, $S_{J/\psi\pi^0} = -\sin2\phi_1$ and $A_{J/\psi\pi^0} = 0$ are expected if other contributions to the decay amplitude can be neglected [7]. If, however, the penguin or other contributions are substantial, the $CP$ violation parameters for this mode may deviate from these values. Employing $SU(3)$ symmetry as well as plausible dynamical assumptions, the results obtained for $B^0 \to J/\psi K_S^0$ decay can be used to estimate the penguin pollution in $B^0 \to J/\psi K_S^0$ decay for a very precise determination of $\sin2\phi_1$ [8].

We obtain the $CP$ asymmetry parameters of $B^0 \to J/\psi\pi^0$,

$$S_{J/\psi\pi^0} = -0.65 \pm 0.21 \text{(stat)} \pm 0.05 \text{(syst)}$$

$$A_{J/\psi\pi^0} = +0.08 \pm 0.16 \text{(stat)} \pm 0.05 \text{(syst)}$$

and the corresponding fit curves are shown in Figure 3.

4. Conclusions

For $B^0 \to D^{*+}D^*-K_S^0$, there is no evidence for direct $CP$ violation and a large dilution of $\sin2\phi_1$ from polarization and resonant structure is implied. In the 3-parameter fit, $J_2/J_0$ appears to be non-zero; a large value of this parameter could indicate the presence of a broad unknown $D^{*+}$ state. According to [6], $2J_2/J_0$ is expected to be positive if this unknown wide resonance exists. The parameter, $2J_2/J_0 \cos2\phi_1$, has been measured, however, a model-dependent inference on the sign of $\cos2\phi_1$ is not possible with current precision. Further details can be found in [9].

For $B^0 \to J/\psi\pi^0$, mixing-induced $CP$ violation was measured with a $2.4\sigma$ significance, consistent with Standard Model expectations and no evidence for direct $CP$ violation was found. Further details can be found in [10].

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