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Belle: $\sin(2\phi_1)$ with charmless and radiative decays

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We present measurements of time-dependent *CP* asymmetries in $B^0 \to \phi K^0$, $\eta' K^0$, $K_S^0 K_S^0 K_S^0$, $K_S^0 \pi^0$, $f_0(980) K_S^0$, $\omega(782) K_S^0$ and $K^+ K^- K_S^0$ decays based on a sample 386×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric e^+e^- collider. These decays are dominated by the $b \to s$ gluonic penguin transition and are sensitive to new *CP*-violating phases from physics beyond the standard model. *CP*-violation parameters $\sin 2\phi_1^{\rm eff}$ and $\mathscr{A}$ for each of the decay modes are obtained from the asymmetries in the distributions of the proper-time intervals between the two B decays. We also present measurements of *CP*-violation parameters for the $b \to s\gamma$ transition channel, $B^0 \to K_S^0 \pi^0 \gamma$.

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1. Introduction

The Standard Model (SM) predicts *CP* violation to occur in B^0 meson decays owing to a complex phase in the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix. This phase is illustrated by plotting the unitarity condition $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$ as vectors in the complex plane: the phase results in a triangle of nonzero height. Various measurements in the B system are sensitive to the internal angles ϕ_1, ϕ_2 and ϕ_3; The angle ϕ_1 is determined by measuring the time dependence of decays to *CP*-eigenstates. This distribution is given by

$$\frac{dN}{d\Delta t} \propto e^{-\Delta t/\tau}[1 - q\Delta\omega + q(1-2\omega)[\mathscr{A}\cos(\Delta m\Delta t) + \mathscr{S}\sin(\Delta m\Delta t)]] \tag{1.1}$$

where $q = +1(-1)$ corresponds to $B^0(\bar{B}^0)$ tags, ω is the mistag probability, $\Delta\omega$ is a possible difference in ω between B^0 and $\bar{B}^0$ tags, and Δm is the B^0-$\bar{B}^0$ mass difference. The *CP*-violating coefficients $\mathscr{A}$ and $\mathscr{S}$ are functions of the parameter λ: $\mathscr{A} = (|\lambda|^2 - 1)/(|\lambda|^2 + 1)$ and $\mathscr{S} = 2\Im(\lambda)/(|\lambda|^2 + 1)$, where

$$\lambda = \frac{q}{p}\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)} \sim \sqrt{\frac{M_{12}^*}{M_{12}}}\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)} = \left(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\right)\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)}$$

In this expression, q and p are the complex coefficients relating the flavor eigenstates B^0 and $\bar{B}^0$ to the mass eigenstates, M_{12} is the off-diagonal element of the B^0-$\bar{B}^0$ mass matrix, and we assume that the off-diagonal element of the decay matrix is much smaller: $\Gamma_{12} \ll M_{12}$. If only one weak phase enters the decay amplitude $A(\bar{B}^0 \to f)$, then $|A(\bar{B}^0 \to f)/A(B^0 \to f)| = 1$ and $\lambda = \eta_f e^{i2\theta}$, where $\eta_f = \pm 1$ is the *CP* of the final state f. For the final states discussed here, $|\theta| = \phi_1$.
$\sin 2\phi_1$ is most accurately measured using $B^0 \to J/\psi K^0$ decays. These decays are dominated by a $b \to c\bar{c}s$ tree amplitude and a $b \to s\bar{c}c$ penguin amplitude, the *CP* parameters are therefore $\mathscr{S} = \sin 2\phi_1$, $\mathscr{A} = 0$. The measurement of $\sin 2\phi_1$ is now extended to the $b \to s$ transition decays in which contributions from New Physics can be expected [1]. The cleanest example is the decay $B \to \phi K^0$. In the SM, this decay occurs through a pure penguin diagram and the *CP* phase ϕ_1 originally acquired in the B^0-$\bar{B}^0$ mixing diagram is not changed. If new particles contribute in the loop, they can introduce new couplings with new phases and the measured $\sin 2\phi_1$ becomes different from the SM prediction [2]. Therefore the measurement of $\sin 2\phi_1$ for such decays can be a sensitive probe to New Physics.
The phenomena of time-dependent *CP* violation in $b \to s\gamma$ decays such as $B^0 \to K_S^0\pi^0\gamma$ are also sensitive to physics beyond the SM. Within the SM, the photon emitted from a B^0 ($\bar{B}^0$) meson is dominantly right-handed (left-handed). Therefore the polarization of the photon carries information on the original b-flavor and the decay is, thus, almost flavor-specific. As a result, the SM predicts a small asymmetry [3] and any significant deviation from this expectation would be a manifestation of new physics. It was pointed out that in decays of the type of $B^0 \to P^0Q^0\gamma$, where P^0 and Q^0 represent any *CP* eigenstate spin-0 neutral particles (e.g. $P^0 = K_S^0$ and $Q^0 = \pi^0$), many new physics effects on the mixing-induced *CP* violation do not depend on the resonant structure of the P^0Q^0 system [4].
The results presented are from the Belle experiment, which runs at the KEKB asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance. Belle's previous measurements [5] of *CP* violation

in $B^0 \to \phi K_S^0$, ϕK_L^0, $\eta' K_S^0$, $K_S^0 K_S^0 K_S^0$, $K_S^0 \pi^0$, $f_0 K_S^0$, ωK_S^0 and $K^+K^-K_S^0$ decays were based on a 253 fb^{-1} data sample containing 275×10^6 $B\bar{B}$ pairs. In this report, we describe improved measurements for these decays incorporating an additional 104 fb^{-1} data sample that contains 111×10^6 $B\bar{B}$ pairs for a total of 386×10^6 $B\bar{B}$ pairs.
At the KEKB energy-asymmetric e^+e^- (3.5 on 8.0 GeV) collider, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and $\bar{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices: $\Delta t \simeq (z_{CP} - z_{\rm tag})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$.
The Belle detector 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 Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [6]. Two different inner detector configurations were used. For the first sample of 152 $\times 10^6$ $B\bar{B}$ pairs, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 123 $\times 10^6$ $B\bar{B}$ pairs, a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used[7].

2. Selection

We reconstruct the following B^0 decay modes to measure CP asymmetries: $B^0 \to \phi K_S^0$, ϕK_L^0, $\eta' K_S^0$, $\eta' K_L^0$, $K_S^0 K_S^0 K_S^0$, $K_S^0 \pi^0$, $f_0 K_S^0$, ωK_S^0, $K^+K^-K_S^0$ and $K_S^0 \pi^0 \gamma$ decays. We exclude K^+K^- pairs that are consistent with a $\phi \to K^+K^-$ decay from the $B^0 \to K^+K^-K_S^0$ sample. The intermediate meson states are reconstructed from the following decays: $\pi^0 \to \gamma\gamma$, $K_S^0 \to \pi^+\pi^-$, $\eta \to \gamma\gamma$, $\rho^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$, $\eta' \rho^0 \gamma$ or $\eta \pi^+\pi^-$, $f_0 \to \pi^+\pi^-$, and $\phi \to K^+K^-$. In addition, $K_S^0 \to \pi^0\pi^0$ decays are used for $B^0 \to \phi K_S^0$ and $\eta' K_S^0$ decays, and $\eta \to \pi^+\pi^-\pi^0$ for the case $B^0 \to \eta' K_S^0$ ($K_S^0 \to \pi^+\pi^-$). The selection is described in detail for each mode in [8, 9].

3. Results

We determine $\mathscr{S}$ and $\mathscr{A}$ for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function (PDF) expected for the signal distribution (Eq. 1.1) is convolved with the proper-time interval resolution $R_{\rm sig}$ which takes into account the finite vertex resolution. This resolution function is determined using flavor-specific B decays governed by semileptonic or hadronic $b \to c$ transitions.

Table 1 sumarizes the fit results of $\mathscr{S}$ and $\mathscr{A}$. We have also measured CP asymmetries in $B^0 \to J/\psi K^0$ decays using the same data sample [10]. The same analysis procedure as that used for the $b \to s$ modes yields $\sin 2\phi_1 = +0.652 \pm 0.039(\rm stat) \pm 0.020(\rm syst)$, which serves as a SM reference point, and $\mathscr{A} = +0.010 \pm 0.026(\rm stat) \pm 0.036(\rm syst)$. We do not see any significant deviation between the results for each $b \to s$ mode and those for $B^0 \to J/\psi K^0$.

Mode	SM expectations for $\mathscr{S}$	$\mathscr{S}$	$\mathscr{A}$
ϕK^0	$+\sin 2\phi_1$	$+0.44\pm0.27\pm0.05$	$+0.14\pm0.17\pm0.07$
ϕK_S^0	$+\sin 2\phi_1$	$+0.19\pm0.32$	$+0.12\pm0.20$
ϕK_L^0	$-\sin 2\phi_1$	-1.54 ± 0.59	$+0.38\pm0.36$
$\eta' K^0$	$+\sin 2\phi_1$	$+0.62\pm0.12\pm0.04$	$-0.04\pm0.08\pm0.06$
$\eta' K_S^0$	$+\sin 2\phi_1$	$+0.60\pm0.14$	-0.04 ± 0.09
$\eta' K_L^0$	$-\sin 2\phi_1$	-0.73 ± 0.29	-0.02 ± 0.18
$K_S^0K_S^0K_S^0$	$-\sin 2\phi_1$	$-0.58\pm0.36\pm0.08$	$+0.50\pm0.23\pm0.06$
$K_S^0\pi^0$	$+\sin 2\phi_1$	$+0.22\pm0.47\pm0.08$	$+0.11\pm0.18\pm0.08$
$f_0K_S^0$	$-\sin 2\phi_1$	$-0.47\pm0.36\pm0.08$	$-0.23\pm0.23\pm0.13$
ωK_S^0	$+\sin 2\phi_1$	$+0.95\pm0.53\ ^{+0.12}_{-0.15}$	$+0.19\pm0.39\pm0.13$
$K^+K^-K_S^0$	$-(2f_+-1)\sin 2\phi_1$	$-0.52\pm0.16\pm0.03$	$-0.06\pm0.11\pm0.07$

Table 1: Results of the fits to the Δt distributions for the $b\to s$ modes. The first error is statistical and the second error is systematic. f_+ is the *CP*-even fraction of the $K^+K^-K_S^0$ state.

We obtain the following results in the $K_S^0\pi^0\gamma$ mode with $K_S^0\pi^0$ invariant mass covering the full range up to 1.8 GeV/c^2:

$$\begin{aligned}\mathscr{S} &= +0.08\pm0.41(\text{stat})\ \pm0.10(\text{syst}),\\ \mathscr{A} &= +0.12\pm0.27(\text{stat})\ \pm0.10(\text{syst}).\end{aligned}$$

These results superseed the ones obtained in a previous publication [11]. We do not find any significant *CP* asymmetry, and therefore no indication of new physics from right handed currents, with the present statistics.

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