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

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We analyze the decay $B^0 \to K^+K^-K^0$ using 383×10^6 $B\bar{B}$ 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 $\beta_{\rm eff} = 0.352 \pm 0.076 \pm 0.026$ rad, corresponding to a *CP* violation significance of 4.8σ. A second solution near $\pi/2 - \beta_{\rm eff}$ is disfavored with a significance of 4.5σ. We also report A_{CP} and $\beta_{\rm eff}$ separately for decays to $\phi(1020)K^0$, $f_0(980)K^0$, and $K^+K^-K^0$ with $m_{K^+K^-} > 1.1$ GeV$/c^2$.

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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 $b \to s\bar{s}s$ decays, such as $B^0 \to K^+K^-K^0$ [2], are expected [3,4]. Deviations from the predicted CP asymmetry behavior for $B^0 \to K^+K^-K^0$ are expected to depend weakly on Dalitz plot (DP) position [5,6]. Since the $b \to s\bar{s}s$ 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 $b \to s\bar{s}s$ decays [3,8–10].

Previous measurements of CP asymmetries in $B^0 \to K^+K^-K^0$ 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 $B^0 \to K^+K^-K^0$ 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 $B^0 \to K^+K^-K^0$ decay over the entire DP. Using this model, we then measure the CP asymmetries for the ϕK^0 and f_0K^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 $B^0 \to K^+K^-K^0$ decays by combining two oppositely charged kaon candidates with a K^0 reconstructed as $K^0_S \to \pi^+\pi^-$ ($B^0_{(+-)}$) [13], $K^0_S \to \pi^0\pi^0$ ($B^0_{(00)}$), or K^0_L ($B^0_{(L)}$). Each $K^0_S \to \pi^0\pi^0$ candidate is formed from two $\pi^0 \to \gamma\gamma$ candidates. Each photon has $E_\gamma > 50$ 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 $-20 < m_{\pi^0\pi^0} - m_{K^0_S} < 30\ \text{MeV}/c^2$. A K^0_L 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 $B^0_{(00)}$ 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 $|\Delta E| < 0.06$ GeV for $B^0_{(+-)}$, or $-0.120 < \Delta E < 0.06$ GeV for $B^0_{(00)}$. For $B^0_{(L)}$ the SR is defined by $-0.01 < \Delta E < 0.03$ GeV [8], and the missing momentum for the entire event is required to be consistent with the calculated K^0_L laboratory momentum.

The main source of background is continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) 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

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

where i = (signal, continuum, $B\bar{B}$ background), and $\mathcal{R}$ is the Δt resolution function [4]. For $B^0_{(L)}$, $\mathcal{P}(m_{\text{ES}})$ is not used. $\mathcal{P}_{\text{Low}}$ is a PDF used only in the low-mass fit, which depends on the event-shape variables and, for $B^0_{(L)}$ 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

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

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

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

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^0_S (K^0_L) mode. We define the amplitude $\overset{(-)}{\mathcal{A}}$ for $\overset{(-)}{B^0}$ decay as a sum of isobar amplitudes [14],

$$\overset{(-)}{\mathcal{A}}(m_{K^+K^-}, \cos\theta_H) = \sum_r \overset{(-)}{\mathcal{A}}_r = \sum_r c_r(1 \mp b_r)e^{i(\varphi_r \mp \delta_r)} \times f_r(m_{K^+K^-}, \cos\theta_H), \qquad (4)$$

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 $R = 1.5\ \mathrm{GeV}^{-1}$; $F_r = 1$ 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 $B^+ \to K^+K^-K^+$ 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 parametrized as $f_{\mathrm{NR},k} = \exp(-\alpha m_k^2)$, where the parameter $\alpha = 0.14 \pm 0.01\ c^4/\mathrm{GeV}^2$ is taken from measurements of $B^+ \to K^+K^-K^+$ 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 $B^0 \to K^+K^-K_S^0$ are modeled using events in the region $5.2 < m_{\mathrm{ES}} < 5.26\ \mathrm{GeV}/c^2$. The region $0.02 < \Delta E < 0.04$ GeV is used for $B^0_{(L)}$. 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

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

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

The selection criteria yield 3266 $B^0_{(+-)}$, 1611 $B^0_{(00)}$, and 27 513 $B^0_{(L)}$ candidates which we fit to obtain the event yields, the isobar coefficients of the DP model, and the CP 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 $\beta_{\mathrm{eff},r} = \beta_{\mathrm{eff}}$. We find 947 ± 37 $B^0_{(+-)}$, 144 ± 17 $B^0_{(00)}$, and 770 ± 71 $B^0_{(L)}$ 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.

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_0K^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
$(K^+K^-)_{\mathrm{NR}}K^0$	1 (fixed)	0 (fixed)	
$(K^+K^0)_{\mathrm{NR}}K^-$	0.33 ± 0.07	1.95 ± 0.27	112.0 ± 14.9
$(K^-K^0)_{\mathrm{NR}}K^+$	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

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 $\beta_{\mathrm{eff}} = 0$ 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 $m_{K^+K^-} < 1.1\ \mathrm{GeV}/c^2$. In this region, we find 1359 $B^0_{(+-)}$, 348 $B^0_{(00)}$, and 7481 $B^0_{(L)}$ 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_0K^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 $B^0 \to K^+K^-K^0$ for the entire DP, in the high-mass region, and for ϕK^0 and f_0K^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_0K^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_0K^0	-0.20 ± 0.31	3.09 ± 0.19

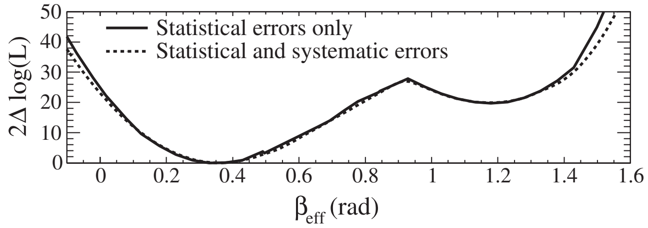

FIG. 1. The change in twice the negative log likelihood as a function of $\beta_{\rm eff}$ for the fit to the whole DP.

f_0, while the other components are fixed to the SM expectations of $\beta_{\rm eff} = 0.370$ 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) $\beta_{\rm eff}$ 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 $\beta_{\rm eff}$ 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 20 032 $B^0_{(L)}$ 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 $\beta_{\rm eff} = 0$ 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.

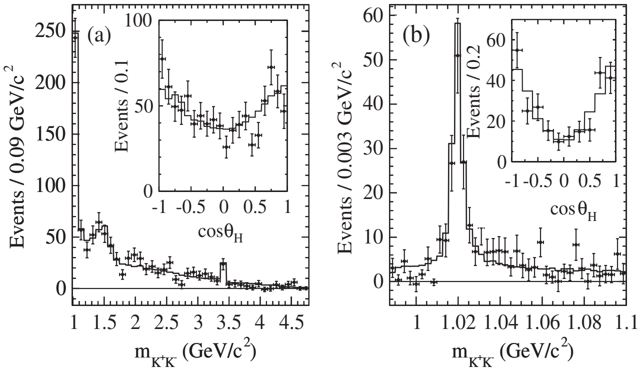

FIG. 2. The distributions of $m_{K^+K^-}$ for signal-weighted [23] $B^0_{(+-)}$ data in (a) the entire DP and (b) the low-mass region. Insets show distributions of $\cos\theta_H$. The histograms are projections of the fit function for the corresponding result.

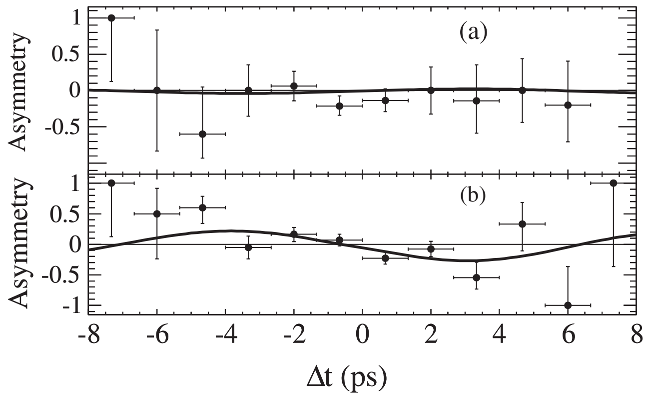

FIG. 3. The raw asymmetry between B^0- and $\bar{B}^0$-tagged signal-weighted [23] events for $B^0_{(+-)}$, in (a) the low-mass region and (b) the high-mass region. The curves are projections of the corresponding fit results.

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 $B^0 \to K^+K^-K^0$ decays. The values of $\beta_{\rm eff}$ 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 $B^0 \to \phi K^0$ and $B^0 \to f_0 K^0$, where we find $\beta_{\rm eff}$ 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}	$\beta_{\rm eff}$	A_{CP}	$\beta_{\rm eff}$	A_{CP}	$\beta_{\rm eff}$	A_{CP}	$\beta_{\rm eff}$
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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