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BaBar: sin(2beta) with charmless and radiative decays

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We present new measurements of time-dependent *CP*-violation parameters in hadronic penguin decays: $B^0 \to K^+K^-K^0_L$, $K^0_S\pi^0\pi^0$, $K^0_SK^0_SK^0_S$, ωK^0_S, $\eta' K^0_L$, and a radiative penguin decay $B^0 \to K^0_S\pi^0\gamma$ in a dataset of around $230 \cdot 10^6$ $B\bar{B}$ pairs collected by the *BABAR* detector at the asymmetric *B* Factory at SLAC. These *CP* asymmetry measurements probe for amplitudes beyond the Standard Model in loop-dominated decays of neutral *B* mesons. While we find a puzzling deviation of *CP*-asymmetry parameters from predicted values, a full confirmation still awaits more data.

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1. Introduction

In the standard model (SM), charged-current transitions among quarks are characterized by CKM [1] couplings that can have *CP*-violating phases and lead to large *CP*-asymmetry in B meson decays. The time-dependent *CP*-asymmetry is obtained by measuring the proper time difference Δt between a fully reconstructed neutral B meson and a partially reconstructed tagging B meson whose decay products are analyzed to determine its flavor. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the flavor of the tagging meson is a B^0 ($\bar{B}^0$) is given by

$$\mathrm{f}_\pm(\Delta t) = \frac{\mathrm{e}^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\,[\,1 \pm S\cdot\sin(\Delta m_d \Delta t) \mp C\cdot\cos(\Delta m_d \Delta t)], \tag{1.1}$$

where τ_{B^0} is the mean B^0 lifetime and Δm_d is the B^0–$\bar{B}^0$ oscillation frequency [2], and S and C are *CP*-violation coefficients.

Decays of B mesons into charmless hadronic final states with the total strangeness of one are dominated by penguin-loop amplitudes. In the penguin decays to hadronic final states, we expect $S \approx -\eta_f \sin 2\beta$ and $C \approx 0$, where β is the $B^0 - \bar{B}^0$ mixing phase, and η_f is *CP* eigenvalue of the final state. Recently, there has been a progress in understanding hadronic uncertainties that can lead to deviations from these predictions. Studies based on the QCD factorization (QCDF) predict deviations of several percent that depend on the decay channel [3]. Another set of estimates based on the SU(3) symmetry of the quark flavor provides upper bounds on the absolute values of the deviations [4] which are consistent but less constraining than the QCDF calculations.

In the radiative decay $B^0(\bar{B}^0) \to K^0_S \pi^0 \gamma$ the photon polarization is predominantly right (left) handed while decays to left (right) handed photons are suppressed by $2m_s/m_b$, where m_s, m_b are masses of s and b quarks, respectively. Interference between decay amplitudes is suppressed by the same factor and we expect to measure $S \approx -2m_s/m_b \sin 2\beta$ and $C \approx 0$. These predictions can be affected by hadronization uncertainties of order 0.1 [5].

Many models beyond the SM introduce new particles with *CP*-violating couplings that can appear in penguin decays and modify *CP*-violation observables. Therefore, any significant deviation in S and C from SM predictions beyond possible hadronization corrections would indicate new phenomena.

2. Summary of Results

The time-dependent *CP*-violation parameters are measured in a dataset of around $230 \cdot 10^6$ $B\bar{B}$ pairs collected by the *BABAR* detector [6] at the asymmetric B Factory at SLAC.

The *CP* eigenvalue of the final state is well defined when all final-state particles are also *CP* eigenstates [7]. However, the final state in $B^0 \to K^+K^-K^0_L$ decays is a mixture of *CP*-even and -odd eigenstates. Assuming that K^0_L is a pure *CP* eigenstate, the *CP* eigenvalue of the 3-body final state is given by the angular momentum between K^+K^- pair. Existence of non-*CP* final states can additionally complicate the measurement, but this has been disfavored by theory [8] and recent searches [9, 10]. We use results of angular-moment analysis that extracted fractions of S and P partial waves in K^+K^- mass bins from $B^0 \to K^+K^-K^0_S$ decays [10] and scale them to the observed yield in $B^0 \to K^+K^-K^0_L$ decays. When ϕK^0_L decays are excluded, we find a dominance

Table 1: Summary of new measurements of *CP* asymmetry parameters in hadronic *B* meson decays that are dominated by penguin diagrams at *BABAR*. Results combined with decay modes that have K^0_S instead of K^0_L in the final state are shown in parentheses.

Mode		$\sin 2\beta$	C
$K^+K^-K^0_L$	[12]	$0.09 \pm 0.33^{+0.13}_{-0.14} \pm 0.10$	$0.54 \pm 0.22^{+0.08}_{-0.09}$
		$(0.41 \pm 0.18 \pm 0.07 \pm 0.11)$	$0.23 \pm 0.12 \pm 0.07$
$K^0_S K^0_S K^0_S$	[14]	$0.63^{+0.28}_{-0.32} \pm 0.04$	$-0.10 \pm 0.25 \pm 0.05$
$K^0_S \pi^0 \pi^0$	[16]	$-0.84 \pm 0.71 \pm 0.08$	$0.27 \pm 0.52 \pm 0.13$
$\eta' K^0_L$	[17]	$0.60 \pm 0.31 \pm 0.04$	$0.10 \pm 0.21 \pm 0.03$
		$(0.36 \pm 0.13 \pm 0.03)$	$(-0.16 \pm 0.09 \pm 0.02)$
ωK^0_S	[18]	$0.50^{+0.34}_{-0.38} \pm 0.02$	$-0.56^{+0.29}_{-0.27} \pm 0.03$

Table 2: Summary of new measurements of *CP* asymmetry parameters in radiative *B* meson decays that are dominated by penguin diagrams at *BABAR*. † $K^{*0} \to K^0_S \pi^0$. ‡ $1.1 < M(K^0_S \pi^0) < 1.8$ GeV/c^2.

Mode		S	C
$K^{*0}\gamma$ †	[19]	$-0.21 \pm 0.40 \pm 0.05$	$-0.40 \pm 0.23 \pm 0.03$
$K^0_S \pi^0 \gamma$ ‡	[19]	$0.9 \pm 1.0 \pm 0.2$	$-1.0 \pm 0.5 \pm 0.2$

of *S*-waves and *CP*-odd final states with a fraction of $f_{CP-odd} = 0.92 \pm 0.07 \pm 0.06$. This result is consistent with an analysis using isospin symmetry [11] and a time-integrated Dalitz plot analysis of $B^0 \to K^+K^-K^0_S$ decays which describes the decay rate over the Dalitz plot as a function of two invariant masses and the flavor tag and assumes nonexistence of direct *CP* violation in decay amplitudes [15].

The decay $B^0 \to K^+K^-K^0_L$ is reconstructed from combination of charged kaons and K^0_L candidates and we find 777 ± 80 signal events. The final state $\eta' K^0_L$ is reconstructed from $K^0_S \to \pi^+\pi^-$ and $\eta' \to \rho\gamma$, $\eta(\gamma\gamma)\pi^+\pi^-$ candidates and we get 137 ± 22 and 303 ± 49 signal events, respectively. In both $B^0 \to K^+K^-K^0_L$ and $K^0_L\eta'$, the K^0_L is identified by the shape of the energy cluster deposited in the electromagnetic calorimeter, or as a set of hits in two or more layers of the muon detector that cannot be associated with any charged track in the event. Since the K^0_L energy is not measured, it is calculated from a constraint that the momentum sum of all decay products equal the B^0 meson mass.

The final state for decay $B^0 \to K^0_S K^0_S K^0_S$ is reconstructed from combination of three K^0_S candidates. When all K^0_S's decay to a $\pi^+\pi^-$ pair we find 88 ± 10 signal events, and if we allow at most one K^0_S to decay to $\pi^0\pi^0$ we find additional $41.0^{+9.2}_{-8.3}$ signal events. The final state $K^0_S\pi^0\pi^0$ is reconstructed from $K^0_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$ candidates, and we find 117 ± 27 signal events. We reconstruct $B^0 \to K^0_S\pi^0\gamma$ decays from $K^0_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$ and find 157 ± 16 signal events consistent with $K^{*0} \to K^0_S\pi^0$ and 59 ± 13 signal events when $1.1 < M(K^0_S\pi^0) < 1.8$ GeV/c^2. Since there are no charged tracks coming from the neutral *B* vertex, the decay point for $B^0 \to K^0_S K^0_S K^0_S$, $B^0 \to K^0_S\pi^0\pi^0$ and $B^0 \to K^0_S\pi^0\gamma$ is found by constraining momenta of the decay products to originate from the interaction point [13].

The final state $K^0_S\omega$ is reconstructed from $K^0_S \to \pi^+\pi^-$ and $\omega \to \pi^+\pi^-\pi^0$ candidates, and we find a total of 92 ± 13 signal events.

New results of *CP* asymmetry measurements from *BABAR* are given in Table 1 for hadronic and Table 2 for radiative decays. The $\sin 2\beta$ parameter in Table 1 is extracted from S coefficient after taking into account the *CP* content of the final state.

3. Conclusion

Measurements of *CP* asymmetry in penguin-dominated decays probe for possible *CP*-violating phases in addition to SM phase β. New *BABAR* measurements are listed in Tables 1,2 while a summary of all existing measurements is given in [2]. There is a hint that the value of the $\sin 2\beta$ parameter extracted from penguin decays can be smaller than predicted by the SM, but a confirmation awaits more data. Future prospects for such measurements at the *BABAR* depend on the available luminosity and the character of new physics amplitudes.

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