

Measurements of CP -Violating Asymmetries in the Decay $B^0 \rightarrow K^+ K^- K^0$

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We analyze the decay $B^0 \rightarrow K^+ K^- K^0$ using $383 \times 10^6 B\bar{B}$ events collected by the BABAR detector at SLAC to extract CP violation parameter values over the Dalitz plot. Combining all $K^+ K^- K^0$ events, we find $A_{CP} = -0.015 \pm 0.077 \pm 0.053$ and $\beta_{\text{eff}} = 0.352 \pm 0.076 \pm 0.026$ rad, corresponding to a CP violation significance of 4.8σ . A second solution near $\pi/2 - \beta_{\text{eff}}$ is disfavored with a significance of 4.5σ . We also report A_{CP} and β_{eff} separately for decays to $\phi(1020)K^0$, $f_0(980)K^0$, and $K^+ K^- K^0$ with $m_{K^+ K^-} > 1.1 \text{ GeV}/c^2$.

In the standard model (SM), the phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] is the sole source of CP violation in the quark sector. Because of interference between decays with and without mixing, this phase yields observable time-dependent CP asymmetries in B^0 meson decays. In particular, significant CP asymmetries in $b \rightarrow s\bar{s}s$ decays, such as $B^0 \rightarrow K^+ K^- K^0$ [2], are expected [3,4]. Deviations from the predicted CP asymmetry behavior for $B^0 \rightarrow K^+ K^- K^0$ are expected to depend weakly on Dalitz plot (DP) position [5,6]. Since the $b \rightarrow s\bar{s}s$ amplitude is dominated by loop contributions, heavy virtual particles beyond the SM might contribute significantly [6,7]. This sensitivity motivates measurements of CP asymmetries in multiple $b \rightarrow s\bar{s}s$ decays [3,8–10].

Previous measurements of CP asymmetries in $B^0 \rightarrow K^+ K^- K^0$ have been performed separately for events with $K^+ K^-$ invariant mass ($m_{K^+ K^-}$) in the ϕ mass [11] region, and for events excluding the ϕ region, neglecting interference effects among intermediate states [3,8,10]. In this Letter we describe a time-dependent DP analysis of $B^0 \rightarrow K^+ K^- K^0$ decay from which we extract the values of the CP violation parameters A_{CP} and β_{eff} by taking into account the complex amplitudes describing the entire B^0 and \bar{B}^0 Dalitz plots. We first extract the values of the parameters of the amplitude model and measure the average CP asymmetry in $B^0 \rightarrow K^+ K^- K^0$ decay over the entire DP. Using this model, we then measure the CP asymmetries for the ϕK^0 and $f_0 K^0$ decay channels, from a “low-mass” analysis of events with $m_{K^+ K^-} < 1.1 \text{ GeV}/c^2$. Finally, we perform a “high-mass” analysis to determine the average CP asymmetry for events with $m_{K^+ K^-} > 1.1 \text{ GeV}/c^2$.

The data sample for this analysis was collected with the BABAR detector [12] at the PEP-II asymmetric-energy $e^+ e^-$ collider at SLAC. Approximately 383×10^6 $B\bar{B}$ pairs recorded at the $\Upsilon(4S)$ resonance were used.

We reconstruct $B^0 \rightarrow K^+ K^- K^0$ decays by combining two oppositely charged kaon candidates with a K^0 reconstructed as $K_S^0 \rightarrow \pi^+ \pi^-$ ($B_{(+ -)}^0$) [13], $K_S^0 \rightarrow \pi^0 \pi^0$ ($B_{(00)}^0$), or K_L^0 ($B_{(L)}^0$). Each $K_S^0 \rightarrow \pi^0 \pi^0$ candidate is formed from two $\pi^0 \rightarrow \gamma\gamma$ candidates. Each photon has $E_\gamma > 50 \text{ MeV}$ and transverse shower shape consistent with an electromagnetic shower. Both π^0 candidates satisfy $100 < m_{\gamma\gamma} < 155 \text{ MeV}/c^2$ and yield an invariant mass $m_{\pi^0 \pi^0}$ in the range $-20 < m_{\pi^0 \pi^0} - m_{K_S^0} < 30 \text{ MeV}/c^2$. A K_L^0 candidate is defined by an unassociated energy deposit in the electromagnetic calorimeter or an isolated signal in the instrumented flux return [8].

For each fully reconstructed B^0 meson (B_{CP}), we use the remaining tracks in the event to reconstruct the decay vertex of the other B meson (B_{tag}) and to identify its flavor

q_{tag} [4]. For each event we calculate the difference $\Delta t \equiv t_{CP} - t_{\text{tag}}$ between the proper decay times of the B_{CP} and B_{tag} mesons and its uncertainty $\sigma_{\Delta t}$.

We characterize $B_{(+ -)}^0$ and $B_{(00)}^0$ candidates using two kinematic variables: the beam-energy-substituted mass m_{ES} and the energy difference ΔE [8]. The signal region (SR) is defined as $m_{\text{ES}} > 5.26 \text{ GeV}/c^2$, and $|\Delta E| < 0.06 \text{ GeV}$ for $B_{(+ -)}^0$, or $-0.120 < \Delta E < 0.06 \text{ GeV}$ for $B_{(00)}^0$. For $B_{(L)}^0$ the SR is defined by $-0.01 < \Delta E < 0.03 \text{ GeV}$ [8], and the missing momentum for the entire event is required to be consistent with the calculated K_L^0 laboratory momentum.

The main source of background is continuum $e^+ e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events. We use event-shape variables to exploit the jetlike structure of these events in order to remove much of this background [8].

We perform an unbinned maximum likelihood fit to the selected $K^+ K^- K^0$ events using the likelihood function defined in Ref. [8]. The probability density function (PDF), \mathcal{P}_i , is given by

$$\mathcal{P}_i = \mathcal{P}(m_{\text{ES}}) \mathcal{P}(\Delta E) \mathcal{P}_{\text{Low}} \mathcal{P}_{\text{DP}}(m_{K^+ K^-}, \cos\theta_H, \Delta t, q_{\text{tag}}) \otimes \mathcal{R}(\Delta t, \sigma_{\Delta t}), \quad (1)$$

where $i = (\text{signal, continuum, } B\bar{B} \text{ background})$, and \mathcal{R} is the Δt resolution function [4]. For $B_{(L)}^0$, $\mathcal{P}(m_{\text{ES}})$ is not used. \mathcal{P}_{Low} is a PDF used only in the low-mass fit, which depends on the event-shape variables and, for $B_{(L)}^0$ only, the missing momentum in the event [8]. We characterize B^0 (\bar{B}^0) events on the DP in terms of $m_{K^+ K^-}$ and $\cos\theta_H$, the cosine of the helicity angle between the K^+ (K^-) and the K^0 (\bar{K}^0) in the rest frame of the $K^+ K^-$ system. The DP PDF for signal events is

$$\mathcal{P}_{\text{DP}} = d\Gamma \times \varepsilon(m_{K^+ K^-}, \cos\theta_H) \times |J|, \quad (2)$$

where $d\Gamma$ is the time- and flavor-dependent decay rate over the DP, ε is the efficiency, and J is the Jacobian of the transformation to our choice of DP coordinates.

The time- and flavor-dependent decay rate is

$$\begin{aligned} \frac{d\Gamma}{d\Delta t} &\propto \frac{e^{-|\Delta t|/\tau}}{2\tau} [|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2 + q_{\text{tag}} 2\text{Im}(\xi \bar{\mathcal{A}} \mathcal{A}^*) \\ &\quad \times \sin\Delta m_d \Delta t - q_{\text{tag}} (|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2) \cos\Delta m_d \Delta t], \end{aligned} \quad (3)$$

where τ and Δm_d are the lifetime and mixing frequency of the B^0 meson, respectively [14]. The parameter $\xi = \eta_{CP} e^{-2i\beta}$, where $\beta = \arg(-V_{cd} V_{cb}^*/V_{td} V_{tb}^*)$ and $V_{qq'}$ are CKM matrix elements [1]. The CP eigenvalue $\eta_{CP} = 1(-1)$ for the K_S^0 (K_L^0) mode. We define the amplitude \mathcal{A} for B^0 decay as a sum of isobar amplitudes [14],

$$\begin{aligned}\bar{\mathcal{A}}(m_{K^+K^-}, \cos\theta_H) &= \sum_r^{(-)} \bar{\mathcal{A}}_r \\ &= \sum_r c_r (1 \mp b_r) e^{i(\varphi_r \mp \delta_r)} \\ &\quad \times f_r(m_{K^+K^-}, \cos\theta_H),\end{aligned}\quad (4)$$

where the minus signs are associated with the $\bar{\mathcal{A}}$, the parameters c_r and φ_r are the magnitude and phase of the amplitude of component r , and we allow for different isobar coefficients for B^0 and \bar{B}^0 decays through the asymmetry parameters b_r and δ_r .

Our isobar model includes resonant amplitudes ϕ , f_0 , $\chi_{c0}(1P)$, and $X_0(1550)$ [15,16], nonresonant terms, and incoherent terms for B^0 decay to D^-K^+ and $D_s^-K^+$. For each resonant term, the function $f_r = F_r T_r Z_r$ describes the dynamical properties, where F_r is the Blatt-Weisskopf centrifugal barrier factor for the resonance decay vertex [17], T_r is the resonant mass line shape, and Z_r describes the angular distribution in the decay [18]. The barrier factor $F_r = 1/\sqrt{1 + (Rq)^2}$ [17] for the ϕ , where \vec{q} is the K^+ momentum in the ϕ rest frame and $R = 1.5 \text{ GeV}^{-1}$; $F_r = 1$ for the scalar resonances. For ϕ decay $Z_r \sim \vec{q} \cdot \vec{p}$, where \vec{p} is the momentum of the K^0 in the ϕ rest frame, while $Z_r = 1$ for the scalar decays. We describe the ϕ , $X_0(1550)$, and $\chi_{c0}(1P)$ with relativistic Breit-Wigner line shapes [14]. For the ϕ and $\chi_{c0}(1P)$ parameters we use average measurements [14]. For the $X_0(1550)$ resonance, we use parameters from our analysis of the $B^+ \rightarrow K^+K^-K^+$ decay [15]. The f_0 resonance is described by a coupled-channel amplitude [19], with the parameter values of Ref. [20].

We include three nonresonant (NR) amplitudes parameterized as $f_{\text{NR},k} = \exp(-\alpha m_k^2)$, where the parameter $\alpha = 0.14 \pm 0.01 \text{ c}^4/\text{GeV}^2$ is taken from measurements of $B^+ \rightarrow K^+K^-K^+$ decays with larger signal samples [15,16]. We include a complex isobar coefficient for each component $k = (K^+K^-, K^+K^0, K^-K^0)$.

PDFs for $q\bar{q}$ background in $B^0 \rightarrow K^+K^-K_S^0$ are modeled using events in the region $5.2 < m_{\text{ES}} < 5.26 \text{ GeV}/c^2$. The region $0.02 < \Delta E < 0.04 \text{ GeV}$ is used for $B_{(L)}^0$. Simulated $B\bar{B}$ events are used to define $B\bar{B}$ background PDFs. We use two-dimensional histogram PDFs to model the DP distributions for $q\bar{q}$ and $B\bar{B}$ backgrounds.

We compute the CP asymmetry parameters for component r from the asymmetries in amplitude (b_r) and phase (δ_r) given in Eq. (4). The rate asymmetry is

$$A_{CP,r} = \frac{|\bar{\mathcal{A}}_r|^2 - |\mathcal{A}_r|^2}{|\bar{\mathcal{A}}_r|^2 + |\mathcal{A}_r|^2} = \frac{-2b_r}{1 + b_r^2}, \quad (5)$$

and $\beta_{\text{eff},r} = \beta + \delta_r$ is the phase asymmetry.

The selection criteria yield 3266 $B_{(+,-)}^0$, 1611 $B_{(00)}^0$, and 27513 $B_{(L)}^0$ candidates which we fit to obtain the event yields, the isobar coefficients of the DP model, and the CP

TABLE I. The isobar amplitudes c_r , phases φ_r , and fractions \mathcal{F}_r from the fit to the full $K^+K^-K^0$ DP. The three NR components are combined for the fraction calculation. Errors are statistical only. Because of interference, $\sum \mathcal{F}_r \neq 100\%$.

Isobar mode	Amplitude c_r	Phase φ_r (rad)	\mathcal{F}_r (%)
ϕK^0	0.0085 ± 0.0010	-0.016 ± 0.234	12.5 ± 1.3
$f_0 K^0$	0.622 ± 0.046	-0.14 ± 0.14	40.2 ± 9.6
$X_0(1550)K^0$	0.114 ± 0.018	-0.47 ± 0.20	4.1 ± 1.3
$(K^+K^-)_{\text{NR}}K^0$	1 (fixed)	0 (fixed)	
$(K^+K^0)_{\text{NR}}K^-$	0.33 ± 0.07	1.95 ± 0.27	112.0 ± 14.9
$(K^-K^0)_{\text{NR}}K^+$	0.31 ± 0.08	-1.34 ± 0.37	
$\chi_{c0}(1P)K^0$	0.0306 ± 0.0049	$^{0.81}_{-2.33} \pm 0.54$	3.0 ± 1.2
D^-K^+	1.11 ± 0.17		3.6 ± 1.5
$D_s^-K^+$	0.76 ± 0.14		1.8 ± 0.6

asymmetry parameters averaged over the DP. The parameters b_r and δ_r are constrained to be the same for all model components, so in this case $A_{CP,r} = A_{CP}$ and $\beta_{\text{eff},r} = \beta_{\text{eff}}$. We find $947 \pm 37 B_{(+,-)}^0$, $144 \pm 17 B_{(00)}^0$, and $770 \pm 71 B_{(L)}^0$ signal events. Isobar coefficients and fractions are reported in Table I, and CP asymmetry results are summarized in Table II. The fraction \mathcal{F}_r for resonance r is computed as in Ref. [15]. Note that there is a $\pm\pi$ rad ambiguity in the $\chi_{c0}(1P)K^0$ phase.

In Fig. 1, we plot twice the change in the negative logarithm of the likelihood as a function of β_{eff} . We find that the CP -conserving case of $\beta_{\text{eff}} = 0$ is excluded at 4.8σ (5.1σ), including statistical and systematic errors (statistical errors only). Also, the interference between CP -even and CP -odd amplitudes leads to the exclusion of the β_{eff} solution near $\pi/2 - \beta$ at 4.5σ (4.6σ).

We also measure CP asymmetry parameters for events with $m_{K^+K^-} < 1.1 \text{ GeV}/c^2$. In this region, we find 1359 $B_{(+,-)}^0$, 348 $B_{(00)}^0$, and 7481 $B_{(L)}^0$ candidates. The fit yields 282 ± 20 , 37 ± 9 , and 266 ± 36 signal events, respectively. The most significant contributions in this region are from ϕK^0 and $f_0 K^0$ decays, with a smaller contribution from the low-mass tail from nonresonant decays. In this fit we vary the amplitude asymmetries b_r and δ_r for the ϕ and

TABLE II. The CP asymmetries for $B^0 \rightarrow K^+K^-K^0$ for the entire DP, in the high-mass region, and for ϕK^0 and $f_0 K^0$ in the low-mass region. The first errors are statistical and the second are systematic. The solutions (1) and (2) from the low-mass fit are discussed in the text.

	A_{CP}	β_{eff} (rad)
Whole DP	$-0.015 \pm 0.077 \pm 0.053$	$0.352 \pm 0.076 \pm 0.026$
High-mass	$-0.054 \pm 0.102 \pm 0.060$	$0.436 \pm 0.087^{+0.055}_{-0.031}$
(1) ϕK^0	$-0.08 \pm 0.18 \pm 0.04$	$0.11 \pm 0.14 \pm 0.06$
(1) $f_0 K^0$	$0.41 \pm 0.23 \pm 0.07$	$0.14 \pm 0.15 \pm 0.05$
(2) ϕK^0	-0.11 ± 0.18	0.10 ± 0.13
(2) $f_0 K^0$	-0.20 ± 0.31	3.09 ± 0.19

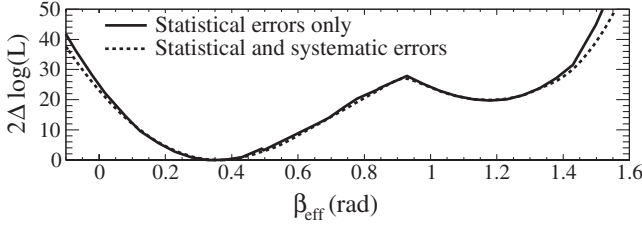


FIG. 1. The change in twice the negative log likelihood as a function of β_{eff} for the fit to the whole DP.

f_0 , while the other components are fixed to the SM expectations of $\beta_{\text{eff}} = 0.370$ rad and $A_{CP} = 0$ [21]. We also vary the isobar coefficient for the ϕ , while fixing the others to the results from the whole DP fit. There are two solutions with likelihood difference of only $\Delta \log L = 0.1$. Solution (1) is consistent with the SM, while in Solution (2) β_{eff} for the f_0 differs significantly from the SM value (Table II). The solutions also differ significantly in the values of the ϕ isobar coefficient. There is also a mathematical ambiguity of $\pm \pi$ rad on β_{eff} for the ϕ , with a corresponding change of $\pm \pi$ rad in the solution for φ_ϕ . This ambiguity is present for both solutions. The fit correlation between the ϕ and f_0 in δ_r is 0.71 [22].

Finally, we perform a fit to extract the average CP asymmetry parameters in the high-mass region. In the 2384 $B^0_{(+-)}$, 1406 $B^0_{(00)}$, and 20032 $B^0_{(L)}$ selected events with $m_{K^+K^-} > 1.1$ GeV/ c^2 , we find signal yields of 673 ± 31 , 87 ± 14 , and 462 ± 56 events, respectively; the CP asymmetry results are shown in Table II. We find that for this fit the CP -conserving case of $\beta_{\text{eff}} = 0$ is excluded at 5.1σ , including statistical and systematic errors.

Figure 2 shows distributions of the DP variables $m_{K^+K^-}$ and $\cos\theta_H$ obtained using the method described in [23]. Figure 3 shows the Δt -dependent asymmetry between B^0 - and \bar{B}^0 -tagged events.

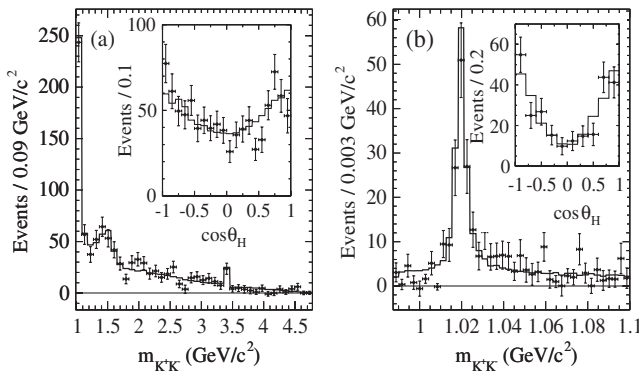


FIG. 2. The distributions of $m_{K^+K^-}$ for signal-weighted [23] $B^0_{(+-)}$ data in (a) the entire DP and (b) the low-mass region. Insets show distributions of $\cos\theta_H$. The histograms are projections of the fit function for the corresponding result.

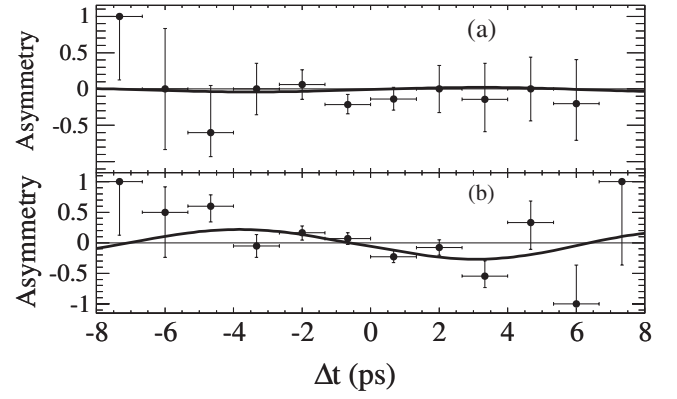


FIG. 3. The raw asymmetry between B^0 - and \bar{B}^0 -tagged signal-weighted [23] events for $B^0_{(+-)}$, in (a) the low-mass region and (b) the high-mass region. The curves are projections of the corresponding fit results.

Systematic errors on the CP -asymmetry parameters are listed in Table III. The fit bias uncertainty includes effects of detector resolution and possible correlations among the fit variables determined from full-detector simulations. We also account for uncertainties due to the isobar model: experimental precision of resonance parameter values, alternate $X_0(1550)$ parameter values [16], and, in the low- and high-mass fits, the statistical uncertainties on the isobar coefficients determined in the fit to the whole DP. Other uncertainties common to many $BABAR$ time-dependent analyses, including those due to fixed PDF parameters, and possible CP asymmetries in the $B\bar{B}$ background, are also taken into account [8,24]. Uncertainties due to fixed PDF parameters are evaluated by shifting the fixed parameters and refitting the data. As a cross-check, we perform the analysis using $B^0_{(+-)}$ alone and find results consistent with those in Table II.

In summary, in a sample of 383×10^6 $B\bar{B}$ meson pairs we simultaneously analyze the DP distribution and measure the time-dependent CP asymmetries for $B^0 \rightarrow K^+K^-K^0$ decays. The values of β_{eff} and A_{CP} are consistent with the SM expectations of $\beta \simeq 0.370$ rad, $A_{CP} \simeq 0$ [21]. The significance of CP violation is 4.8σ , and we reject the solution near $\pi/2 - \beta$ at 4.5σ . We also measure CP asymmetries for the decays $B^0 \rightarrow \phi K^0$ and $B^0 \rightarrow f_0 K^0$, where we find β_{eff} lower than the SM expectation by about

TABLE III. A summary of the systematic errors on the CP asymmetry parameter values.

Source	Whole DP		High-mass		ϕK^0		$f_0 K^0$	
	A_{CP}	β_{eff}	A_{CP}	β_{eff}	A_{CP}	β_{eff}	A_{CP}	β_{eff}
Fit Bias	0.003	0.001	0.014	0.008	0.03	0.06	0.06	0.03
Isobar model	0.004	0.009	0.025	$^{+0.051}_{-0.024}$	0.00	0.01	0.01	0.03
Other	0.052	0.024	0.053	0.018	0.02	0.01	0.03	0.02
Total	0.053	0.026	0.060	$^{+0.055}_{-0.031}$	0.04	0.06	0.07	0.05

2σ . The CP parameters in the high-mass region are compatible with SM expectations, and we observe CP violation at the level of 5.1σ .

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