
**THE MEASUREMENT OF TIME-DEPENDENT CP -VIOLATING
ASYMMETRIES IN LOOP-DOMINATED B DECAYS WITH $BABAR$**

ANDREAS HÖCKER

(representing the $BABAR$ Collaboration)

Laboratoire de l'Accélérateur Linéaire,

IN2P3-CNRS et Université Paris-Sud – Bât. 200, BP34 – F-91898 Orsay, France

E-mail: hoecker@lal.in2p3.fr

We report on preliminary measurements of time-dependent CP asymmetries in neutral B decays to CP eigenstates with transition amplitudes that are dominated by penguin-type loops. The results are obtained from a data sample of up to 227 million $T(4S) \rightarrow B\bar{B}$ decays collected with the $BABAR$ detector at the PEP-II asymmetric-energy B -meson Factory at SLAC. The amplitudes of the effective mixing-induced CP asymmetries, $\sin 2\beta_{\text{eff}}$, are derived from decay-time distributions of events in which one neutral B meson is fully reconstructed in a final state without charm and the other B meson is determined to be either a B^0 or \bar{B}^0 from its decay products.

1 Introduction

Since the precise measurement of $\sin 2\beta$ from the time-dependent CP -asymmetry analyses of $b \rightarrow c\bar{c}s$ decays^{1,2}, considerable effort is spent at the B -Factory experiments to determine the corresponding quantity from penguin-loop-dominated (charmless) B decays (“ s -penguin decays”), such as $B^0 \rightarrow \phi K^0$, $\eta' K^0$, $f_0(980)K^0$, S -wave dominated $K^+K^-K^0$ and $\pi^0 K^0$. Due to the large virtual mass scales occurring in the penguin loops, additional diagrams with heavy particles in the loops and new CP -violating phases may contribute to the decay amplitudes. The measurement of CP violation in these channels and the comparison with the charmonium reference value is therefore a sensitive probe for physics beyond the Standard Model (SM). Due to the different non-perturbative strong-interaction properties of the various s -penguin decays, the NP-induced deviation from $\sin 2\beta$ is expected to be channel-dependent.

There is a variety of reasons why specific contributions of New Physics (NP) are expected at or below the TeV scale. Among these are the gauge hierarchy problem of the SM Higgs sector, Baryogenesis, Grand Unification of the gauge couplings and the strong

CP problem. If the NP is not flavor blind it should be present in the flavor sector, and detectable in loop-induced B decays.^{3,4} However, the present insignificance of NP effects already sets strong boundary conditions on the generic flavor structure of the NP, hence favoring minimal flavor-violating schemes.⁵

Assuming penguin dominance and neglecting CKM-suppressed amplitudes, s -penguin decays carry approximately the same weak phase as the decay $B^0 \rightarrow J/\psi K_s^0$. Their mixing-induced CP -violating parameters are expected to be^{3,6} $-\eta_f \times \sin 2\beta \simeq -\eta_f \times 0.7$ in the SM^a, where η_f is the CP eigenvalue of the final state f .

This simple relation is altered by the presence of a suppressed $V_{us}V_{ub}^*$ penguin diagram in all s -penguin decays, and a corresponding color-suppressed tree-level diagram in three-body decays (such as $K^+K^-K^0$) or resonant decays with non- $s\bar{s}$ flavor contributions (like $\eta' K^0$, $f_0 K^0$ and $\pi^0 K^0$). As a consequence, only an effective $\sin 2\beta_{\text{eff}} = -\eta_f \times S$ is determined. Naive dimensional arguments may allow us to derive coarse estimates for the mode-specific theoretical systematics on the amplitude level. We

^aWith these assumptions, the expected phase shift is $2\beta_{\text{eff}} - 2\beta = -\arg[(V_{tb}V_{ts}^*V_{cb}^*V_{cs})^2] \simeq 2.1^\circ$.

find an uncertainty of $\mathcal{O}(5\%)$ (corresponding to a $2\beta_{\text{eff}}$ shift of about 2°) for the golden mode ϕK^0 , $\mathcal{O}(10\%)$ for the silver-plated modes $\eta' K^0$, $f_0 K^0$ or $K^+ K^- K^0$, and $\mathcal{O}(20\%)$ for the bronze-plated modes that have no $s\bar{s}$ component ($\pi^0 K^0$ and similar). Computations based on QCD factorization generally find smaller deviations.⁷ Bounds on $2\beta_{\text{eff}} - 2\beta$ can be derived from SU(3) flavor-symmetry relations,⁸ which are however weak at present.

We present in this summary preliminary measurements of CP -violating asymmetries in all of the above mentioned s -penguin decays. The data used for these measurements were accumulated with the *BABAR* detector⁹ at the PEP-II asymmetric-energy e^+e^- storage ring at SLAC. The sample consists of 227×10^6 $B\bar{B}$ pairs (209×10^6 for $f_0(980)K_s^0$) collected at the $\Upsilon(4S)$ resonance. Detailed descriptions of the individual analyses presented here are given in Refs.¹⁰ In Ref.⁹ we describe the silicon vertex tracker (SVT) and drift chamber used for track and vertex reconstruction, the Cherenkov detector (DIRC), the electromagnetic calorimeter (EMC), and the instrumented flux return (IFR).

With $\Delta t \equiv t_{CP} - t_{\text{tag}}$ defined as the proper time interval between the decay of the fully reconstructed B_{CP}^0 and that of the other meson B_{tag}^0 , the time-dependent decay rate is given by

$$f_{Q_{\text{tag}}}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left(1 + Q_{\text{tag}} S \sin(\Delta m_d \Delta t) - Q_{\text{tag}} C \cos(\Delta m_d \Delta t) \right), \quad (1)$$

where $Q_{\text{tag}} = 1(-1)$ when the tagging meson B_{tag}^0 is a $B^0(\bar{B}^0)$, τ is the mean B^0 lifetime, and Δm_d is the $B^0\bar{B}^0$ oscillation frequency. The parameter S is non-zero if there is mixing-induced CP violation, while a non-zero value for C would indicate direct CP violation. At least two interfering decay amplitudes with different weak and strong phases

are required to obtain $C \neq 0$. Hence we do not expect to observe significant direct CP violation in any of the channels studied if the assumption of penguin dominance is correct.

2 Analysis Techniques

We reconstruct signal candidates from combinations of a K_s^0 candidate decaying to $\pi^+\pi^-$, and a $\phi \rightarrow K^+K^-$, $\eta' \rightarrow (\eta\pi^+\pi^-, \rho^0\gamma)$, $f_0(980) \rightarrow \pi^+\pi^-$, K^+K^- (excluding ϕ), or a π^0 candidate. We also reconstruct the mode $B^0 \rightarrow \phi K_L^0$, where a K_L^0 candidate is identified either as an unassociated cluster of energy in the EMC or as a cluster of hits in the IFR. For the $B^0 \rightarrow \eta' K_s^0$ decay, also $K_s^0 \rightarrow \pi^0\pi^0$ and $\eta \rightarrow (\gamma\gamma, \pi^+\pi^-\pi^0)$ decays are considered so that the reconstructed signal amounts to 46% (not containing the detector acceptance) of the total $\eta' K_s^0$ production.

We use strong particle identification from the DIRC, the tracking system and the EMC, to identify pions and kaons in the final state. Two kinematic variables are used to discriminate between signal- B decays and combinatorial background: the difference ΔE between the center-of-mass (CM) energy of the B candidate and the CM beam energy, and the beam-energy-substituted B -candidate mass m_{ES} , defined in the laboratory frame. In the $\pi^0 K_s^0$ analysis, these variables are replaced by the unconstrained B -candidate mass $m_{\text{rec}} = |q_B|$, and the missing mass $m_{\text{miss}} = |q_{e^+e^-} - \hat{q}_B|$, where $q_{e^+e^-}$ is the four-momentum of the e^+e^- system and \hat{q}_B is the four-momentum of the B candidate after applying a B^0 -mass constraint. The missing mass has a slightly better resolution than m_{ES} and, by construction, m_{rec} and m_{miss} have a vanishing linear correlation coefficient.

Continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events are the dominant background. To enhance discrimination between signal and continuum, we use a multivariate analyzer (MVA), which is a Fisher discriminant or a

neural network (NN), to combine four discriminating variables: the cosine of the angle between the CM B direction and the z axis (along the beam direction), the cosine of the angle between the thrust axis of the B candidate and the z axis, and the topological monomials L_0 , L_2 (see Refs.¹⁰).

Monte Carlo (MC)-simulated events are used to study the background from other B decays. The charmless modes are grouped into different classes with similar kinematic and topological properties. In the $K^+K^-K_S^0$ analysis exclusive $b \rightarrow c$ decays with the same final state as the signal are vetoed by cuts on their invariant masses.

The time difference Δt is obtained from the measured distance between the z positions of the B_{CP}^0 and B_{tag}^0 decay vertices, and the boost $\beta\gamma = 0.56$ of the e^+e^- system. Due to the K_S^0 lifetime, the Δt determination is particularly challenging for the $\pi^0K_S^0$ final state. To select valid candidates for this mode, at least 4 SVT hits are required for each of the decay pions (about 60% of the events). While the Δt information of the rejected events is not used, they contribute to the measurement of the C coefficient. We determine Δt from a global constrained fit to the entire $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ decay tree that takes the information on the beam energy and the position of the interaction point into account. To further improve the Δt resolution, the sum of the two measured B^0 lifetimes is constrained to 2τ with an uncertainty of $\sqrt{2}\tau$ in the fit.

A new NN-based algorithm¹¹ has been developed to determine the flavor of the B_{tag}^0 . In addition to the information exploited by the algorithm described in Ref.¹, it uses low-momentum electrons, $A \rightarrow p\pi$ decays, and additional correlations among identified kaon candidates. The resulting effective tagging efficiency amounts to $Q \simeq 30.5\%$. The tagging efficiencies, mistag probabilities, mistag biases and also the Δt resolution parameters are determined from a fit to fully recon-

structed B decays to charm.

We use unbinned extended maximum-likelihood fits to extract the event yields and the CP parameters defined in Eq. (1). In these fits, the likelihood for a given event is the sum of the signal, continuum and the B -background likelihoods, weighed by their respective event yields. We use as fit variables Δt , ΔE , m_{ES} , the MVA (all modes) as well as the resonance mass and decay angle (ϕK_S^0 and $f_0(980)K_S^0$). In the case of ϕK_L^0 the B -mass kinematic constraint is necessary to determine the K_L^0 momentum so that m_{ES} cannot be exploited in the fit. The signal reference shapes for the fit variables are obtained from MC simulation, validated with control samples from fully reconstructed B decays to charm of similar topology. As many background shape parameters as possible are simultaneously determined by the fit to reduce the use of prior assumptions.

The $K^+K^-K_S^0$ final state has unknown a priori CP content so that the CP -even fraction, f_{even} , has to be extracted experimentally. Two different methods are applied, of which the first one (described below) provides the main result, and the second is a cross check. We study the K^+K^- helicity angle distribution $|A_{B^0 \rightarrow K^+K^-K_S^0}(\cos\theta)|^2 = \sum_{\ell=0,1,2} \langle P_\ell \rangle \times P_\ell(\cos\theta)$, where P_ℓ are Legendre polynomials of order ℓ . The average moments $\langle P_\ell \rangle$ are computed by means of background-subtracted signal weights returned by the fit.¹² We find $f_{\text{even}} = A_S^2/(A_S^2 + A_P^2) = 0.89 \pm 0.08 \pm 0.06$, where the first error is statistical and the second systematic, and where the S - and P -wave amplitude-squared are given by $A_S^2 = \sqrt{2}\langle P_0 \rangle - \sqrt{5/2}\langle P_2 \rangle$ and $A_P^2 = \sqrt{5/2}\langle P_2 \rangle$. Assuming isospin invariance, f_{even} can also be obtained from the ratio¹³ $2\Gamma(B^+ \rightarrow K^+K_S^0K_S^0)/\Gamma(B^0 \rightarrow K^+K^-K_S^0)$, for which we find 0.75 ± 0.11 (statistical error only), in agreement with the result from the moments analysis.

| Mode | Yield | $\sin 2\beta_{\text{eff}}$ | C |
|-------------------------------|-----------------------------|---|---------------------------|
| $B \rightarrow \phi K^0$ | (ϕK_S^0) 114 ± 12 | $+0.50 \pm 0.25^{+0.07}_{-0.04}$ | $0.00 \pm 0.23 \pm 0.05$ |
| | (ϕK_L^0) 98 ± 18 | | |
| $B \rightarrow \eta' K_S^0$ | 819 ± 38 | $+0.27 \pm 0.14 \pm 0.03$ | $-0.21 \pm 0.10 \pm 0.03$ |
| $B \rightarrow f_0(980)K_S^0$ | 152 ± 19 | $+0.95^{+0.23}_{-0.32} \pm 0.10$ | $-0.24 \pm 0.31 \pm 0.15$ |
| $B \rightarrow K^+K^-K_S^0$ | 452 ± 28 | $+0.55 \pm 0.22 \pm 0.04 \pm 0.11_{CP}$ | $+0.10 \pm 0.14 \pm 0.06$ |
| $B \rightarrow \pi^0 K_S^0$ | 300 ± 23 | $+0.35^{+0.30}_{-0.33} \pm 0.04$ | $+0.06 \pm 0.18 \pm 0.06$ |

Table 1. Preliminary fit results for the different s -penguin modes. The second column gives the observed signal yield, the third the effective $\sin 2\beta_{\text{eff}} = -\eta_f \times S$ value, and the last column the result for the C parameter. The first errors given are statistical and the second systematic. The third error given for $\sin 2\beta_{\text{eff}}(K^+K^-K_S^0)$ is due to the uncertainty on the CP -even fraction.

3 Results

The fit results for the event yields and CP parameters are given in Table 1. In the case of $K^+K^-K_S^0$, $\sin 2\beta_{\text{eff}}$ and f_{even} (approximately related through $\sin 2\beta_{\text{eff}} \sim S/(2f_{\text{even}} - 1)$) are simultaneously determined by the fit. The individual $\sin 2\beta_{\text{eff}}$ results for the ϕK_S^0 (0.29 ± 0.31) and ϕK_L^0 (1.05 ± 0.51) subsamples agree within statistical errors. We have also measured the charge asymmetry in the decay $B^+ \rightarrow \phi K^+$ for which we find the null result $A_{\phi K^+} = (\Gamma(\phi K^-) - \Gamma(\phi K^+))/\Sigma = +0.054 \pm 0.056 \pm 0.012$.

All measurements reported here are statistics limited. The systematic errors are dominated by the opposite CP background and the reference shape modeling (ϕK^0), the fit bias ($\eta' K_S^0$, $f_0(980)K_S^0$ and $K^+K^-K_S^0$), the interference with other resonances ($f_0(980)K_S^0$), and the background tagging asymmetries and SVT alignment ($\pi^0 K_S^0$). All measurements have in common the uncertainty due to the unknown CP violation on the tag-side.

The individual $\sin 2\beta_{\text{eff}}$ results are in agreement with the charmonium value,¹¹ with the exception of $\eta' K_S^0$, which exhibits a 3.0σ discrepancy (neglecting theoretically motivated deviations). Overall, the results are in agreement with but more precise than the corresponding numbers from the Belle Collaboration¹⁵.

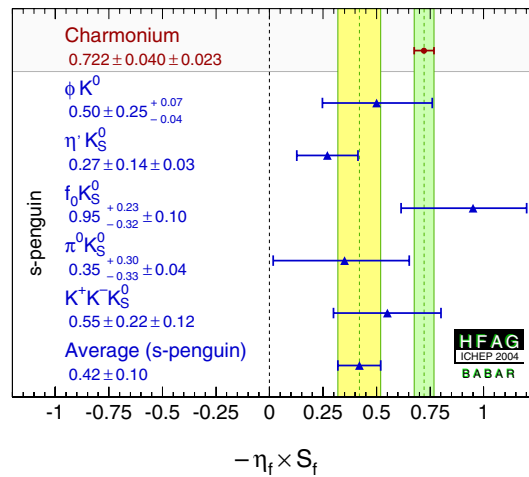


Figure 1. Compilation of preliminary results on $\sin 2\beta_{\text{eff}}$ from charmonium and s -penguin decays. The averages, indicated by the shaded bands, are obtained ignoring theoretical uncertainties.

A graphical compilation of the results is given in Fig. 1. We find the s -penguin average $\sin 2\beta_{\text{eff}} = 0.42 \pm 0.10$ (C.L. = 0.40), where theoretical uncertainties are ignored. The difference with the charmonium reference amounts to 2.7 standard deviations (σ). Adding the aforementioned individual theoretical uncertainties, and treating them as allowed ranges,¹⁴ the significance of the discrepancy drops to 2.0σ .

None of the modes studied exhibits non-zero direct CP violation. The s -penguin average is $C = -0.081 \pm 0.073$ (C.L. = 0.43).

4 Summary

We have presented preliminary results on mixing-induced and direct CP violation for penguin-loop-dominated B decays, using the full Summer 2004 data sample. We have observed¹⁶ and updated the new silver-plated mode $B^0 \rightarrow f_0(980)K_S^0$. Sophisticated vertexing¹⁷ allows us to measure the mixing-induced CP asymmetry in $B^0 \rightarrow \pi^0 K_S^0$, using the K_S^0 decay into $\pi^+\pi^-$. With the exception of $B^0 \rightarrow \eta' K_S^0$, all individual s -penguin modes are in agreement with the charmium result, but most of them tend to lower $\sin 2\beta_{\text{eff}}$ values so that their average appears to be somewhat low.

With the significant decrease in the statistical errors, the B -meson Factories enter the era of precision CP -violation measurements in loop processes.

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