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Measurement of the Branching Fractions and CP Asymmetry of $B \to D(0)_{(CP)} K^-$ Decays with the B\(\textit{B}\)\(\textit{A}\)\(\textit{B}AR\) Detector

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We present a study of $B^- \rightarrow D^{0}_{CP}K^-$ decays, where $D^{0}_{CP}$ is reconstructed in CP-even channels, based on a sample of $(88.8 \times 10^6) \ Y(4S) \rightarrow BB$ decays collected with the BABAR detector at the PEP-II $e^+ e^-$ storage ring. We measure the ratio of Cabibbo-suppressed to Cabibbo-favored branching fractions $\mathcal{B}(B^- \rightarrow D^{0}_{CP}K^-)/\mathcal{B}(B^- \rightarrow D^{0}_{CP}\pi^-) = (8.8 \pm 1.6(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-2}$ and the CP asymmetry.
The recent observation of $CP$ violation in the $B$ meson system [1] has provided a clean measurement of the angle $\beta$ of the unitarity triangle. Although this measurement is in good agreement with the expectations of the standard model derived from other measurements of weak interactions, further measurements of $CP$ violation in $B$ decays are needed to overconstrain the unitarity triangle and confirm the Cabibbo-Kobayashi-Maskawa (CKM) mechanism or observe deviations from it. A theoretically clean measurement of the angle $\gamma = \arg(-V_{ud}V_{ub}^*)/V_{cd}V_{cb}^*$ can be obtained from the study of $B^- \to D^{(s)}K^{(*)}$ decays by exploiting the interference between the $b \to c\bar{s}s$ and $b \to u\bar{c}s$ decay amplitudes [2]; among the proposed methods, the one originally proposed by Gronau, Wyler, and London exploits the interference between $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$ when the $D^0$ and $\bar{D}^0$ decay to $C$P eigenstates.

We define the ratios of Cabibbo-suppressed to Cabibbo-favored branching fractions

$$R_{(CP\pm)} = \frac{B(B^- \to D^{(s)}_{(CP\pm)}K^-)}{B(B^- \to D^{(s)}_{(CP\pm)}\pi^-)} + \frac{B(B^+ \to \bar{D}^{(s)}_{(CP\pm)}K^+) + B(B^+ \to \bar{D}^{(s)}_{(CP\pm)}\pi^+)}{B(B^- \to D^{(s)}_{(CP\pm)}K^-) + B(B^- \to D^{(s)}_{(CP\pm)}\pi^-)}$$

(1)

with $D^0$ reconstructed in Cabibbo-allowed or $CP$-even/odd eigenstate ($D^0_{CP\pm}$) channels, and the direct $CP$ asymmetry

$$A_{CP\pm} = \frac{B(B^- \to D^{(s)}_{CP\pm}K^-) - B(B^- \to D^{(s)}_{CP\pm}\pi^-)}{B(B^- \to D^{(s)}_{CP\pm}K^-) + B(B^- \to D^{(s)}_{CP\pm}\pi^-)}$$

(2)

Neglecting the $D^0 - \bar{D}^0$ mixing and the ratio $r_\pi$ of the amplitudes of the $B^- \to D^0\pi^-$ and $B^- \to D^0\pi^-$ processes ($r_\pi \ll 0.02$), $R_{CP\pm}/R = 1 + r_\pi^2 \pm 2r_\pi \cos\delta \cos\gamma$ and $A_{CP\pm} = \pm 2r_\pi \sin\delta \sin\gamma/(1 + r_\pi^2 \pm 2r_\pi \cos\delta \cos\gamma)$, where $r_\pi = 0.1 - 0.2$ is the magnitude of the ratio of the amplitudes for the processes $B^- \to \bar{D}^0K^-$ and $B^- \to D^0K^-$, and $\delta$ is the (unknown) relative strong phase between these two amplitudes [2]. The measurement of $R$, $R_{CP\pm}$, and $A_{CP\pm}$ allows us to constrain the three unknowns $r_\pi$, $\delta$, and the CKM angle $\gamma$.

In this Letter we present the measurement of $R$, $R_{CP\pm}$, and $A_{CP\pm}$. The measurement of $R$ uses a sample of $61.0 \times 10^6 \ Y(4S)$ decays in $\BB$ pairs collected with the $BaBar$ detector at the PEP-II asymmetric-energy $B$ factory. The measurements of $R_{CP\pm}$ and $A_{CP\pm}$ use a sample of $88.8 \times 10^6 \ BB$ pairs. Since the $BaBar$ detector is described in detail elsewhere [3], only the components that are crucial to this analysis are summarized here. Charged-particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH).
We reconstruct $B$ meson candidates by combining a $D^0$ candidate with a track $h$. For the non-CP modes, the charge of the track $h$ must match that of the kaon from the $D^0$ meson decay. We select $B$ meson candidates by using the beam-energy-substituted mass $m_{ES} = \sqrt{(E_i^2/2 + p_i \cdot p_B)^2/E_B^2 - p_B^2}$ and the energy difference $\Delta E = E_B - E_i^2/2$, where the subscripts $i$ and $B$ refer to the initial $e^+e^-$ system and the $B$ candidate, respectively, and the asterisk denotes the center-of-mass (CM) frame. The $m_{ES}$ distributions for $B^+ \to D^0 h^-$ signals are Gaussian distributions centered at the $B$ mass with a resolution of 2.6 MeV/c$^2$, which does not depend on the decay mode or on the nature of the prompt track. In contrast, the $\Delta E$ distributions depend on the mass assigned to the prompt track and on the $D^0$ momentum resolution. We evaluate $\Delta E$ with the kaon mass hypothesis so that the distributions are centered near zero for $B^- \to D^0 K^-$ events and shifted by approximately 50 MeV for $B^- \to D^0 \pi^- \pi^+$ events. The $\Delta E$ resolution is about 20 MeV for the $D^0 \to \pi^- \pi^+$ mode and typically 17 MeV for the other $D^0$ decay modes. We select $B$ mesons in the range 5.2 < $m_{ES}$ < 5.3 GeV/c$^2$ with the exception of the $D^0 \to \pi^- \pi^+$ mode, for which $m_{ES}$ is required to be within 3$\sigma$ of the mean value. All $B$ candidates are selected in the range $-0.10 < \Delta E < 0.13$ GeV. For events with multiple $B^- \to D^0 h^-$ candidates, the best candidate is chosen based on the values of $M(D^0)$ and $m_{ES}$; this happens in fewer than 1% of the selected events for two-body $D^0$ decays and in $\approx 4\%$ of the events for the other $D^0$ decays.

To reduce backgrounds from continuum production of light quarks, we make use of two quantities that exploit the different topologies of $e^+e^- \to q\bar{q}(q = u, d, s, c)$ and $B\bar{B}$ events. The first quantity is the normalized second Fox-Wolfram moment $R_2 = H_2/H_0$, where $H_i$ is the $i$-order Fox-Wolfram moment of all the charged tracks and neutral clusters in the event. Only events with $R_2 < 0.5$ are selected. The second quantity is the angle $\theta_T$ between the thrust axes of the $B$ candidate and of the remaining charged tracks and neutral clusters, evaluated in the CM. We require $|\cos \theta_T| < 0.9$ for the $D^0 \to K^- \pi^+$ mode and $|\cos \theta_T| < 0.7$ for the $D^0 \to K^- \pi^+ \pi^- \pi^-$ and $D^0 \to K^- \pi^+ \pi^- \pi^- \pi^-$ modes. For the $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^- \pi^-$ modes an additional quantity is used to suppress further the continuum background: the angle $\theta_{PH}$ between the direction of one of the decay products of the $D^0$ and the direction of flight of the $B$, in the $D^0$ rest frame. The quantities $\cos \theta_T$ and $\cos \theta_{PH}$ are uncorrelated for the signal but not for the continuum background. This correlation is exploited to make a more efficient cut in the $\cos \theta_T = \cos \theta_{PH}$ plane.

The total reconstruction efficiencies, based on simulated signal events, are 42%($K^- \pi^+$), 14%($K^- \pi^- \pi^+ \pi^-$), 8%($K^- \pi^+ \pi^0$), 34%($K^- K^+$), and 36%($\pi^- \pi^+$).

The main contributions to the $B\bar{B}$ background for the non-CP modes come from the processes $B \to D^+ h$ ($h = \pi, K$), $B^- \to D^0 \rho^-$, and misreconstructed $B^- \to D^0 h^-$. For $D^0_{CP}$ decays, the backgrounds $B^- \to K^- K^+ K^-$ and $B^- \to K^- \pi^+ \pi^- \pi_0$ [7] must also be considered, since they have the same $\Delta E$ and $m_{ES}$ distribution as the $D^0 K^-$ signal. The resonant component of these decays is negligible after the selection requirements for the CP modes.

For each $D^0$ decay mode an extended unbinned maximum-likelihood fit to the selected data events determines the signal and background yields $n_i$ ($i = 1$ to $M$, where $M$ is the total number of signal and background channels). Two kinds of signal events, $B^- \to D^0 \pi^- \pi^+$ and $B^- \to D^0 K^-$, are considered, while the number of background sources depends on the $D^0$ channel. For non-CP modes we consider four kinds of backgrounds: candidates selected either from continuum or from $B\bar{B}$ events, in which the prompt track is either a pion or a kaon. In the case of $D^0 \to K^- K^+$ we consider two kinds of background depending on the nature of the prompt track. Finally, in the case of $D^0 \to \pi^- \pi^+$ we consider four contributions: the $B^- \to K^- \pi^- \pi^-$ and $B^- \to \pi^- \pi^- \pi^+$ decays and two kinds of generic background depending on the nature of the prompt track.

The input variables to the fit for the non-CP and the $D^0 \to K^- K^+$ modes are $m_{ES}$, $\Delta E$, and a particle identification probability for the prompt track based on the Cherenkov angle $\theta_c$, the momentum $p$, and the polar angle $\theta$ of the track. For the $D^0 \to \pi^- \pi^+$ mode, $m_{ES}$ is replaced by $M(D^0)$. This allows us to separate the $B^- \to D^0 K^-$ from the nonresonant $B^- \to K^- \pi^+ \pi^-$ contributions since the $(\pi^- \pi^+)$-invariant-mass distribution peaks at the $D^0$ mass for signal while it is featureless for background. The extended likelihood function $L$ is defined as

$$L = \exp \left( -\sum_{i=1}^{M} n_i \prod_{j=1}^{N} \sum_{i=1}^{M} n_i P_i(\hat{x}_j; \hat{\alpha}_i) \right),$$  

where $N$ is the total number of observed events. The $M$ functions $P_i(\hat{x}_j; \hat{\alpha}_i)$ are the probability density functions (PDFs) for the variables $\hat{x}_j$, given the set of parameters $\hat{\alpha}_i$. They are evaluated as a product $P_i = P_i(\Delta E, x) \times P_i(\theta_c)$, where $x = m_{ES}$ or $M(D^0)$ depending on the $D^0$ channel.

The Gaussian shape of the $m_{ES}$ PDF for signal events is determined from a pure sample of $B^- \to D^0 \pi^-$, $D^0 \to K^- \pi^-$ decays selected from on-resonance data. The $\Delta E$ distribution for $B^- \to D^0 K^-$ signal events is parametrized with a Gaussian distribution whose parameters are determined from a pure sample of $B^- \to D^0 \pi^-$ events selected after the pion mass is assigned to the prompt track. The displaced $\Delta E$ distribution for $B^- \to D^0 \pi^-$ is parametrized with a sum of two Gaussian distributions. The shape of $M(D^0)$ is also described by a Gaussian distribution whose parameters are determined from data.

The parameters for the $\Delta E$ and $m_{ES}$ distributions for the continuum background of the non-CP and $D^0 \to K^- K^+$ modes are determined from off-resonance data.
The background shape in $\Delta E$ is parametrized with a linear function, while that of the $m_{ES}$ is parametrized with an ARGUS threshold function [8] $f(m_{ES}) = m_{ES}^{0.1} - y^2 \exp[-\xi(1 - y^2)]$, where $y = m_{ES}/m_0$ and $m_0$ is the mean CM energy of the beams. The correlation between $m_{ES}$ and $\Delta E$ for the generic $BB$ background is taken into account with a two-dimensional PDF determined from simulated events through a method based on the kernel estimation [9] technique. For the $D^0 \to K^- K^+$ mode the contribution from the nonresonant $B^- \to K^- K^+ K^+$ decays is estimated [7] and added to the continuum and the generic $BB$ background.

The $\Delta E$ and $M(D^0)$ distributions for the continuum and generic $BB$ background of the $D^0 \to \pi^- \pi^+$ mode are determined from off-resonance data and simulated events, respectively. The $\Delta E$ distribution is described by a linear function while $M(D^0)$ is parametrized with the sum of a linear function (combinatorial background) and a Gaussian distribution (real $D^0 \to \pi^- \pi^+$). The $M(D^0)$ PDFs of the nonresonant $B^- \to h^- \pi^- \pi^+$ decays are described by linear functions, while the $\Delta E$ distributions are parametrized with one or two Gaussian distributions, as for the $B^- \to D^0 h^-$ signals.

Finally, the parametrization of the particle identification PDF is performed by fitting with a Gaussian distribution the background-subtracted distribution of the difference between the reconstructed and expected Cherenkov angles of the kaons and pions from $D^0$ decays, in a pure $D^{*-} \to D^0 \pi^+$ ($D^0 \to K^- \pi^+$) control sample.

The results of the fit are summarized in Table I. Figure 1 shows the distributions of $\Delta E$ for the combined non-$CP$ and $CP$ modes after enhancing the $B \to D^0 K$ purity by requiring that the prompt track be consistent with the kaon hypothesis and that $|m_{ES} - \langle m_{ES} \rangle| < 3\sigma$ ($|M(\pi^- \pi^+) - \langle M(\pi^- \pi^+) \rangle| < 3\sigma$ for $D^0 \to \pi^- \pi^+$). The projection of a likelihood fit, modified to take into account the tighter selection criteria, is overlaid in Fig 1.

The ratios $R$ and $R_{CP+}$ are computed by scaling the ratios of the numbers of $B^- \to D^0 K^-$ and $B^- \to D^0 \pi^-$ mesons by correction factors that account for small differences in the efficiency between $B^- \to D^0 K^-$ and $B^- \to D^0 \pi^-$ selection, estimated with simulated signal samples. The results are listed in Table II.

The direct $CP$ asymmetry $A_{CP+}$ for the $B^\pm \to D^0_{CP} K^\mp$ decays is calculated from the measured yields of positive and negative charged meson decays reported in Table I. We measure $A_{CP+} = 0.07 \pm 0.17(\mathrm{stat}) \pm 0.06(\mathrm{syst})$.

Systematic uncertainties in the ratios $R$, $R_{CP+}$ and in the $CP$ asymmetry $A_{CP+}$ arise primarily from uncertainties in signal yields due to imperfect knowledge of the PDF shapes. The parameters of the analytical PDFs are varied by $\pm 1\sigma$ and the difference in the signal yields is taken as a systematic uncertainty. When a $BB$ PDF is parametrized through the kernel estimation, we repeat the fit using several statistically independent simulated $BB$ samples to define the PDF. The width of the distribution of the difference between the new yields and the original yield is taken as the systematic uncertainty.

The uncertainties in the branching fractions of the channels contributing to the $BB$ background have been taken into account. The correlations between the different

### TABLE I. Results from the maximum-likelihood fit. For the $D^0 \to K^+ K^-$ and $D^0 \to \pi^- \pi^+$ modes we quote the results for the fits performed on the whole sample and on the $B^-$ and $B^+$ subsamples.

<table>
<thead>
<tr>
<th>$D^0$ mode</th>
<th>$N(B \to D^0 \pi)$</th>
<th>$N(B \to D^0 K)$</th>
<th>$N[Y(4S)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^- \pi^+$</td>
<td>$4440 \pm 69$</td>
<td>$360 \pm 21$</td>
<td>$61.0 \times 10^6$</td>
</tr>
<tr>
<td>$K^- \pi^+ \pi^-$</td>
<td>$2914 \pm 56$</td>
<td>$242 \pm 18$</td>
<td>$61.0 \times 10^6$</td>
</tr>
<tr>
<td>$K^- \pi^- \pi^0$</td>
<td>$2650 \pm 56$</td>
<td>$208 \pm 18$</td>
<td>$61.0 \times 10^6$</td>
</tr>
<tr>
<td>$K^- K^+$</td>
<td>$565 \pm 25$</td>
<td>$44.3 \pm 9.0$</td>
<td>$88.8 \times 10^6$</td>
</tr>
<tr>
<td>$K^- K^+ [B^+]$</td>
<td>$286 \pm 18$</td>
<td>$16.7 \pm 5.8$</td>
<td>$88.8 \times 10^6$</td>
</tr>
<tr>
<td>$K^- K^+ [B^-]$</td>
<td>$280 \pm 18$</td>
<td>$27.8 \pm 6.8$</td>
<td>$88.8 \times 10^6$</td>
</tr>
<tr>
<td>$\pi^- \pi^+$</td>
<td>$195 \pm 17$</td>
<td>$24.2 \pm 7.2$</td>
<td>$88.8 \times 10^6$</td>
</tr>
<tr>
<td>$\pi^- \pi^+ [B^+]$</td>
<td>$99 \pm 12$</td>
<td>$16.8^{+5.6}_{-4.9}$</td>
<td>$88.8 \times 10^6$</td>
</tr>
<tr>
<td>$\pi^- \pi^+ [B^-]$</td>
<td>$96 \pm 12$</td>
<td>$6.5^{+4.1}_{-3.3}$</td>
<td>$88.8 \times 10^6$</td>
</tr>
</tbody>
</table>

(Continued on next page)
TABLE II. Measured ratios $R$ and $R_{CP+}$ for different $D^0$ decay modes. The first error is statistical, the second is systematic.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B(B \rightarrow DK)/B(B \rightarrow D\pi)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^-\pi^+$</td>
<td>8.4 ± 0.5 ± 0.2</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$</td>
<td>8.7 ± 0.7 ± 0.2</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-\pi^+\pi^0$</td>
<td>7.7 ± 0.7 ± 0.3</td>
</tr>
<tr>
<td>Weighted mean</td>
<td>8.31 ± 0.35 ± 0.20</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-K^+$</td>
<td>8.0 ± 1.7 ± 0.6</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^-\pi^+$</td>
<td>12.9 ± 4.0±1.1</td>
</tr>
<tr>
<td>Weighted mean</td>
<td>8.8 ± 1.6 ± 0.5</td>
</tr>
</tbody>
</table>

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