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


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We analyze the decay $B^0 \rightarrow K^+K^0$ using 383 million $B\bar{B}$ 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 $\beta_{eff} = 0.352 \pm 0.076 \pm 0.026$ rad, corresponding to a CP violation significance of 4.9$\sigma$. A second solution near $\pi/2 - \beta_{eff}$ is disfavored with a significance of 4.5$\sigma$. We also report $A_{CP}$ and $\beta_{eff}$ 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. Due to 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 $\phi$ mass [11] region, and for events excluding the $\phi$ mass region, neglecting interference effects among intermediate states [3, 8, 10]. In this Letter we describe a time-dependent Dalitz plot analysis of $B^0 \rightarrow K^+K^-K^0$ decay from which we extract the values of the CP violation parameters $A_{CP}$ and $\beta_{eff}$ 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 Dalitz plot. Using this model, we then measure the CP asymmetries for the $\phi K^0$ and $f_0 K^0$ decay channels, from a “low-mass” analysis of events with $m_{K^+K^-} < 1.1$ GeV/c$^2$. Finally, we perform a “high-mass” analysis to determine the average CP asymmetry for events with $m_{K^+K^-} > 1.1$ 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 million $B\bar{B}$ 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 $K^0_S \rightarrow \pi^+\pi^-$ ($B^-\pi^+$) [13], $K^0_L \rightarrow \pi^0\pi^0$ ($B^0_{(0)}$), or $K^0_S \rightarrow \pi^0\pi^0$ ($B^0_{(0)}$). Each $K^0_S \rightarrow \pi^0\pi^0$ candidate is formed from two $\pi^0$ candidates. Each photon has $E_\gamma > 50$ MeV and transverse shower shape consistent with an electromagnetic shower. Both $\pi^0$ candidates satisfy $100 < m_{\gamma\gamma} < 155$ MeV/c$^2$ and yield an invariant mass $m_{e^+e^-}$ in the range $-20 < m_{e^+e^-} - m_{K^0_S} < 30$ MeV/c$^2$. A $K^0_S$ 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 $\Delta t \equiv t_{CP} - t_{tag}$ between the proper decay times of the $B_{CP}$ and $B_{tag}$ mesons, and its uncertainty $\sigma_{\Delta t}$.

We characterize $B^0_{(\pm)}$ and $B^0_{(0)}$ candidates using two kinematic variables: the beam-energy-substituted mass $m_{ES}$ and the energy difference $\Delta E$ [8]. The signal region (SR) is defined as $m_{ES} > 0.26$ GeV/c$^2$, and $|\Delta E| < 0.06$ GeV for $B^0_{(\pm)}$, or $-0.120 < \Delta E < 0.06$ GeV for $B^0_{(0)}$. For $B^0_{(\pm)}$ 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 $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events. We use event-shape variables to exploit the jet-like 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), $P_i$, is given by

$$P_i = P(m_{ES}) \cdot P(\Delta E) \cdot P_{low} \cdot P_{CP}(m_{K^+K^-}, \cos \theta_H, \Delta t, q_{tag}) \otimes R(\Delta t, \sigma_{\Delta t}),$$

where $i = \text{signal, continuum, } B\bar{B} \text{ background}$, and $R$ is the $\Delta t$ resolution function [4]. For $B^0_{(\pm)}$, $P(m_{ES})$ is not used. $P_{low}$ is a supplementary PDF used only in the low-mass fit, which depends on the event-shape variables and, for $B^0_{(\pm)}$, the missing momentum in the event [8]. We characterize $B^0$ ($\bar{B}^0$) events on the Dalitz plot 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 Dalitz plot PDF for signal events is

$$P_{CP} = d\Gamma \cdot \varepsilon(m_{K^+K^-}, \cos \theta_H) \cdot |J|,$$

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

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

where $\tau$ and $\Delta m_d$ are the lifetime and mixing frequency of the $B^0$ meson, respectively [14]. The parameter $\xi = \eta_{\text{CP}} e^{-2i\beta}$, where $\beta = \arg(-V_{ud} V_{ub}^* / V_{ud} V_{ub}^*)$ and $V_{qq'}$ are CKM matrix elements [1]. The CP eigenvalue $\eta_{\text{CP}}$ is 1 (−1) for the $K^0_s ((K^0)^0)$ mode. We define the amplitude $\tilde{A}$ for $B^0$ decay as a sum of isobar amplitudes [14],

$$\tilde{A}(m_{K^+K^-}, \cos \theta_H) = \sum_r \bar{A}_r,$$

where the minus signs are associated with the $\bar{A}$, the parameters $c_r$ and $\varphi_r$ 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 $\delta_r$.

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

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

Continuum background PDFs for $B^0 \to K^+K^-\bar{K}^0$ are modeled using events in the region $5.2 < m_{ES} < 5.26 \text{ GeV}/c^2$. The region $0.02 < \Delta E < 0.04 \text{ GeV}$ is used for $B^0_{(L)}$. Samples of simulated $B\bar{B}$ events are used to define $B\bar{B}$ background PDFs. We use two-dimensional histogram PDFs to model the Dalitz plot distributions for continuum and $B\bar{B}$ backgrounds.

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

$$A_{CP,r} = \frac{|\bar{A}_r|^2 - |A_r|^2}{|\bar{A}_r|^2 + |A_r|^2} = -2b_r \frac{1 + b_r^r}{1 + b_r^r},$$

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

The selection criteria yield 3266 $B^0(\rightarrow \phi K \bar{K})$, 1611 $B^0(00)$, and 27513 $B^0_{(L)}$ candidates which we fit to obtain the event yields, the isobar coefficients of the Dalitz plot model, and the CP asymmetry parameters averaged over the Dalitz plot. The parameters $b_r$ and $\delta_r$ 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 $947 \pm 37 B^0(\rightarrow \phi K \bar{K})$, $144 \pm 17 B^0(00)$, and $770 \pm 71 B^0_{(L)}$ signal events. Isobar coefficients and fractions are reported in Table I, and CP asymmetry results are summarized in Table II. The fraction $F_r$ for resonance $r$ is computed as in Ref. [15]. The sum of the fractions is greater than one due to interference. Note that there is a $\pm \pi$ rad ambiguity in the $\chi_{c0}(1P)K^0$ phase.

Our $B^0 \to K^+K^-\bar{K}^0$ analysis is also used to study the CP asymmetry of hadronic decays which may be related to vacuum polarization effects in flavor mixing. In Fig. 1, we plot twice the change in the negative logarithm of the likelihood as a function of $\beta_{\text{eff}}$. We find that the CP-conserving case of $\beta_{\text{eff}} = 0$ is excluded at 4.8$\sigma$ (5.1$\sigma$), including statistical and systematic errors (statistical errors only). Also, the interference between CP-even and CP-odd amplitudes leads to the exclusion of the $\beta_{\text{eff}}$ solution near $\pi/2 - \beta$ at 4.5$\sigma$ (4.6$\sigma$).

We also measure CP asymmetry parameters for events with $m_{K^+K^-} < 1.1 \text{ GeV}/c^2$. In this region, we find 1359 $B^0_{(L)}$, 348 $B^0(00)$, and 7481 $B^0_{(L)}$ candidates. The fit yields $282 \pm 20, 37 \pm 9$ and $266 \pm 36$ signal events, respectively. The most significant contributions in this region are from $\phi K^0$ and $f_0K^0$ decays, with a smaller contribution from the low-mass tail from non-resonant decays. In this fit we vary the amplitude asymmetries $b_r$ and $\delta_r$ for the $\phi$ and $f_0$, while the other components are fixed to the SM

<table>
<thead>
<tr>
<th>Isobar Mode</th>
<th>Amplitude $c_r$</th>
<th>Phase $\varphi_r$ (rad)</th>
<th>$F_r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K^0$</td>
<td>0.0085 ± 0.0010</td>
<td>$-0.016 \pm 0.234$</td>
<td>12.5 ± 1.3</td>
</tr>
<tr>
<td>$f_0 K^0$</td>
<td>0.622 ± 0.046</td>
<td>$-0.14 \pm 0.14$</td>
<td>40.2 ± 9.6</td>
</tr>
<tr>
<td>$X_0(1550)K^0$</td>
<td>0.114 ± 0.018</td>
<td>$-0.47 \pm 0.20$</td>
<td>4.1 ± 1.3</td>
</tr>
<tr>
<td>$(K^+K^-)_{NR}K^0$</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
<td></td>
</tr>
<tr>
<td>$(K^+K^-)_{NR}K^-$</td>
<td>0.33 ± 0.07</td>
<td>1.95 ± 0.27</td>
<td>112.0 ± 14.9</td>
</tr>
<tr>
<td>$(K^-K^-)_{NR}K^+$</td>
<td>0.31 ± 0.08</td>
<td>$-1.34 \pm 0.37$</td>
<td></td>
</tr>
<tr>
<td>$X_0(1P)K^0$</td>
<td>0.0306 ± 0.0049</td>
<td>$-0.23 \pm 0.54$</td>
<td>3.0 ± 1.2</td>
</tr>
<tr>
<td>$D^+K^-$</td>
<td>1.11 ± 0.17</td>
<td>3.6 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>$D^-K^+$</td>
<td>0.76 ± 0.14</td>
<td>1.8 ± 0.6</td>
<td></td>
</tr>
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</table>
FIG. 1: The change in twice the negative log likelihood as a function of \( \beta_{\text{eff}} \) for the fit to the whole Dalitz plot.

FIG. 2: The distributions of mass for signal-weighted [23] \( B_{sL}^{0}\) 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.

expectations of \( \beta_{\text{eff}} = 0.370 \) rad and \( A_{\text{CP}} = 0 \) [21]. We also vary the isobar coefficient for the \( \phi \), 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) \( \beta_{\text{eff}} \) for the \( f_0 \) differs significantly from the SM value (Table II). The solutions also differ significantly in the values of the \( \phi \) isobar coefficient. There is also a mathematical ambiguity of \( \pm \pi \) rad on \( \beta_{\text{eff}} \) for the \( \phi \), with a corresponding change of \( \pm \pi \) rad in the solution for \( \varphi_\phi \). This unresolvable ambiguity is present for both solutions. The fit correlation between \( \delta_r \) for the \( \phi \) and that for the \( f_0 \) is 0.71 [22].

Finally, we perform a fit to extract the average \( CP \) asymmetry parameters in the high-mass region. In the 2384 \( B_{sL}^0(\pm) \), 1406 \( B_{sL}^0(\mp) \), and 20032 \( B_{sL}^0(\pm) \) 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. Based on the change in the likelihood, 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 Dalitz plot variables \( m_{K^+K^-} \) and \( \cos \theta_H \) obtained using the background-subtraction method described in [23]. Figure 3 shows the \( \Delta t \)-dependent asymmetry between \( B^0 \)- and \( \bar{B}^0 \)-tagged events.

TABLE II: The \( CP \)-asymmetries for \( B^0 \to K^+K^-K^0 \) for the entire DP, in the high-mass region, and for \( \phi K^0 \) 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.

<table>
<thead>
<tr>
<th></th>
<th>( A_{\text{CP}} )</th>
<th>( \beta_{\text{eff}} ) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole DP</td>
<td>-0.015 ± 0.077 ± 0.055</td>
<td>0.352 ± 0.076 ± 0.026</td>
</tr>
<tr>
<td>High-mass</td>
<td>-0.054 ± 0.102 ± 0.060</td>
<td>0.436 ± 0.087 ± 0.035</td>
</tr>
<tr>
<td>(1) ( \phi K^0 )</td>
<td>-0.08 ± 0.18 ± 0.04</td>
<td>0.11 ± 0.14 ± 0.06</td>
</tr>
<tr>
<td>(1) ( f_0 K^0 )</td>
<td>0.41 ± 0.23 ± 0.07</td>
<td>0.14 ± 0.15 ± 0.05</td>
</tr>
<tr>
<td>(2) ( \phi K^0 )</td>
<td>-0.11 ± 0.18 ± 0.01</td>
<td>0.10 ± 0.13 ± 0.01</td>
</tr>
<tr>
<td>(2) ( f_0 K^0 )</td>
<td>-0.20 ± 0.31 ± 0.04</td>
<td>3.09 ± 0.19 ± 0.04</td>
</tr>
</tbody>
</table>

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 on isobar model parameters and for \( X_0(1550) \) parameters [16]. Other uncertainties, including those due to fixed PDF parameters, and possible \( CP \) asymmetries in the \( B \bar{B} \) background are also taken into account [8, 24]. As a cross-check, we perform the analysis using \( B_{sL}^0(\pm) \) alone and find \( A_{\text{CP}} = -0.061 ± 0.088 \) (stat), \( \beta_{\text{eff}} = 0.357 ± 0.080 \) (stat) in the fit to the whole DP; low- and high-mass results are also consistent with the results in Table II.

In summary, in a sample of 383 million \( B \bar{B} \) meson pairs we simultaneously analyze the Dalitz plot distribution and measure the time-dependent \( CP \) asymmetries for \( B^0 \to K^+K^-K^0 \) decays. The values of \( \beta_{\text{eff}} \) and \( A_{\text{CP}} \) are consistent with the SM expectations of \( \beta \approx 0.370 \) rad, \( A_{\text{CP}} \approx 0 \) [21]. The significance of \( CP \)
TABLE III: A summary of the systematic errors on the CP asymmetry parameter values.

<table>
<thead>
<tr>
<th>Source</th>
<th>Whole DP</th>
<th>High-mass</th>
<th>φK0</th>
<th>f0K0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACP βeff</td>
<td>ACP βeff</td>
<td>ACP βeff</td>
<td>ACP βeff</td>
</tr>
<tr>
<td>Fit Bias</td>
<td>0.003 0.001</td>
<td>0.014 0.008</td>
<td>0.03 0.06 0.06 0.03</td>
<td></td>
</tr>
<tr>
<td>Isobar model</td>
<td>0.004 0.009</td>
<td>0.025 +0.051 −0.024</td>
<td>0.00 0.01 0.01 0.03</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0.052 0.024</td>
<td>0.053 0.018</td>
<td>0.02 0.01 0.03 0.02</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.053 0.026</td>
<td>0.060 +0.020 −0.033</td>
<td>0.04 0.06 0.07 0.05</td>
<td></td>
</tr>
</tbody>
</table>

violation is 4.8σ, and we reject the solution near π/2 − β at 4.5σ. In a fit to the low-mass region of the Dalitz plot, we measure CP asymmetries for the decays B0 → φK0 and B0 → f0K0, where we find βeff lower than the SM expectation by about 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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* Deceased
† Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡ Also with Università della Basilicata, Potenza, Italy
§ Also with Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
¶ Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom

[11] Throughout, φ and f0 refer to the φ(1020) and f0(980), respectively.