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CP Violation in $b \to s$ Decays and New Physics Phases

ALEXEI GARMASH
(for the Belle Collaboration)
Department of Physics, Princeton University
Jadwin Hall, Princeton New Jersey 08544, U.S.A.

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We present new measurements of CP-violation parameters in $B^0 \to \phi K^0$, $K^+K^-K^0_S$, $f_0(980)K^0_S$, $\eta' K^0_S$, ωK^0_S, $K^0_S\pi^0$, and $K^{*0}\gamma$ ($K^{*0} \to K^0_S\pi^0$) decays based on a sample of 275×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric e^+e^- collider. One neutral B meson is fully reconstructed in one of the specified decay channels, and the flavor of the accompanying B meson is identified from its decay products. CP-violation parameters for each of the decay modes are obtained from the asymmetries in the distributions of the proper-time intervals between the two B decays. All results are preliminary.

Keywords: CP violation; charmless decays

1. Introduction

CP violation in the flavor-changing $b \to s$ transitions is sensitive to physics at a very high-energy scale. Theoretical studies indicate that large deviations from standard model (SM) expectations are allowed for time-dependent CP asymmetries in B^0 meson decays [1]. Belle's previous measurement of the $B^0 \to \phi K^0_S$ decay, which is dominated by the $b \to s\bar{s}s$ transition, yielded a value that differs from the SM expectation by 3.5 standard deviations [2]. Measurements with a larger data sample are required to elucidate this difference. It is also essential to examine additional modes that may be sensitive to the same $b \to s$ penguin amplitude.

In the SM, CP violation arises from an irreducible phase, the Kobayashi-Maskawa (KM) phase, in the weak-interaction quark-mixing matrix. In particular, the SM predicts CP asymmetries in the time-dependent rates for B^0 and $\overline{B}^0$ decays to a CP eigenstate f_{CP}. In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{CP}f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a final state f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence given by

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q \cdot \Big[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)\Big]\right\}. \quad (1)$$

Here $\mathcal{S}$ and $\mathcal{A}$ are CP-violation parameters, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 ($\overline{B}^0$). To a good approximation, the SM predicts $\mathcal{S} = -\xi_f \sin 2\phi_1$, where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states, and $\mathcal{A} = 0$ for both $b \to c\bar{c}s$ and $b \to s\bar{s}s$ transitions. Possible contribution from $b \to u$ tree transition is estimated to be in the range from few per cent to about ten per cent depending on the final state [5]. In our analysis we neglect $b \to u$ contribution.

Another class of decays that proceed via the penguin transition is radiative $b \to s\gamma$ decays. Within the SM, the photon emitted from a B^0 ($\overline{B}^0$) meson is dominantly right-handed (left-handed). Therefore the polarization of the photon carries information on the original b-flavor; the decay is thus almost flavor-specific. The SM predicts a small asymmetry $\mathcal{S} \sim -2(m_s/m_b)\sin 2\phi_1$, where m_b (m_s) is the b-quark (s-quark) mass [6]. Any significant deviation from this expectation would be a manifestation of physics beyond the SM.

Recently Belle and BaBar measured time-dependent CP asymmetries in $B^0 \to J/\psi K^0_S$ and related decay modes, which are governed by the $b \to c\bar{c}s$ transition, and already determined $\sin 2\phi_1$ rather precisely; the present world average value is $\sin 2\phi_1 = +0.726 \pm 0.037$ [3]. This serves as a firm reference point for the SM.

2. Data Sample and Analysis Technique

Our previous measurements for $B^0 \to \phi K^0_S$, $K^+K^-K^0_S$ and $\eta' K^0_S$ were based on a 140 fb^{-1} data sample (DS-I) with 152×10^6 $B\overline{B}$ pairs [2]. In this report, we describe improved measurements incorporating an additional 113 fb^{-1} data sample that contains 123×10^6 $B\overline{B}$ pairs (DS-II) for a total of 275×10^6 $B\overline{B}$ pairs. Two inner detector configurations were used. A 2.0 cm radius beampipe and a 3-layer silicon vertex detector (SVD-I) were used for DS-I, while a 1.5 cm radius beampipe, a 4-layer silicon detector (SVD-II) and a small-cell inner drift chamber were used for DS-II [4].

In this update we include additional ϕK^0_S, $K^0_S \to \pi^0\pi^0$ and $\eta' K^0_S$, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0$ subdecay modes that were not used in the previous analysis. We also perform new measurements of CP asymmetries for the following CP-eigenstate B^0 decay modes: $B^0 \to \phi K^0_L$ and $f_0(980)K^0_S$ for $\xi_f = +1$; $B^0 \to \omega K^0_S$ and $K^0_S\pi^0$ for $\xi_f = -1$. The decays $B^0 \to \phi K^0_S$ and ϕK^0_L are combined in this analysis by redefining $\mathcal{S}$ as $-\xi_f\mathcal{S}$ to take the opposite CP parities into account, and are collectively called "$B^0 \to \phi K^0$". The CP asymmetries for the decay $B^0 \to \omega K^0_S$ are measured for the first time. Finally, we also measure time-dependent CP violation in the decay $B^0 \to K^{*0}\gamma$ ($K^{*0} \to K^0_S\pi^0$), which is not a CP eigenstate but is sensitive to physics beyond the SM. Yet another final state that is not a CP eigenstate is $K^+K^-K^0_S$. We find that the $K^+K^-K^0_S$ state is primarily $\xi_f = +1$; a measurement of the $\xi_f = +1$ fraction with DS-I gives $1.03 \pm 0.15(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ [2]. In the following determination of $\mathcal{S}$ and $\mathcal{A}$, we fix $\xi_f = +1$ for this mode.

Table 1. Results of the fits to the Δt distributions. Errors are statistical and systematic. We combine $B^0 \to \phi K_S^0$ and $B^0 \to \phi K_L^0$ decays to obtain $\mathcal{S}_{\phi K^0}$ and $\mathcal{A}_{\phi K^0}$.

Mode	SM expectation for $\mathcal{S}$	$\mathcal{S}$	$\mathcal{A}$
ϕK^0	$+\sin 2\phi_1$	$+0.06 \pm 0.33 \pm 0.09$	$+0.08 \pm 0.22 \pm 0.09$
$K^+K^-K_S^0$	$-\sin 2\phi_1$	$-0.49 \pm 0.18 \pm 0.04$	$-0.08 \pm 0.12 \pm 0.07$
$f_0(980)K_S^0$	$-\sin 2\phi_1$	$+0.47 \pm 0.41 \pm 0.08$	$-0.39 \pm 0.27 \pm 0.08$
$\eta' K_S^0$	$+\sin 2\phi_1$	$+0.65 \pm 0.18 \pm 0.04$	$-0.19 \pm 0.11 \pm 0.05$
ωK_S^0	$+\sin 2\phi_1$	$+0.75 \pm 0.64 {}^{+0.13}_{-0.16}$	$+0.26 \pm 0.48 \pm 0.15$
$K_S^0\pi^0$	$+\sin 2\phi_1$	$+0.30 \pm 0.59 \pm 0.11$	$-0.12 \pm 0.20 \pm 0.07$
$K^{*0}\gamma$ ($K^{*0} \to K_S^0\pi^0$)	$-2(m_s/m_b)\sin 2\phi_1$	$-0.79^{+0.63}_{-0.50} \pm 0.10$	0.0 (fixed)

We determine $\mathcal{S}$ and $\mathcal{A}$ for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function expected for the signal distribution, is given by Eq. (1) incorporating the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function, which takes into account the finite vertex resolution.

For the decays $B^0 \to K_S^0\pi^0$ and $K^{*0}\gamma$ ($K^{*0} \to K_S^0\pi^0$), the B vertex reconstruction technique is validated using $B^0 \to J/\psi K_S^0$ events where the B decay vertex is reconstructed with K_S^0 and the IP constraint rather than charged tracks from J/ψ. A CP fit to the $B^0 \to J/\psi K_S^0$ sample gives $\mathcal{S}_{J/\psi K_S^0} = +0.68 \pm 0.10(\text{stat})$ and $\mathcal{A}_{J/\psi K_S^0} = +0.02 \pm 0.04(\text{stat})$, which are in good agreement with the world average values. Thus, we conclude that the vertex resolution for the $B^0 \to K_S^0\pi^0$ and $B^0 \to K^{*0}\gamma$ ($K^{*0} \to K_S^0\pi^0$) decays is well understood. The only free parameters in the final fit are $\mathcal{S}$ and $\mathcal{A}$.

Event selections and analysis technique are described in details in Ref. [7] and references therein. Here we only discuss the results.

3. Results of *CP* Asymmetry Measurements

Table 1 summarizes the fit results of $\mathcal{S}$ and $\mathcal{A}$. We define the raw asymmetry in each Δt bin by $(N_{q=+1} - N_{q=-1})/(N_{q=+1} + N_{q=-1})$, where $N_{q=+1(-1)}$ is the number of observed candidates with $q = +1(-1)$ [8]. Figures 1(a-c) show the raw asymmetries for some channels. Note that these projections onto the Δt axis do not take into account event-by-event information (such as the signal fraction, the wrong tag fraction and the vertex resolution), which is used in the unbinned maximum-likelihood fit.

Various crosschecks of the measurement are performed. We reconstruct charged B meson decays that are the counterparts of the $B^0 \to f_{CP}$ decays and apply the same fit procedure. All results for the $\mathcal{S}$ term are consistent with no CP asymmetry, as expected. Lifetime measurements are also performed for the f_{CP} modes and the corresponding charged B decay modes. The fits yield τ_{B^0} and τ_{B^+} values consistent with the world-average values. MC pseudo-experiments are generated for each decay mode to perform ensemble tests. We find that the statistical errors obtained in our

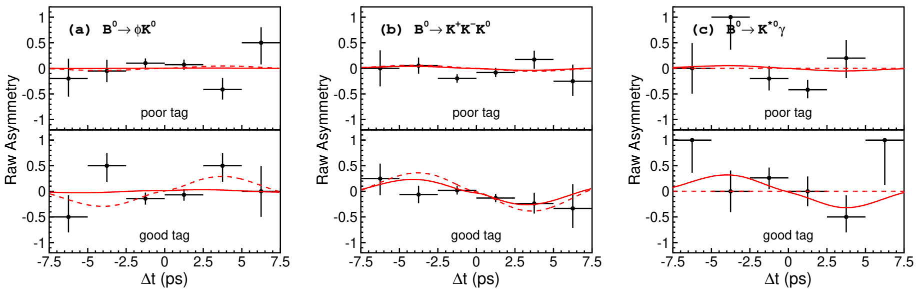

Fig. 1. The asymmetry, A, in each Δt bin for (a) $B^0 \to \phi K^0$, (b) $B^0 \to K^+K^-K^0_S$ and (d) $B^0 \to K^{*0}\gamma$. The solid curves show the result of the unbinned maximum-likelihood fit. The dashed curves show the SM expectation with $\sin 2\phi_1 = +0.73$ ($\mathcal{S} = 0$ for $B^0 \to K^{*0}\gamma$) and $\mathcal{A} = 0$.

measurements are all consistent with the expectations from the ensemble tests.

For the $B^0 \to \phi K^0$ decay, a fit to DS-I alone yields $\mathcal{S} = -0.68 \pm 0.46(\text{stat})$ and $\mathcal{A} = -0.02 \pm 0.28(\text{stat})$, while a fit to DS-II alone yields $\mathcal{S} = +0.78 \pm 0.45(\text{stat})$ and $\mathcal{A} = +0.17 \pm 0.33(\text{stat})$. Note that the results for DS-I differ from our previously published results [2] $\mathcal{S} = -0.96 \pm 0.50^{+0.09}_{-0.11}$ and $\mathcal{A} = -0.15 \pm 0.29 \pm 0.07$, as decays $B^0 \to \phi K^0_L$ and ϕK^0_S ($K^0_S \to \pi^0\pi^0$) are included in this analysis. From MC pseudo-experiments, the probability that the difference between $\mathcal{S}$ values in DS-I and DS-II is larger than the observed one (1.46) is estimated to be 4.5%. As all the other checks also yield results consistent with expectations, we conclude that the difference in $\mathcal{S}_{\phi K^0}$ between the two datasets is due to a statistical fluctuation.

Averaging the result of $\mathcal{S}$ measurement for all the $b \to s$ channels (except $B^0 \to K^{*0}\gamma$), we obtain $\sin 2\phi_1 = +0.43^{+0.12}_{-0.11}$ as a weighted average, where the error includes both statistical and systematic errors. The result differs from the SM expectation by 2.4 standard deviations.

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