Studies of penguin dominated $B$ decays at Belle

Y. Yusa$^1$ and Belle Collaboration

Virginia Polytechnic Inst. and State Univ.

February 26, 2008

Abstract. We present measurements of $CP$ violation parameter $\phi_1/\beta$ in $B^0$ decays that are dominated by $b \to cc\alpha$, $b \to sq\bar{q}$ and $b \to dq\bar{q}$ transitions. The results are based on a large sample of $BB$ pairs recorded at the $T(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric $e^+e^-$ collider. $CP$ violation parameters for each decay mode are obtained from the asymmetries in the distributions of the proper-time intervals between the reconstructed $B$ and the accompanying $B$ meson.

PACS. PACS-key 11.30.Er – PACS-key 12.15.Hh – PACS-key 13.25.Hw

1 Introduction

The Standard Model (SM) describes $CP$ violation in $B^0$ meson decays using the complex phase of the $3 \times 3$ Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. In the decay chain $T(4S) \to B^0\bar{B}^0 \to f_{CP}f_{tag}$, where one of the $B$ mesons decays at time $t_{CP}$ to a final state $f_{CP}$ and the other decays at time $t_{tag}$ to a final state $f_{tag}$ that distinguishes between $B^0$ and $\bar{B}^0$, the decay rate has time dependence [2] given by $\mathcal{P}(\Delta t) = e^{-|\Delta t|/\tau_{B^0}}[1 + q[S_f \sin(\Delta m_d\Delta t) + A_f \cos(\Delta m_d\Delta t)]]$. Here $S_f$ and $A_f$ are $CP$-violation parameters, $\tau_{B^0}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $\Delta t = t_{CP} - t_{tag}$, and the $b$-flavor charge is $q = +1(-1)$ when the tagging $B$ meson is a $B^0(\bar{B}^0)$. To a good approximation, the SM predicts $S_f = -\xi_f \sin 2\phi_1$ and $A_f = 0$ for both $b \to cc\alpha$ and $b \to sq\bar{q}$ transitions, where $\xi_f = +1(-1)$ corresponds to $CP$-even (odd) final states. Recent theoretical studies within the SM framework [3] find that the effective $\sin 2\phi_1$ values, $\sin 2\phi_{1eff}$, obtained from $b \to sq\bar{q}$ are expected to agree within $O(0.01)$ with $\sin 2\phi_1$ from the $b \to cc\alpha$ transition. A comparison of $CP$-violation parameters between these theoretically clean $b \to sq\bar{q}$ modes and $b \to cc\alpha$ decays is an important test of the SM. On the other hand, $S_f$ is expected to be small for $b \to dq\bar{q}$ transition because the weak and quark mixing phases cancel [4]. In this paper, we report measurement of time-dependent $CP$-asymmetries of penguin dominated $B$ meson decays. Among the final states, $\phi K_{S}^0$, $\eta' K_{S}^0$, $\omega K_{S}^0$, $K_{S}^{0}\pi^0$ and $J/\psi K_{S}^0$ are $CP$ eigenstates with $\xi_f = -1$, while $\phi K_{L}^0$, $\eta K_{L}^0$, $f_0 K_{S}^0$, $K_{L}^0\pi^0\pi^0$, $K_{S}^{0}\pi^0\pi^0$, $K_{S}^{0}\pi^0\pi^0$ and $J/\psi K_{L}^0$ are $CP$ eigenstates with $\xi_f = +1$. Since $B^0 \to K^+K^- K_S^0$ is a $CP$-even and $-\text{odd}$ mixture, of both $b$ has $\xi_f = -(2f_+ - 1)$, where $f_+$ is the $CP$-even fraction, measured to be $0.93 \pm 0.09 \pm 0.05$ assuming isospin relation [5]. The $CP$ asymmetry parameters for $b \to dq\bar{q}$ transition are measured from $B^0 \to K_S^0 K_S^0$ decay mode.

2 Measurement of $CP$ violation parameters

At the KEKB energy-asymmetric $e^+e^-$ (3.5 on 8.0 GeV) collider [6], the $T(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beam line, ($z$-axis). Since the $B^0$ meson pair is approximately at rest in the $T(4S)$ center-of-mass system (c.m.s.), $\Delta t$ can be determined from the displacement in $z$ between the $f_{CP}$ and $f_{tag}$ decay vertices: $\Delta t \approx (z_{f_{CP}} - z_{f_{tag}})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$. The Belle detector [7] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_S$ mesons and to identify muons (KLM).

The intermediate meson states are reconstructed from the following decays: $\pi^0 \to \gamma\gamma$, $K_S^0 \to \pi^+\pi^-$ (denoted by $K^+\pi^-$ hereafter) or $\pi^0\pi^0$ (denoted by $K_S^{00}$ hereafter), $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$, $\rho \to \pi^+\pi^-\pi^0$, $\phi \to \eta\pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$, $f_0 \to \pi^+\pi^-\pi^0$, $\phi \to K^+K^-$ and $J/\psi \to \ell^+\ell^-$ ($\ell = \mu, e$). We use all combinations of the intermediate states except for the following cases: $\eta \to \pi^+\pi^-\pi^0$ candidates are not used for $B^0 \to \eta K^0_S$ decays; $\eta \to \rho^0\gamma$ candidates are not used for $B^0 \to \eta' K^0_S$ decays; $K^0_S$ candidates are not used for $B^0 \to J/\psi K^0_S$, $f_0 K^0_S$, $\omega K^0_S$, $K_L^0\pi^0\pi^0$, $K_S^0\pi^0\pi^0$ and $K_S^0\pi^0\pi^0$ decays.

\textsuperscript{a} Email:yyusa@vt.edu
We determine CP parameters $S_f$ and $A_f$ for each mode by performing an unbinned maximum-likelihood fit to the observed $\Delta t$ distribution. The probability density function (PDF) expected for the signal distribution, $P_{\text{sig}}(\Delta t; S_f, A_f, q, w_1, \Delta m)$, is given by the time-dependent decay rate of signal incorporating the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\text{sig}}(\Delta t)$, which takes into account the finite vertex resolution. The resolution and wrong-tag fractions are determined by a multi-parameter fit to the $\Delta t$ distribution of a high-statistics control sample of semileptonic and hadronic $b \to c$ decays [8,13]. We determine the following likelihood for each event:

$$L_i = (1 - f_{\text{ol}}) \int \left[ \frac{f_{\text{sig}}}{P_{\text{sig}}(\Delta t')} R_{\text{sig}}(\Delta t_i - \Delta t') + (1 - f_{\text{sig}}) P_{\text{bkg}}(\Delta t') R_{\text{bkg}}(\Delta t_i - \Delta t') \right] d(\Delta t') + f_{\text{ol}} P_{\text{ol}}(\Delta t_i).$$

The signal probability $f_{\text{sig}}$ depends on the $r$ region and is calculated on an event-by-event basis as a function of the following variables: $\Delta E$ and $M_{bc}$ for $B^0 \to J/\psi K^0_S$ or $\bar{B}^0 \to J/\psi K^0_S$ and $\phi K^0_S$; $M_{bc}$ and $R_{\text{ol}}/b$ for $B^0 \to \phi(\to K^0_SK^0_L) K^0_S$, $\Delta E$, $M_{bc}$ and $R_{\text{ol}}/b$ for the other modes. $P_{\text{bkg}}(\Delta t')$ is a PDF for background events, which is convoluted with the background resolution function $R_{\text{bkg}}$. The term $P_{\text{ol}}(\Delta t)$ is a broad Gaussian function that represents a small outlier component [8,13]. The $S_f$ and $A_f$ are determined by maximizing the likelihood function $L = \prod_i L_i$, where the product is over all events. Table 1 summarizes the fit results for $2\sigma_{\text{eff}}$ and $A_f$. Figures 1 and 2 show the $\Delta t$ distributions and asymmetries for good tag quality events of $r > 0.5$. The dominant sources of systematic error for $2\sigma_{\text{eff}}$ stem from the uncertainties in the resolution function and in the background fraction. The dominant sources for $A_f$ are the effects of tag-side interference (TSI) [13], the uncertainties in the background fraction, in the vertex reconstruction and in the resolution function. We study the possible correlations between $R_{\text{ol}}/b$, $p_{\text{cms}}^b$ and $r$ PDFs used for $\phi K^0_S$ and $\eta' K^0_S$, which are neglected in the nominal result, and include their effect in the systematic uncertainties in the background fraction. Other contributions come from uncertainties in wrong tag fractions, the background $\Delta t$ distribution, $\tau_{\text{FG}}$ and $\Delta m_{\text{FG}}$. A possible fit bias is examined by fitting a large number of MC events and is found to be small. The dominant sources of systematic errors for the $B^0 \to J/\psi K^0_S$ mode are the uncertainties in the vertex reconstruction, in the resolution function, in the background fraction, in the flavor tagging, a possible fit bias, and the effect of the TSI. Other contributions are negligible. We add each contribution in quadrature to obtain the total systematic uncertainty. The systematic errors are summarized in Table 2.

3 Summary

For the $B^0 \to \eta' K^0_S$ mode, we determine the statistical significance from the obtained statistical uncertainties, taking into account the effect of the systematic uncertainties. The Feldman-Cousins frequentist approach
Table 1. Number of signal $N_{signal}$ and results of the fits to $\Delta t$ distributions. The first errors are statistical and the second errors are systematic. The third error for $\sin 2\phi_1^{\text{eff}}$ of $K^+ K^- K_S^0$ mode is an additional systematic error arising from the uncertainty of the $\xi_f = +1$ fraction.

| Mode                | $N_{signal}$     | $\sin 2\phi_1^{\text{eff}}$ | $A_f$     |
|---------------------|------------------|-------------------------------|-----------|
| $\phi K^0$          | $307 \pm 21$ ($K_S^0$, $114 \pm 17$ ($K_L^0$)) | $+0.50 \pm 0.21 \pm 0.06$ | $+0.07 \pm 0.15 \pm 0.05$ |
| $\eta K^0$          | $1421 \pm 46$ ($K_S^0$, $454 \pm 39$ ($K_L^0$)) | $+0.64 \pm 0.10 \pm 0.04$ | $-0.01 \pm 0.07 \pm 0.05$ |
| $\omega K_S^0$      | $118 \pm 17$     | $+0.11 \pm 0.46 \pm 0.06$ | $-0.09 \pm 0.29 \pm 0.06$ |
| $K_S^0 \pi^0$       | $515 \pm 31$     | $+0.33 \pm 0.35 \pm 0.08$ | $-0.05 \pm 0.14 \pm 0.05$ |
| $K_S^0 \pi^0 \pi^0$ | $307 \pm 32$     | $-0.43 \pm 0.49 \pm 0.09$ | $-0.17 \pm 0.24 \pm 0.05$ |
| $f_0 K_S^0$         | $377 \pm 25$     | $+0.18 \pm 0.23 \pm 0.11$ | $-0.15 \pm 0.15 \pm 0.07$ |
| $K_S^0 K_S^0 K_S^0$ | $185 \pm 17$     | $+0.30 \pm 0.32 \pm 0.08$ | $+0.31 \pm 0.20 \pm 0.07$ |
| $K^+ K^- K^0$       | $840 \pm 34$     | $+0.68 \pm 0.15 \pm 0.03$ | $-0.09 \pm 0.10 \pm 0.05$ |
| $J/\psi K^0$        | $7484 \pm 87$ ($K_S^0$), $6512 \pm 123$ ($K_L^0$) | $\sin 2\phi_1 = +0.642 \pm 0.031 \pm 0.017$ | $+0.018 \pm 0.021 \pm 0.014$ |

Fig. 1. Background subtracted $\Delta t$ distributions and asymmetries for event with good tag ($r > 0.5$) for $B^0 \to \eta K^0$, $\phi K^0$, $K_S^0 K_S^0 K_S^0$ and $J/\psi K^0$. Dashed lines show the SM expectation from $B^0 \to J/\psi K^0$ measurement.

Table 2. Dominant source of systematic error.

|                | $\phi K^0$ | $\eta K^0$ | $\omega K_S^0$ | $K_S^0 \pi^0$ | $K_S^0 \pi^0 \pi^0$ | $f_0 K_S^0$ | $K_S^0 K_S^0 K_S^0$ | $K^+ K^- K^0$ | $K_S^0 K_S^0 K_S^0$ | $J/\psi K^0$ |
|----------------|-----------|------------|----------------|---------------|---------------------|-------------|---------------------|--------------|--------------------|-------------|
| $\sin 2\phi_1^{\text{eff}}$ | 0.04 | 0.05 | 0.07 | 0.04 | 0.04 | 0.02 | 0.05 | 0.08 | 0.06 | 0.006 |
| Resolution function | 0.04 | 0.02 | 0.04 | < 0.01 | 0.05 | 0.04 | 0.06 | 0.01 | 0.04 | 0.006 |
| Background fraction | 0.01 | < 0.01 | < 0.01 | 0.05 | 0.09 | 0.01 | < 0.01 | 0.04 | 0.001 |
| $A_f$ | 0.02 | 0.01 | 0.02 | < 0.01 | 0.02 | < 0.01 | 0.02 | 0.05 | < 0.01 | 0.001 |
| Resolution function | 0.04 | 0.02 | 0.02 | < 0.01 | 0.03 | 0.03 | 0.06 | 0.07 | 0.02 | 0.009 |
| Background fraction | 0.02 | 0.02 | 0.02 | < 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.009 |
| Vertex reconstruction | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.009 |
Dashed lines show the SM expectation from individual any significant difference between the results for each event with good tag (r > 0.5) for \(B^0 \to f_0K_S^0, K^+K^-K^0, K_S^0\pi^0, \omega K_S^0, K_S^0\pi^0\) and \(K_S^0K_S^0\). We conclude that we have observed mixing-induced CP violation in the mode \(B^0 \to J/\psi K^0\). The significance of CP violation that is equivalent to 5.6 standard deviations for a Gaussian error. We do not find any significant difference between the results for each individual \(b \to s\bar{q}q\) and \(b \to d\bar{q}\bar{q}\) mode and those predicted from SM. Since some models of new physics predict such effects, our results can be used to constrain these models. However, many models predict smaller deviations that we cannot rule out with the current experimental sensitivity. Therefore, further measurements with much larger data samples are required in order to search for new, beyond the SM, CP-violating phases in the \(b \to s\) transition.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC and KIP of CAS (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MIST (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

References

1. M. Kobayashi and T. Masukawa, Prog Theor. Phys. 49, 652 (1973).
2. A. B. Carter and A. I. Sanda, Phys Rev. D 23, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. B193, 85 (1981).
3. M. Beneke and M. Neubert, Nucl. Phys. B675, 333 (2003); M. Beneke, Phys. Lett. B 620, 143 (2005); S. Mishima, talk given at second joint workshop on a Super B-factory, April 2005, Hawaii, arXiv:hep-ex/0507037.
4. R. Fleischer and S. Recksiegel, Eur. Phys. J. C 38, 251 (2004).
5. A. Garmash et al. (Belle Collaboration), Phys. Rev. D 69, 012001 (2004).
6. S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume.
7. A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002).
8. K. Abe et al. (Belle Collaboration) Phys. Rev. D 71, 072003 (2005).
9. K. Abe et al. (Belle Collaboration) arXiv:hep-ex/0507037.
10. A. Garmash et al. (Belle Collaboration), Phys. Rev. D 69, 012001 (2004); Phys. Rev. D 72 094003 (2005).
11. H. Kakuno et al., Nucl. Instrum. Methods Phys. Res., sect. A 533, 516 (2004).
12. H. Tajima et al., Nucl. Instrum. Methods Phys. Res., sect. A 533, 370 (2004).
13. K. F. Chen et al. (Belle Collaboration) Phys. Rev. D 72, 012004 (2005).
14. O. Long, M. Baak, R. N. Cahn and D. Kirkby, Phys. Rev. D 68, 034010 (2003).
15. G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998).