

Measurement of CP observables for the decays $B^\pm \rightarrow D_{CP}^0 K^{*\pm}$

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

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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 $B^- \rightarrow D^{(*)0}K^{(*)-}$ decay channels in which the favored $b \rightarrow c\bar{u}s$ and suppressed $b \rightarrow u\bar{c}s$ tree amplitudes interfere [1,2]. Results on the $B^- \rightarrow D^{(*)0}K^-$ 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 $B^- \rightarrow D^0 K^{*0}(892)^-$ and $B^- \rightarrow \bar{D}^0 K^{*-}$ when both D^0 and \bar{D}^0 decay to the same *CP* eigenstate (D_{CP}^0). Reference to a charge conjugate mode is implied throughout this paper unless otherwise stated.

We follow [2,8] and define:

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

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

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

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

$$\mathcal{A}_{CP\pm} = \frac{\pm 2r_B \sin\delta \sin\gamma}{\mathcal{R}_{CP\pm}}, \quad (2)$$

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

$$x^\pm \equiv r_B \cos(\delta \pm \gamma), \quad (3)$$

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

To search for $B^- \rightarrow D_{CP}^0 K^{*-}$ 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 (232×10^6 $B\bar{B}$ pairs) and 20.4 fb^{-1} at an energy 40 MeV below the peak.

To reconstruct $B^- \rightarrow D^0 K^{*-}$ decays, we select K^{*-} candidates in the $K^{*-} \rightarrow K_S^0 \pi^-$, $K_S^0 \rightarrow \pi^+ \pi^-$ mode and D^0 candidates in eight decay channels, $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^+ \pi^-$ (non-*CP* final states); $K^+ K^-$, $\pi^+ \pi^-$ (*CP*+ eigenstates); and $K_S^0 \pi^0$, $K_S^0 \phi$, $K_S^0 \omega$ (*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_S^0 decays.

K_S^0 candidates are formed from oppositely charged tracks assumed to be pions with a reconstructed invariant mass within $13 \text{ MeV}/c^2$ (4 standard deviations) from the known K_S^0 mass [11], $m_{K_S^0}$. All K_S^0 candidates are refitted so that their invariant mass equals $m_{K_S^0}$ (mass constraint). For those retained to build a D_{CP-}^0 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_S^0 coming from the interaction point. The K_S^0 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_S^0 and a charged particle with a vertex constraint. We select K^{*-} candidates which have an invariant mass within $75 \text{ MeV}/c^2$ of the known value [11]. Finally, since the K^{*-} in $B^- \rightarrow D^0 K^{*-}$ is polarized, we require $|\cos\theta_H| \geq 0.35$, where θ_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 $e^+ e^- \rightarrow q\bar{q}$ ($q \in \{u, d, s, c\}$) continuum, since the former is distributed as $\cos^2\theta_H$ and the latter is flat.

Some decay modes of the D^0 contain a π^0 . We combine pairs of photons to form a π^0 candidate with a total energy

greater than 200 MeV and an invariant mass between 115 and 150 MeV/ c^2 . A mass-constrained fit is applied to the selected π^0 candidates. Composite particles included in the $CP-$ modes are vertex constrained. Candidate ϕ (ω) mesons are constructed from K^+K^- ($\pi^+\pi^-\pi^0$) particle combinations with the invariant mass required to be within 12 (20) MeV/ c^2 or 2 standard deviations of the known values [11]. Two further requirements are made on the ω candidates. The magnitude of the cosine of the helicity angle between the D^0 momentum in the rest frame of the ω and the normal to the plane containing all three decay pions must be greater than 0.25. The Dalitz angle [12], defined as the angle between the momentum of one daughter pion in the ω rest frame and the direction of one of the other two pions in the rest frame of the two pions, must have a cosine with a magnitude less than 0.9.

Except for the $K_S^0\pi^0$ final state, all D^0 candidates are mass and vertex constrained. We select D^0 candidates with an invariant mass differing from the known mass [11] by less than 12 MeV/ c^2 for all channels except $K_S^0\pi^0$ (30 MeV/ c^2) and $K_S^0\omega$ (20 MeV/ c^2). These limits are about twice the corresponding rms mass resolutions.

To suppress the background due to $e^+e^- \rightarrow q\bar{q}$ reactions, we require $|\cos\theta_B| \leq 0.9$, where θ_B is defined as the angle between the B candidate momentum in the $Y(4S)$ rest frame and the beam axis. In $q\bar{q}$ background events the $\cos\theta_B$ distribution is uniform, while for B mesons it follows a $\sin^2\theta_B$ distribution. We also use global event shape variables to distinguish between $q\bar{q}$ continuum events, which have a two-jet-like topology in the $Y(4S)$ rest frame, and $B\bar{B}$ events, which are more spherical. We require $|\cos\theta_T| \leq 0.9$ where θ_T is the angle between the thrust axes of the B candidate and that of the rest of the event. We construct a linear discriminant [13] from $\cos\theta_T$ and Legendre monomials [14] describing the energy flow in the rest of the event.

We identify B candidates using two nearly independent kinematic variables: the beam-energy-substituted mass $m_{ES} \equiv \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - p_B^2}$ and the energy difference $\Delta E = E_B^* - \sqrt{s}/2$, where E and p are energy and momentum, the subscripts 0 and B refer to the e^+e^- -beam system and the B candidate respectively; s is the square of the center-of-mass (CM) energy and the asterisk labels the CM frame. For signal modes, the m_{ES} distributions are all described by the same Gaussian function \mathcal{G} centered at the B mass with a 2.6 MeV/ c^2 resolution (for $D^0 \rightarrow K_S^0\pi^0$ the peak is slightly wider, 2.7 MeV/ c^2). The ΔE distributions are centered on zero for signal with a resolution of 11 to 13 MeV for all channels except $K_S^0\pi^0$ for which the resolution is asymmetric and about 30 MeV. We define a signal region through the requirement $|\Delta E| < 50$ (25) MeV for $K_S^0\pi^0$ (all other modes).

A background for $B^- \rightarrow D^0(\pi^+\pi^-)K^{*-}(K_S^0\pi^-)$ is the decay $B^- \rightarrow D^0(K_S^0\pi^+\pi^-)\pi^-$ which contains the same final state as the signal but has a branching fraction 600

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 χ^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 $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$; 5.5%, 10.0%, and 2.4% for the $CP-$ modes $D^0 \rightarrow K_S^0\pi^0$, $K_S^0\phi$, and $K_S^0\omega$; 13.3%, 4.3%, and 8.2% for the non- CP modes $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$.

To study $B\bar{B}$ backgrounds we look in sideband regions away from the signal region in ΔE and m_{D^0} . We define a ΔE sideband in the interval $-100 \leq \Delta E \leq -60$ and $60 \leq \Delta E \leq 200$ MeV for all modes except $D^0 \rightarrow K_S^0\pi^0$ for which the inside limit is ± 95 rather than 60 MeV. The sideband region in m_{D^0} 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 ΔE and m_{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_{D^0} sideband in the fit described below.

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

Since the values of ξ obtained for each data sample were found to be consistent with each other, albeit with large

statistical uncertainties, we have constrained ξ 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 B background.

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 re-

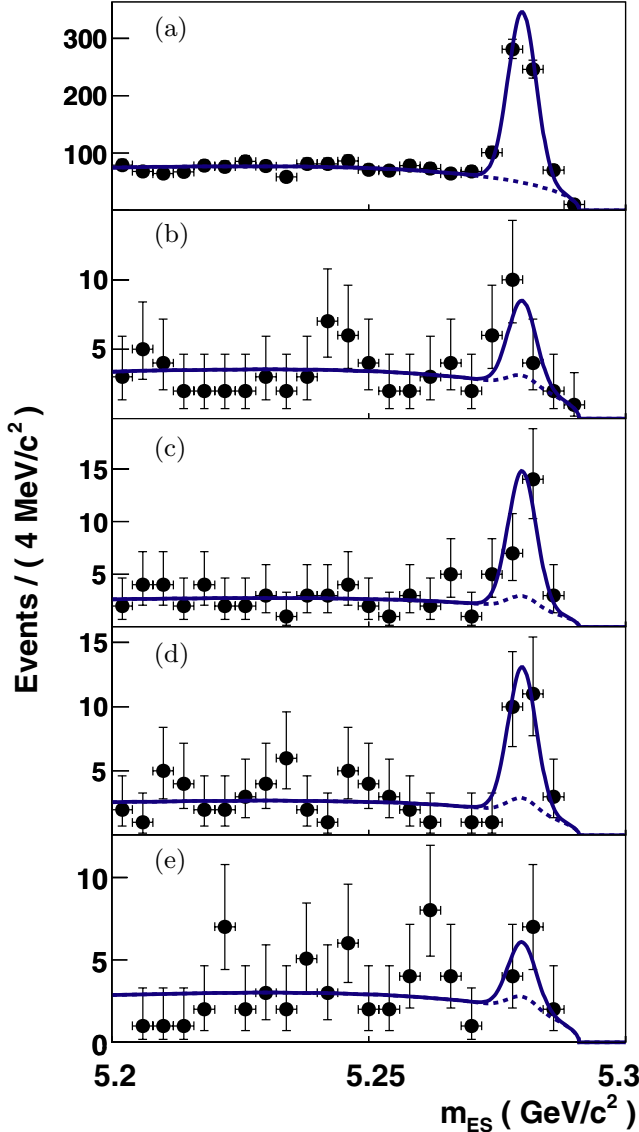


FIG. 1 (color online). Distributions of m_{ES} in the signal region for the non- CP modes in B^\pm decays (a), the $CP+$ modes in B^+ (b) and B^- (c) decays, and the $CP-$ modes in B^+ (d) and B^- (e) decays. The dashed curve indicates the contribution from the doubly-peaking B background estimated from a simultaneous fit to the D^0 sideband (not shown).

TABLE I. Results from the fits. For each D^0 mode class, we give the event yield, the peaking background contribution N_{peak} , \mathcal{A}_{CP} , and \mathcal{R}_{CP} . The uncertainties are statistical only.

	Yield	N_{peak}	\mathcal{A}_{CP}	\mathcal{R}_{CP}
non- CP	489 ± 27	20.1 ± 5.6		
$CP+$	37.6 ± 7.4	4.1 ± 1.3	-0.08 ± 0.19	1.96 ± 0.40
$CP-$	14.8 ± 5.9	3.0 ± 2.3	-0.24 ± 0.35	0.73 ± 0.29

sults 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 ± 5.1 (K^+K^-), 17.4 ± 5.0 ($\pi^+\pi^-$), 10.9 ± 4.1 ($K_S^0\pi^0$), 3.1 ± 3.2 ($K_S^0\phi$), and 3.8 ± 2.7 ($K_S^0\omega$).

Although most systematic errors cancel for \mathcal{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 ± 0.008 . We assign a systematic uncertainty of ± 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 $\mathcal{A}_{\text{peak}}$, a systematic error on \mathcal{A}_{CP} would be given by $\mathcal{A}_{\text{peak}} \times \frac{b}{c}$, where b is the contribution of the peaking background and c the signal yield. Assuming conservatively $|\mathcal{A}_{\text{peak}}| \leq 0.5$, we obtain systematic errors of ± 0.06 and ± 0.10 on \mathcal{A}_{CP+} and \mathcal{A}_{CP-} , respectively.

Since \mathcal{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_S^0 reconstruction efficiency for $CP-$ modes of the D^0 (2.0% per K_S^0), the π^0 reconstruction efficiency for the $K_S^0\pi^0$ 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 ± 0.11 and ± 0.055 for \mathcal{R}_{CP+} and \mathcal{R}_{CP-} , respectively.

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

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

$$\mathcal{R}_{CP-} = \frac{\mathcal{R}_{CP-}^{\text{obs}}}{(1 + \epsilon)},$$

where ϵ 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 ϕK_S^0 signal. We have no information for the ωK_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 ± 0.01 and ± 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 2π 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 ± 0.051 for $\mathcal{A}_{CP\pm}$ and ± 0.035 for $\mathcal{R}_{CP\pm}$. 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^\pm 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 ± 0.012 and 0.019 ± 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 γ .

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