Measurement of Time-Dependent CP Asymmetries in $B^0 \rightarrow D^{(s)} \bar{D}^+$ Decays

We present a first measurement of $CP$ asymmetries in neutral $B$ decays to $D^+D^-$, and updated $CP$ asymmetry measurements in decays to $D^{*+}D^-$ and $D^{*-}D^+$. We use fully reconstructed decays collected in a data sample of $(232 \pm 3) \times 10^6$ $Y(4S) \rightarrow B\bar{B}$ events in the BABAR detector at the PEP-II asymmetric-energy $B$ Factory at SLAC. We determine the time-dependent $CP$ asymmetry parameters to be $S_{D^{*+}D^-} = -0.54 \pm 0.35 \pm 0.07$, $C_{D^{*+}D^-} = 0.09 \pm 0.25 \pm 0.06$, $S_{D^0D^*} = -0.29 \pm 0.33 \pm 0.07$, $C_{D^0D^*} = 0.17 \pm 0.24 \pm 0.04$, $S_{D^*D^0} = -0.29 \pm 0.63 \pm 0.06$, and $C_{D^*D^0} = 0.11 \pm 0.35 \pm 0.06$, where in each case the first error is statistical and the second error is systematic.

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Charge-parity ($CP$) violation is described in the standard model (SM) by a single irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix $V$ [1]. The $B$-meson system provides an excellent probe for testing the completeness of the CKM mechanism in a variety of $CP$ asymmetries [2]. Measurements of $CP$ violation in $B^0 \rightarrow (c \bar{c})K^{0(*)}$ decays [3] by the BABAR [4] and Belle [5] collaborations have precisely determined the parameter $\sin 2\beta$, where $\beta$ is $\arg[-V_{ub}V_{cb}^*/V_{ub}V_{cb}^*]$. The current world average of $\sin 2\beta = 0.726 \pm 0.037$ is in good agreement with the range implied by other measurements in the context of the SM [6], providing evidence that the CKM mechanism is the main source of $CP$ violation in the quark sector.

Decays of $B^0$ mesons to pairs of charged $D^{(*)}$ mesons can also be used to determine $\sin 2\beta$. These decays proceed to leading order via a tree-level color-allowed $b \rightarrow c\bar{c}d$ transition. The presence of a gluonic penguin contribution with a different weak phase is expected to change the magnitude of the $CP$ asymmetry by not more than a few percent [7]. However, additional contributions from non-SM processes may lead to large shifts in some models [8]. Interference between SM penguin and tree amplitudes can additionally provide some sensitivity to the angle $\gamma = \arg[-V_{ub}V_{ub}^*/V_{ub}V_{ub}^*]$ [9].

In this Letter we present a first measurement of $CP$ asymmetries in the recently observed decay $B^0 \rightarrow D^+D^-$ [10] and improved measurements of $CP$ asymmetries in $B^0 \rightarrow D^{*+}D^-$ and $B^0 \rightarrow D^{*-}D^+$ decays [11,12]. The results are based on an analysis of $(232 \pm 3) \times 10^6$ $Y(4S) \rightarrow B\bar{B}$ decays recorded by the BABAR detector [13] at the SLAC PEP-II $e^+e^-$ collider.

The selection of $B^0 \rightarrow D^{*+}D^-$ candidates is similar to that of our previous analysis [11]. We reconstruct $D^{*+}$ in its decay to $D^0\pi^+$, where the $D^0$ is reconstructed in one of four final states: $K^-\pi^+, K^-\pi^0\pi^0, K^-\pi^+\pi^-\pi^0$, or $K_S^0\pi^+\pi^-$. The $D^-$ is reconstructed in the final states $K^+\pi^-\pi^0$ or $K_S^0\pi^-\pi^0$. The $K_S^0$ candidates are reconstructed from $\pi^-\pi^+$ pairs within 15 MeV/$c^2$ of the nominal $K_S^0$ mass [14]. The transverse flight distance of the $K_S^0$ from the primary event vertex is required to be greater than 2 mm, and the angle between the $K_S^0$ momentum vector and flight direction must be less than 11.5°. The $\pi^0$ candidates are reconstructed as photon pairs with an invariant mass between 115 and 150 MeV/$c^2$; each photon must have energy above 30 MeV in the laboratory frame and the sum of the photon energies must exceed 200 MeV. We require the $D^0$ and $D^\pm$ candidates to have reconstructed invariant masses within 20 MeV/$c^2$ of their respective nominal masses, except for $D^0$ decays with a $\pi^0$ daughter, which must be within 35 MeV/$c^2$ of the nominal $D^0$ mass. The $B^0 \rightarrow D^+D^-$ candidates are reconstructed solely through the decay of $D^+ \rightarrow K^-\pi^+\pi^-$. Charged kaons are required to be incompatible with a pion hypothesis on the basis of detected Cherenkov light and energy loss information [13].

To reduce background from continuum events ($e^+e^- \rightarrow q\bar{q}$, $q = u,d,s,c$), we exploit the contrast between the spherical topology of $B\bar{B}$ events and the more jetlike nature of continuum events. We require the ratio of the second-to-zeroth order Fox-Wolfram moments [15] to be less than 0.6. We also use a Fisher discriminant, constructed as an optimized linear combination of 11 event shape variables [16]: the momentum flow in nine concentric cones around the thrust axis of the reconstructed $B^0$ candidate, the angle between that thrust axis and the beam axis, and the angle between the line of flight of the $B^0$ candidate and the beam axis. The Fisher discriminant selection requirement increases the signal significance by 2% in the case of $B^0 \rightarrow D^{*+}D^-$ and 9% in the case of $B^0 \rightarrow D^+D^-$. For each candidate, we construct a likelihood variable $L_{\text{mass}}$ from the differences between the reconstructed masses and the nominal masses of the $D^{*+}$, $D^+$, and $D^0$ candidates [11]. The $L_{\text{mass}}$ variable is the product of the likelihood functions for the three candidate types. The likelihood for $D^+$ and $D^0$ is parametrized with a single Gaussian function, while the mass difference $m_{D^{*+}} - m_{D^0}$ is parameterized as the sum of two Gaussian functions. The computed value of $L_{\text{mass}}$ and the difference $\Delta E$ between measured energy of the $B^0$ candidate in the center-of-mass frame and half the center-of-mass energy, $\Delta E \equiv E^* - (\sqrt{s}/2)$, are used to reduce the combinatoric background. Maximum allowed values for both $-\ln L_{\text{mass}}$ and $|\Delta E|$ are set for each individual final state separately, optimized using a Monte Carlo simulation [17] to obtain the highest expected signal significance.

The technique for measuring the $CP$ asymmetries is analogous to previous BABAR measurements described in detail elsewhere [18]. After the reconstruction of a
B0 → D(+)0 D− candidate BCP, we assign the remaining tracks in the event to the other B meson B_{tag}. We compute a proper time difference Δt and its estimated uncertainty σ_{Δt} from the reconstructed decay vertices of BCP and B_{tag}. The tracks assigned to B_{tag} are used to determine the B_{tag} flavor and thus the flavor of the BCP meson at Δt = 0 [19]. Events are classified in one of six tag categories and must have an estimated probability w of assigning the wrong flavor to B_{tag} less than 45%.

Taking into account the uncertainty in the vertex position and tag flavor, the observed Δt distribution for B0 → D(+)0 D− signal events F_{CP}^{Δt}(Δt) is described by

$$F_{CP}^{Δt}(Δt) = Γ(Δt')(1 ± Δw (1 - 2w))[S_f sin(Δm_{ij}Δt') - C_f cos(Δm_{ij}Δt')] \otimes R(Δt - Δt'; σ_{Δt}),$$

where Γ(Δt') = (e^{-|Δt'|/τ_{0}})/(4τ_{0}) and the difference between the observed and true decay time differences Δt - Δt' is described by the empirical resolution function R(Δt - Δt'; σ_{Δt}). This function is parameterized as the sum of three Gaussians, a “core” and a “tail” Gaussian, each with a width and mean proportional to σ_{Δt}, and an outlier Gaussian centered at zero with a width of 8 ps. The values of the B0 lifetime τ_{0} and the B0 → B0 oscillation frequency Δm_{K} are fixed to (1.536 ± 0.014) ps and (0.502 ± 0.007) ps⁻¹ respectively [14]. We determine S_f and C_f separately for D⁺D⁻, D⁺⁺D⁻, and D⁺⁻D⁺. If only tree-graph contributions are present, we expect S_f = C_f = 0. Additionally, under these conditions we have S_{D⁺⁺D⁻} = -sin2β; S_{D⁺⁻D⁺} = 0, and C_{D⁺⁻D⁻} = -C_{D⁺⁺D⁺}. If the magnitudes of the amplitudes for B0 → D⁺⁺D⁻ and B0 → D⁺⁻D⁺ are equal [7], then C_{D⁺⁺D⁻} = C_{D⁺⁻D⁺} = 0. To determine the values of w, and the difference in incorrect tag assignment Δw between B0 and B0 reversed, for each of the tag categories, and to increase the precision on the resolution function parameters, we simultaneously fit to a large sample B_{raw} of reconstructed neutral B decays to the flavor eigenstates D(0)-h⁺ (h⁺ = π⁺, ρ⁺, and a₁⁺) and J/ψK(0)-K⁺π⁻, which is described by the empirical resolution function R(Δt - Δt'; σ_{Δt}) [18].

The beam energy substituted mass m_{ES} = [[s/2 + p_i + p_B/2/E_1 - p_B/2]]/2, where the initial e⁺e⁻ four-momentum (E_i, p_i) and the B momentum p_B are defined in the laboratory frame, is used to determine the composition of the reconstructed D(0)±D± samples. We use only the region m_{ES} > 5.2 GeV/c², which includes a large sideband of pure background events. These events are included in order to determine the properties of the combinatoric background present in the signal region. Backgrounds are incorporated with empirical descriptions of their Δt spectra. The backgrounds include prompt decays (associated with background from continuum events), and nonprompt decays with a Δt description similar to Eq. (1). Both components are convolved with a resolution function distinct from that of the signal, parametrized as the sum of two Gaussians. Based on Monte Carlo studies we expect a significant flavor asymmetry in the nonprompt background of the B0 → D(±)D± samples, because the D(±) candidate is usually a true D± while the D± is more often incorrectly reconstructed. This flavor asymmetry is parameterized via values of C_f and S_f of the nonprompt background that are allowed to vary in the fit.

The Δt and m_{ES} distributions are fit simultaneously. The m_{ES} distribution, shown in Fig. 1, allows a determination of a signal probability for each event. In signal events, the values of m_{ES} accumulate near the nominal B0 mass with a resolution of approximately 2.6 MeV/c². The fitted m_{ES} shapes consist of a Gaussian distribution for the signal and an ARGUS function [20] for the combinatoric background. The total number of selected candidates N_{cand} and the signal yield N_{sig} are shown in Table I. From detailed Monte Carlo simulations of generic B decays, we expect

![FIG. 1 (color online). Distribution of m_{ES} for (a) B_{0} → D⁺⁺D⁻, (b) B_{0} → D⁺⁻D⁺, and (c) B_{0} → D⁺⁺D⁻ candidates. The shaded areas represent the contributions from background events. The dashed and solid curves describing the background and signal plus background distributions, respectively, are explained in the text.](131802-5)
TABLE I. Signal yield and purity for each of the samples. The purity is defined as the fraction of signal events $N_{\text{sig}}/N_{\text{cand}}$ in the region $m_{ES} > 5.27$ GeV/c$^2$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{\text{cand}}$</th>
<th>$N_{\text{sig}}$</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow D^+ D^-$</td>
<td>993</td>
<td>126 ± 16</td>
<td>0.49 ± 0.03</td>
</tr>
<tr>
<td>$B^{0*} \rightarrow D^{*+} D^-$</td>
<td>1038</td>
<td>145 ± 16</td>
<td>0.49 ± 0.03</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+ D^-$</td>
<td>538</td>
<td>54 ± 11</td>
<td>0.37 ± 0.06</td>
</tr>
</tbody>
</table>

some background events to peak in the $m_{ES}$ signal region due to cross feed from other decay modes. The fraction of events in the signal Gaussian due to this peaking background is estimated to be $(7.0 \pm 6.2)\%$ for $B^0 \rightarrow D^{*\pm} D^{-}$ and $(13.6 \pm 6.2)\%$ for $B^0 \rightarrow D^{\mp} D^-$.

The increase in statistics since our last measurement [11] for $B^0 \rightarrow D^{\pm} D^{-}$ has allowed some refinements in the analysis. These include an improved treatment of signal probabilities as determined from the $m_{ES}$ spectrum, and additional floating parameters for the description of the background of the CP sample. We have also improved the event reconstruction, candidate selection, and tag-flavor determination. The present effective tagging efficiency is $Q = 30.5\%$ [19], a relative increase of 5% over the algorithm previously used.

We perform separate fits for each of the three CP samples. There are, in total, 54 floating parameters describing the $\Delta t$ distributions. These are $C_f$ and $S_f$ for signal (2) and background (2), the average mistag fractions $w_i$ and the differences $\Delta w_i$ between $B^0$ and $\bar{B}^0$ mistag fractions for each tag category $i$ (12), parameters for the signal $\Delta t$ resolution (7), parameters for background $\Delta t$ distribution (4) and resolution (3) of the $B_{\text{flav}}$ and $CP$ samples, and values for $w_i$ and $\Delta w_i$ for the prompt (12) and nonprompt (12) background of the $B_{\text{flav}}$ sample.

The likelihood fits yield the following results:

$$S_{D^{+}D^{-}} = -0.54 \pm 0.35(\text{stat}) \pm 0.07(\text{syst}),$$
$$C_{D^{+}D^{-}} = 0.09 \pm 0.25(\text{stat}) \pm 0.06(\text{syst}),$$
$$S_{D^{-}D^{+}} = -0.29 \pm 0.33(\text{stat}) \pm 0.07(\text{syst}),$$
$$C_{D^{-}D^{+}} = 0.17 \pm 0.24(\text{stat}) \pm 0.04(\text{syst}),$$
$$S_{D^{0}D^{0}} = -0.29 \pm 0.63(\text{stat}) \pm 0.06(\text{syst}),$$
$$C_{D^{0}D^{0}} = 0.11 \pm 0.35(\text{stat}) \pm 0.06(\text{syst}).$$

Projections of the fit onto $\Delta t$ for the three different CP samples are shown in Fig. 2, together with the raw CP asymmetry

$$A_{CP}^{\text{raw}}(\Delta t) = \frac{N_+(\Delta t) - N_-(\Delta t)}{N_+(\Delta t) + N_-(\Delta t)},$$

where $N_+(\Delta t)$ [$N_-(\Delta t)$] is the number of $B^0 \rightarrow D^{(\pm)\mp} D^\mp$ events with a $B^0$ ($\bar{B}^0$) tag.

The systematic uncertainties on $S_f$ and $C_f$ are separately evaluated for each of the decay modes. The dominant systematic uncertainty is the precision to which we are able to ascertain, using a Monte Carlo simulation, that the measurement method is unbiased (giving systematic uncertainties in the range 0.03–0.06). Other important uncertainties are due to the amount of peaking background and its potential CP asymmetry (0.01–0.02); assumptions on the $\Delta t$ resolution function (0.01–0.03); and potential differences between the mistag fractions for the $B_{\text{flav}}$ and $B_{CP}$ samples (0.01–0.02). Further sources of systematic uncertainty include the shape of the $m_{ES}$ distribution.

FIG. 2 (color online). Distribution of $\Delta t$ and fit projections for $B^{0*} \rightarrow D^{*+} D^-$ (left), $B^0 \rightarrow D^{-} D^{+}$ (middle), and $B^0 \rightarrow D^+ D^-$ (right) candidates in the signal region $m_{ES} > 5.27$ GeV/c$^2$ with a $B^0$ tag (a) or a $\bar{B}^0$ tag (b). The time-dependent CP asymmetry is also shown (c). The shaded areas represent the contributions from background events.

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detector misalignment, uncertainty in the beam energies, and the possible interference between the suppressed $\bar{b} \rightarrow \bar{u}c\bar{d}$ amplitude with the favored $b \rightarrow c\bar{u}d$ amplitude for some tagside decays [21]. The total systematic uncertainty is considerably smaller than in our previous measurement (0.10–0.14), primarily due to fewer assumptions about the background of the $CP$ sample.

In summary, we have performed a first measurement of $CP$ asymmetries in the decay $B^0 \rightarrow D^+ D^-$. We have also updated our $CP$ asymmetry measurements in $B^0 \rightarrow D^{*+} D^-$ and $B^0 \rightarrow D^{*-} D^+$, superseding our previously published results [11]. Since the dominant uncertainties are statistical, we anticipate improved precision with data collected in the future.

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[3] Charge conjugate reactions are included implicitly unless otherwise noted.