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Measurement of $CP$ observables for the decays $B^\pm \to D_{CP}^0$
MEASUREMENT OF CP OBSERVABLES FOR THE ...

Physical Review D 72, 071103 (2005)

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Using a sample of $232 \times 10^6$ $Y(4S) \to B \bar{B}$ events collected with the BABAR detector at the PEP-II $B$ Factory in 1999–2004, we study $B^- \to D^0 K^{*(892)^-}$ decays where $K^{*-} \to K^0_s \pi^-$ and $D^0 \to K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^-$ (non-CP final states); $K^{+} K^{-}$, $\pi^+ \pi^-$ (CP$^+$ eigenstates); $K_0^0$, $K_2^0$, and $K_3^0$ (CP$^-$ eigenstates). We measure four observables that are sensitive to the angle $\gamma$ of the CKM unitarity triangle; the partial-rate charge asymmetries $A_{CP\pm}$ and the ratios of the $B$-decay branching fraction in $CP\pm$ and non-$CP$ decays $R_{CP\pm}$:

\[ R_{CP\pm} = \frac{A_{CP\pm}}{A_{CP^\mp}}, \]

\[ A_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm}^0 K^{*-}) - \Gamma(B^+ \to D_{CP\pm}^0 K^{*-})}{\Gamma(B^- \to D_{CP\pm}^0 K^{*-}) + \Gamma(B^+ \to D_{CP\pm}^0 K^{*-})}. \]

Both $A_{CP}$ and $R_{CP}$ carry CP-violating information. Neglecting $D^0\bar{D}^0$ mixing, they can be expressed as follows:

\[ R_{CP\pm} = 1 \pm 2r_B \cos \delta \cos \gamma + r_B^2, \]

\[ A_{CP\pm} = \frac{\pm 2r_B \sin \delta \sin \gamma}{R_{CP\pm}}, \]

where $\delta$ is the CP-conserving strong phase difference between the $B^- \to \bar{D}^0 K^{*-}$ (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° 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 $B^- \to D_{CP}^0 K^{*-}$ decays we use data collected with the BABAR detector at [10] at the PEP-II storage ring. The sample corresponds to an integrated luminosity of 211 fb$^{-1}$ at the $Y(4S)$ resonance ($232 \times 10^6 B \bar{B}$ 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 $K^{-} \to K^0_s \pi^-$, $K_2^0 \to \pi^+ \pi^- \pi^0$ mode and $D^0$ candidates in eight decay channels, $D^0 \to K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^-$ (non-CP final states); $K^+ K^-$, $\pi^+ \pi^- \pi^0$ (CP$^+$ eigenstates); and $K_3^0$, $K_2^0$, $K_0^0$ (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 $K_3^0$ decays.

$K_3^0$ 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 $K_3^0$ mass [11], $m_{K_3^0}$. All $K_3^0$ candidates are refitted so that their invariant mass equals $m_{K_3^0}$ (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 to be consistent with a $K_3^0$ coming from the interaction point. The $K_3^0$ 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 $K_3^0$ 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 $|\cos \theta_H| \approx 0.35$, 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
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^− (π^+π^-π^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^0_Sπ^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^0_Sπ^0 (30 MeV/c^2) and K^0_Sω (20 MeV/c^2). These limits are about twice the corresponding rms mass resolutions.

To suppress the background due to e^+e^- → q̅q reactions, we require |cosθ_R| ≤ 0.9, where θ_R is defined as the angle between the B candidate momentum in the Y(4S) rest frame and the beam axis. In q̅q background events the cosθ_R distribution is uniform, while for B mesons it follows a sin^2θ_R distribution. We also use global event shape variables to distinguish between q̅q continuum events, which have a two-jet-like topology in the Y(4S) rest frame, and B̅B events, which are more spherical. We require |cosθ_f| ≤ 0.9 where θ_f 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 cosθ_f 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_EGS ≡ \sqrt{(s/2 + p_B \cdot p_B)/E_B^2 - p^2_B} and the energy difference ∆E = E_B - √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_EGS distributions are all described by the same Gaussian function G centered at the B mass with a 2.6 MeV/c^2 resolution (for D^0 → K^0_Sπ^0 the peak is slightly wider, 2.7 MeV/c^2). The ∆E distributions are centered on zero for signal with a resolution of 11 to 13 MeV for all channels except K^0_Sπ^0 for which the resolution is asymmetric and about 30 MeV. We define a signal region through the requirement |∆E| < 50 (25) MeV for K^0_Sπ^0 (all other modes).

A background for B^+ → D^0(π^+π^-)K^−(K^0_Sπ^0) is the decay B^− → D^0(K^0_Sπ^+π^-)π^− 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^0_Sπ^+π^- 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 → K^+K^- and π^+π^−; 5.5%, 10.0%, and 2.4% for the CP− modes D^0 → K^0_Sω, K^0_Sφ, and K^0_Sω; 13.3%, 4.3%, and 8.2% for the non-CP modes D^0 → K^-π^+, K^-π^−π^0, and K^-π^−π^+π^-.

To study BB̅ backgrounds we look in sideband regions away from the signal region in ∆E and m_EGS. We define a ∆E sideband in the interval −100 ≤ ∆E ≤ −60 and 60 ≤ ∆E ≤ 200 MeV for all modes except D^0 → K^0_Sπ^0 for which the inside limit is ±95 rather than 60 MeV. The sideband region in m_EGS 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 ∆E and m_EGS. 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_π^0 sideband in the fit described below.

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

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

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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 $m_{fp}$ 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 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 $23.1 \pm 5.1$ ($K^+K^-$), $17.4 \pm 5.0$ ($\pi^+\pi^-$), $10.9 \pm 4.1$ ($K^0_0\pi^0$), $3.1 \pm 3.2$ ($K^0_0\phi$), and $3.8 \pm 2.7$ ($K^0_0\omega$).

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 $A_{peak}$, a systematic error on $A_{CP}$ would be given by $A_{peak} \times \frac{2b}{c}$, where $b$ is the contribution of the peaking background and $c$ the signal yield. Assuming conservatively $|A_{peak}| \leq 0.5$, 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 $K^0_0$ reconstruction efficiency for $CP^-$ modes of the $D^0$ (2.0% per $K^0_0$), the $\pi^0$ reconstruction efficiency for the $K^0_0\pi^0$ 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 $K^0_0\phi$ and $K^0_0\omega$ channels. In this case, the observed quantities, $A_{CP^-}^{obs}$ and $R_{CP^-}^{obs}$ are corrected:

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

$$R_{CP^-} = \frac{R_{CP^-}^{obs}}{(1 + \epsilon)}.$$
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 $\phi(980) \rightarrow K^+ K^-$, 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 $\mathcal{A}_{CP^\pm}$ and $\pm 0.035$ 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 $0.022 \pm 0.012$ 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 $x$. These quantities can be combined with other $D^{(*)}K^{(*)}$ measurements to estimate $r_B$ more precisely and improve our understanding of the angle $\gamma$.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A.P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.


[15] The function is $\mathcal{A}(m_{ES}) = m_{ES} \sqrt{1 - x^2} \exp[-\xi(1 - x^2)]$, 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).