MEASUREMENT OF CP OBSERVABLES FOR THE

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Using a sample of $232 \times 10^6 \ Y(4S) \to \babar$ events collected with the BABAR detector at the PEP-II B Factory in 1999–2004, we study $B^- \to D_s^0 K^{*(892)}_L^-$ decays where $K^{*-} \to K^0_s \pi^- \pi^+$ and $D^0 \to K^- \pi^+$, $K^- \pi^- \pi^0$, $K^- \pi^+ \pi^- \pi^0$ (non-CP final states); $K^{+} K^-$, $\pi^+ \pi^+ \pi^- \pi^0$ ($CP+$ eigenstates); $K^0_{S(0)}$, $K^0_{S(0)}$, and $K^0_{S(0)}$ ($CP-$ eigenstates). We measure four observables that are sensitive to the angle $\gamma$ of the CKM unitarity triangle; the partial-rate charge asymmetries $\mathcal{A}_{\text{CP} \pm}$ and the ratios of the $B$-decay branching fraction in $CP^\pm$ and non-CP decays $\mathcal{R}_{\text{CP} \pm}$: $\mathcal{A}_{\text{CP} \pm} = -0.08 \pm 0.19(\text{stat}) \pm 0.08(\text{syst})$, $\mathcal{R}_{\text{CP} -} = 0.26 \pm 0.40(\text{stat}) \pm 0.12(\text{syst})$, $\mathcal{R}_{\text{CP} +} = 1.96 \pm 0.40(\text{stat}) \pm 0.11(\text{syst})$, and $\mathcal{R}_{\text{CP} -} = 0.65 \pm 0.26(\text{stat}) \pm 0.08(\text{syst})$.

The measurement of CP violation in $B$-meson decays offers a means to over-constrain the unitarity triangle. A theoretically clean determination of the angle $\gamma = \arg(-V_{ud}^{*} V_{ub} / V_{cd}^{*} V_{cb})$ is provided by the $B^+ \to D^{(*)0} K^{(*)+}$ decay channels in which the favored $b \to c \ell \nu s$ and suppressed $b \to u c s$ tree amplitudes interfere [1,2]. Results on the $B^+ \to D^{(*)0} K^{(*)+}$ decays have been published by the BABAR [3–5] and BELLE [6,7] collaborations. In this paper, we present a study based on the interference between $B^- \to D^{0} K^{*(892)}_L^- \to D^{0} K^{*(892)}_L^- \to D^{0} K^{*+} \to D^{0} K^{+}\pi^- \pi^+$ when both $D^0$ and $D^{0*}$ decay to the same $CP$ eigenstate ($D^{0*}_{CP}$). Reference to a charge conjugate mode is implied throughout this paper unless otherwise stated.

We follow [2,8] and define:

$$\mathcal{R}_{\text{CP} \pm} = 2 \frac{\Gamma(B^- \to D^0_{CP} K^{*-}) + \Gamma(B^+ \to D^0_{CP} K^{*+}) - \Gamma(B^- \to D^{0*}_{CP} K^{*-}) - \Gamma(B^+ \to D^{0*}_{CP} K^{*+})}{\Gamma(B^- \to D^0 K^{*-}) + \Gamma(B^+ \to D^0 K^{*+}) + \Gamma(B^- \to D^{0*} K^{*-}) + \Gamma(B^+ \to D^{0*} K^{*+})},$$

$$\mathcal{A}_{\text{CP} \pm} = \frac{\Gamma(B^- \to D^0_{CP} K^{*-}) - \Gamma(B^+ \to D^0_{CP} K^{*+}) + \Gamma(B^- \to D^{0*}_{CP} K^{*-}) + \Gamma(B^+ \to D^{0*}_{CP} K^{*+})}{\Gamma(B^- \to D^0 K^{*-}) + \Gamma(B^+ \to D^0 K^{*+}) - \Gamma(B^- \to D^{0*} K^{*-}) - \Gamma(B^+ \to D^{0*} K^{*+})}. $$

Both $\mathcal{A}_{\text{CP}}$ and $\mathcal{R}_{\text{CP}}$ carry CP-violating information. Neglecting $D^{0*}$ mixing, they can be expressed as follows:

$$\mathcal{R}_{\text{CP} \pm} = 1 \pm 2 r_B \cos \delta \cos \gamma + r_B^2,$$

$$\mathcal{A}_{\text{CP} \pm} = \pm 2 r_B \sin \delta \sin \gamma \mathcal{R}_{\text{CP} \pm},$$

where $\delta$ is the CP-conserving strong phase difference between the $B^- \to D^{0*} K^{*-}$ (suppressed) and $B^- \to D^0 K^{*-}$ (favored) amplitudes, $r_B \approx 0.1–0.3$ [8] is the magnitude of their ratio, and $\gamma$ is the CP-violating weak phase difference. A value close to $60^\circ$ is favored for $\gamma$ when one combines all measurements related to the unitarity triangle [9]. It is useful to introduce also new variables,

$$x^\pm = r_B \cos(\delta \pm \gamma),$$

which are better behaved (more Gaussian) in the region where $r_B$ is small.

To search for $B^- \to D^0_{CP} K^{*-}$ decays we use data collected with the BABAR detector [10] at the PEP-II storage ring. The sample corresponds to an integrated luminosity of 211 fb$^{-1}$ at the $Y(4S)$ resonance ($232 \times 10^6 \ babar$ pairs) and 20.4 fb$^{-1}$ at an energy 40 MeV below the peak.

To reconstruct $B^- \to D^0 K^{*-}$ decays, we select $K^{*-}$ candidates in the $K^{*-} \to K^0_s \pi^-$, $K^0_{S(0)} \to \pi^+ \pi^- \pi^0$ mode and $D^0$ candidates in eight decay channels, $D^0 \to K^- \pi^+$, $K^- \pi^- \pi^0$, $K^- \pi^+ \pi^- \pi^0$ (non-CP final states); $K^+ K^-$, $\pi^+ \pi^- \pi^0$ ($CP+$ eigenstates); and $K^0_{S(0)}$, $K^0_{S(0)}$, $K^0_{S(0)}$ ($CP-$ eigenstates). We optimize our event selection to minimize the statistical error on the signal yield, determined for each channel using simulated signal and background events. Particle identification is required for all charged particles except for the pions from $K^0_{S(0)}$ decay.

$K^0_S$ candidates are formed from oppositely charged tracks assumed to be pions with a reconstructed invariant mass within 13 MeV$/c^2$ (4 standard deviations) from the known $K^0_S$ mass [11], $m_{K^0_S}$. All $K^0_S$ candidates are refit so that their invariant mass equals $m_{K^0_S}$ (mass constraint). For those retained to build a $D^0_{CP}$ candidate the tracks are also constrained to emerge from a single vertex (vertex constraint). For those retained to build a $K^{*-}$ we further require their flight direction and length be consistent with a $K^0_S$ coming from the interaction point. The $K^0_S$ candidate flight path and momentum must make an acute angle and the flight length in the plane transverse to the beam direction must exceed its uncertainty by 3 standard deviations. $K^{*-}$ candidates are formed from a $K^0_S$ and a charged particle with a vertex constraint. We select $K^{*-}$ candidates which have an invariant mass within 75 MeV$/c^2$ of the known value [11]. Finally, since the $K^{*-}$ in $B^- \to D^0 K^{*-}$ is polarized, we require $|\cos \theta_H| \geq 0.35$, where $\theta_H$ is the angle in the $K^{*-}$ rest frame between the daughter pion and the parent $B$ momentum. The helicity distribution discriminates well between a $B$-meson decay and an event from the $e^+ e^- \to q \bar{q}$ ($q \in \{u, d, s, c\}$) continuum, since the former is distributed as $\cos \theta_H$ and the latter is flat.

Some decay modes of the $D^0$ contain a $\pi^0$. We combine pairs of photons to form a $\pi^0$ candidate with a total energy.
times larger. We therefore explicitly veto any selected \( B \) candidate containing a \( K_S^0\pi^+\pi^- \) combination within 25 MeV/c\(^2\) of the \( D^0 \) mass. No background remains.

In those events where we find more than one acceptable \( B \) candidate (less than 25\% of selected events depending on the \( D^0 \) mode), we choose that with the smallest \( \chi^2 \) formed from the differences of the measured and true \( D^0 \) and \( K^- \) masses scaled by the mass spread which includes the resolution and, for the \( K^- \), the natural width. Simulations show that no bias is introduced by this choice and the correct candidate is picked at least 82\% of the time.

According to simulation of signal events, the total reconstruction efficiencies are 13.1\% and 14.2\% for the \( CP^+ \) modes \( D^0 \to K^+K^- + \pi^+\pi^- \); 5.5\%, 10.0\%, and 2.4\% for the \( CP^- \) modes \( D^0 \to K_0^0\pi^0, K_0^0\phi, \) and \( K_0^0\omega; \) 13.3\%, 4.3\%, and 8.2\% for the non-\( CP \) modes \( D^0 \to K^-\pi^+, \)

In those events where we find more than one acceptable \( B \) candidate (less than 25\% of selected events depending on the \( D^0 \) mode), we choose that with the smallest \( \chi^2 \) formed from the differences of the measured and true \( D^0 \) and \( K^- \) masses scaled by the mass spread which includes the resolution and, for the \( K^- \), the natural width. Simulations show that no bias is introduced by this choice and the correct candidate is picked at least 82\% of the time.

To study \( B\bar{B} \) backgrounds we look in sideband regions away from the signal region in \( \Delta E \) and \( m_{\text{ES}} \). We define a \( \Delta E \) sideband in the interval \(-100 \leq \Delta E \leq -60 \) and \( 60 \leq \Delta E \leq 200 \) MeV for all modes except \( D^0 \to K_0^0\pi^0 \) for which the inside limit is \( \pm 95 \) rather than 60 MeV. The sideband region in \( m_{\text{ES}} \) is defined by requiring that this quantity differs from the \( D^0 \) mass peak by more than 4 standard deviations. It provides sensitivity to doubly-peaking background sources which mimic signal both in \( \Delta E \) and \( m_{\text{ES}} \). This pollution comes from either charmed or charmless \( B \)-meson decays that do not contain a true \( D^0 \). As many of the possible contributions to this background are not well known, we attempt to measure its size by including the \( m_{\text{ES}} \) sideband in the fit described below.

An unbinned extended maximum likelihood fit to \( m_{\text{ES}} \) distributions in the range \( 5.2 \leq m_{\text{ES}} \leq 5.3 \) GeV/c\(^2\) is used to determine yields and \( CP \)-violating quantities \( \mathcal{A}_{CP} \) and \( R_{CP} \). We use the same Gaussian function \( G \) to describe the signal shape for all modes considered. The combinatorial background in the \( m_{\text{ES}} \) distribution is modeled with a threshold function \([15] \mathcal{A}\). Its shape is governed by one parameter \( \xi \) that is left free in the fit. We fit simultaneously \( m_{\text{ES}} \) distributions of nine samples: the non-\( CP \), \( CP^+ \), and \( CP^- \) samples for (i) the signal region, (ii) the \( m_{\text{ES}} \) sideband, and (iii) the \( \Delta E \) sideband. We fit three probability density functions (PDF) weighted by the unknown event yields. For the \( \Delta E \) sideband, we use \( \mathcal{A} \). For the \( m_{\text{ES}} \) sideband (sb) we use \( a_{1b} \cdot \mathcal{A} + b_{1b} \cdot G \), where \( G \) accounts for the doubly-peaking \( B \) decays. For the signal region PDF, we use \( a \cdot \mathcal{A} + b \cdot G + c \cdot G \), where \( b = N_{\text{peak}} \) is scaled from \( b_{1b} \) according to the ratio of the \( m_{\text{ES}} \) signal window to sideband widths and \( c \) is the number of \( B^\pm \to D^0K^\pm \) signal events. The non-\( CP \) mode sample, with relatively high statistics, helps constrain the PDF shapes for the low statistics \( CP \) mode distributions. The \( \Delta E \) sideband sample helps define the \( \mathcal{A} \) background shape.

Since the values of \( \xi \) obtained for each data sample were found to be consistent with each other, albeit with large
statistical uncertainties, we have constrained $\xi$ to have the same value for all data samples in the fit. The simulation shows that the use of the same Gaussian parameters for all signal modes introduces only negligible systematic corrections. We assume that the $B$ decays found in the $m_{D^0}$ sideband have the same final states as the signal and we fit the same Gaussian to the doubly-peaking sideband. The doubly-peaking $B$ background is assumed to not violate $CP$ and is therefore split equally between the $B^-$ and $B^{+}$ subsamples. This assumption is considered further when we discuss the systematic uncertainties. The fit results are shown graphically in Fig. 1 and numerically in Table I.

The statistical significance of the $CP^+$ and $CP^-$ yields are 6.8 and 2.7 standard deviations, respectively. The yields for each individual mode are $23.1 \pm 5.1 (K^+ K^-), 17.4 \pm 5.0 (\pi^+ \pi^-), 10.9 \pm 4.1 (K^0_\pi^0), 3.1 \pm 3.2 (K^0_\phi)$, and $3.8 \pm 2.7 (K^0_\omega)$.

Although most systematic errors cancel for $A_{CP}$, an asymmetry inherent to the detector or data processing may exist. After performing the analysis on a high statistics $B^- \rightarrow D^0 \pi^-$ sample (not applying the $K^-$ selection), the final sample shows an asymmetry of $-0.019 \pm 0.008$. We assign a systematic uncertainty of $\pm 0.027$. The second substantial systematic effect is a possible $CP$ asymmetry in the peaking background. Although there is no physics reason that requires the peaking background to be asymmetric, it cannot be excluded. We note that if there were an asymmetry $A_{\text{peak}}$, a systematic error on $A_{CP}$ would be given by $A_{\text{peak}} \times \frac{b}{c}$, where $b$ is the contribution of the peaking background and $c$ the signal yield. Assuming conservatively $|A_{\text{peak}}| \leq 0.5$, we obtain systematic errors of $\pm 0.06$ and $\pm 0.10$ on $A_{CP^+}$ and $A_{CP^-}$, respectively.

Since $R_{CP}$ is a ratio of rates of processes with different final states of the $D^0$, we must consider the uncertainties affecting the selection algorithms for the different $D$ channels. This results in small correction factors which account for the difference between the actual detector response and the simulation model. The main effects stem from the approximate modeling of the tracking efficiency (1.2% per track), the $K^0_S$ reconstruction efficiency for $CP^-$ modes of the $D^0$ (2.0% per $K^0_S$), the $\pi^0$ reconstruction efficiency for the $K^0_\pi^0$ channel (3%) and the efficiency and misidentification probabilities from the particle identification (2% per track). A substantial effect is the uncertainty on the measured branching fractions [11]. Altogether, we obtain systematic uncertainties equal to $\pm 0.11$ and $\pm 0.055$ for $R_{CP^+}$ and $R_{CP^-}$, respectively.

Another systematic correction is applied to the $CP^-$ measurements which arises from a possible $CP^+$ background for the $K^0_\phi$ and $K^0_\omega$ channels. In this case, the observed quantities, $A_{CP^-}^{\text{obs}}$ and $R_{CP^-}^{\text{obs}}$ are corrected:

$$A_{CP^-} = (1 + \epsilon)A_{CP^-}^{\text{obs}} - \epsilon A_{CP^+}^{\text{obs}};$$

$$R_{CP^-} = \frac{R_{CP^-}^{\text{obs}}}{(1 + \epsilon)}.$$
where $\epsilon$ is the ratio of $CP^+$ background to $CP^-$ signal. There is little information on this $CP^+$ background. An investigation in BABAR of the $D^0 \rightarrow K^- K^+ K_S^0$ Dalitz plot indicates that the dominant background for $D^0 \rightarrow K_S^0 \phi$ comes from the decay $a_0(980) \rightarrow K^+ K^-$, at the level of $(25 \pm 1)$% the size of the $\phi K_S^0$ signal. We have no information for the $\omega K_S^0$ channel and assume $(30 \pm 30)$%. Adding the most frequent $K_S^0 \pi^0$ mode which does not suffer such a $CP^+$ pollution, we estimate $\epsilon = (13 \pm 7)$%. The systematic error associated with this correction is $\pm 0.01$ and $\pm 0.04$ for $\mathcal{A}_{CP^+}$ and $\mathcal{R}_{CP^+}$, respectively.

To account for the nonresonant $K_S^0 \pi^-$ pairs under the $K^{*-}$, we vary by $2\pi$ all the strong phases in a conservative model which incorporates $S$-wave $K\pi$ pairs in both $b \rightarrow c \bar{u} s$ and $b \rightarrow u \bar{c} s$ amplitudes. This background induces systematic variations of $\pm 0.051$ for $\mathcal{A}_{CP^+}$ and $\pm 0.035$ for $\mathcal{R}_{CP^+}$. We add the systematic uncertainties in quadrature and quote the final results:

$$\mathcal{A}_{CP^+} = -0.08 \pm 0.19(\text{stat}) \pm 0.08(\text{syst}),$$

$$\mathcal{A}_{CP^-} = -0.26 \pm 0.40(\text{stat}) \pm 0.12(\text{syst}),$$

$$\mathcal{R}_{CP^+} = 1.96 \pm 0.40(\text{stat}) \pm 0.11(\text{syst}),$$

$$\mathcal{R}_{CP^-} = 0.65 \pm 0.26(\text{stat}) \pm 0.08(\text{syst}).$$

These results also can be expressed in terms of $x^+$ defined in Equation (3):

$$x^+ = 0.32 \pm 0.18(\text{stat}) \pm 0.07(\text{syst}),$$

$$x^- = 0.33 \pm 0.16(\text{stat}) \pm 0.06(\text{syst}),$$

where the $CP^+$ pollution systematic effects increase $x^+$ and $x^-$ by $0.022 \pm 0.012$ and $0.019 \pm 0.010$, respectively. From Eq. (1) we find $r_B^2 = 0.30 \pm 0.25$.

In summary, we have studied the decays of charged $B$ mesons to a $K^+(892)^-$ and a $D^0$, where the latter is seen in final states of even and odd $CP$. We express the results with $\mathcal{R}_{CP}$, $\mathcal{A}_{CP}$, and $x^\pm$. These quantities can be combined with other $D^{(*)} K^{(*)}$ measurements to estimate $r_B$ more precisely and improve our understanding of the angle $\gamma$.

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[15] The function is $\mathcal{A}(m_{ES}) \propto m_{ES}\sqrt{1-x^2}\exp[-x(1-x^2)]$, where $x = 2m_{ES}/\sqrt{s}$ and $\xi$ is a fit parameter; H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 185, 218 (1987); 241, 278 (1990).