Measurement of Time-Dependent CP Asymmetries in $B^0 \to D^{(*)\pm}D^{\mp}$ Decays

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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 $(232 \pm 3) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ events in the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. We determine the time-dependent asymmetry parameters to be $S_{D^{*+}D^-} = -0.54 \pm 0.35 \pm 0.07$, $C_{D^{*+}D^-} = 0.09 \pm 0.25 \pm 0.06$, $S_{D^{*-}D^+} = -0.29 \pm 0.33 \pm 0.07$, $C_{D^{*-}D^+} = 0.17 \pm 0.24 \pm 0.04$, $S_{D^+D^-} = -0.29 \pm 0.63 \pm 0.06$, and $C_{D^+D^-} = 0.11 \pm 0.35 \pm 0.06$, 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 $B^0 \to (c\bar{c})K^{0(*)}$ decays [3] by the *BABAR* [4] and Belle [5] collaborations have precisely determined the parameter $\sin 2\beta$, where β is $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$. 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 $b \to c\bar{c}d$ 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 $\gamma = \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$ [9].

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

The selection of $B^0 \to D^{*+}D^-$ 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: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, or $K_S^0\pi^+\pi^-$. The D^- is reconstructed in the final states $K^+\pi^-\pi^-$ or $K_S^0\pi^-$. 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 π^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 π^0 daughter, which must be within 35 MeV/c^2 of the nominal D^0 mass. The $B^0 \to D^+D^-$ candidates are reconstructed solely through the decay of $D^{\mp} \to K^{\pm}\pi^{\mp}\pi^{\mp}$. 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 ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$), 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 $B^0 \to D^{*\pm}D^{\mp}$ and 9% in the case of $B^0 \to D^+D^-$.

For each candidate, we construct a likelihood variable $\mathcal{L}_{\text{mass}}$ from the differences between the reconstructed masses and the nominal masses of the D^{*+}, D^+, and D^0 candidates [11]. The $\mathcal{L}_{\text{mass}}$ 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 $\mathcal{L}_{\text{mass}}$ and the difference ΔE between measured energy of the B^0 candidate in the center-of-mass frame and half the center-of-mass energy, $\Delta E \equiv E_B^* - (\sqrt{s}/2)$, are used to reduce the combinatoric background. Maximum allowed values for both $-\ln\mathcal{L}_{\text{mass}}$ 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

$B^0 \to D^{(*)\pm} D^{\mp}$ candidate B_{CP}, we assign the remaining tracks in the event to the other B meson $B_{\rm tag}$. We compute a proper time difference Δt and its estimated uncertainty $\sigma_{\Delta t}$ from the reconstructed decay vertices of B_{CP} and $B_{\rm tag}$. The tracks assigned to $B_{\rm tag}$ are used to determine the $B_{\rm tag}$ flavor and thus the flavor of the B_{CP} meson at $\Delta t = 0$ [19]. Events are classified in one of six tag categories and must have an estimated probability w of assigning the wrong flavor to $B_{\rm tag}$ less than 45%.

Taking into account the uncertainty in the vertex position and tag flavor, the observed Δt distribution for $B^0 \to D^{(*)\pm} D^{\mp}$ signal events $F_{\pm}^{CP}(\Delta t)$ is described by

$$F_{\pm}^{CP}(\Delta t) = \Gamma(\Delta t')\{1 \mp \Delta w \pm (1-2w)[S_f \sin(\Delta m_d \Delta t') - C_f \cos(\Delta m_d \Delta t')]\} \otimes R(\Delta t - \Delta t'; \sigma_{\Delta t}), \quad (1)$$

where $\Gamma(\Delta t') = (e^{-|\Delta t'|/\tau_{B^0}})/(4\tau_{B^0})$ and the difference between the observed and true decay time differences $\Delta t - \Delta t'$ is described by the empirical resolution function $R(\Delta t - \Delta t'; \sigma_{\Delta t})$. This function is parametrized as the sum of three Gaussians, a "core" and a "tail" Gaussian, each with a width and mean proportional to $\sigma_{\Delta t}$, and an outlier Gaussian centered at zero with a width of 8 ps. The values of the B^0 lifetime τ_{B^0} and the $B^0 - \bar{B}^0$ oscillation frequency Δm_d 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 $S_{D^+D^-} = -\sin 2\beta; C_{D^+D^-} = 0$, and $C_{D^{*+}D^-} = -C_{D^{*-}D^+}$. Additionally, under these conditions we have $S_{D^{*+}D^-} = -X\sin(2\beta + \delta)$ and $S_{D^{*-}D^+} = -X\sin(2\beta - \delta)$, with $X = \sqrt{1 - C^2_{D^{*-}D^+}}$ and where δ is the difference of the strong phases for $B^0 \to D^{*+}D^-$ and $B^0 \to D^{*-}D^+$. If the magnitudes of the amplitudes for $B^0 \to D^{*+}D^-$ and $B^0 \to D^{*-}D^+$ 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 B^0 and $\bar{B}^0$, for each of the tag categories, and to increase the precision on the resolution function parameters, we simultaneously fit to a large sample $B_{\rm flav}$ of reconstructed neutral B decays to the flavor eigenstates $D^{(*)-}h^+$ ($h^+ = \pi^+$, ρ^+, and a_1^+) and $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$ [18].

The beam energy substituted mass $m_{\rm ES} \equiv [(s/2 + \vec{p}_i \cdot \vec{p}_B)^2/E_i^2 - \vec{p}_B^{\,2}]^{1/2}$, where the initial total e^+e^- four-momentum $(E_i, \vec{p}_i)$ and the B momentum $\vec{p}_B$ are defined in the laboratory frame, is used to determine the composition of the reconstructed $D^{(*)\pm}D^{\mp}$ samples. We use only the region $m_{\rm ES} > 5.2$ GeV$/c^2$, 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 $B^0 \to D^{*\pm}D^{\mp}$ samples, because the $D^{*\pm}$ candidate is usually a true $D^{*\pm}$ while the $D^{\pm}$ is more often incorrectly reconstructed. This flavor asymmetry is parametrized via values of C_f and S_f of the nonprompt background that are allowed to vary in the fit.

The Δt and $m_{\rm ES}$ distributions are fit simultaneously. The $m_{\rm ES}$ distribution, shown in Fig. 1, allows a determination of a signal probability for each event. In signal events, the values of $m_{\rm ES}$ accumulate near the nominal B^0 mass with a resolution of approximately 2.6 MeV$/c^2$. The fitted $m_{\rm ES}$ shapes consist of a Gaussian distribution for the signal and an ARGUS function [20] for the combinatoric background. The total number of selected candidates $N_{\rm cand}$ and the signal yield $N_{\rm sig}$ are shown in Table I. From detailed Monte Carlo simulations of generic B decays, we expect

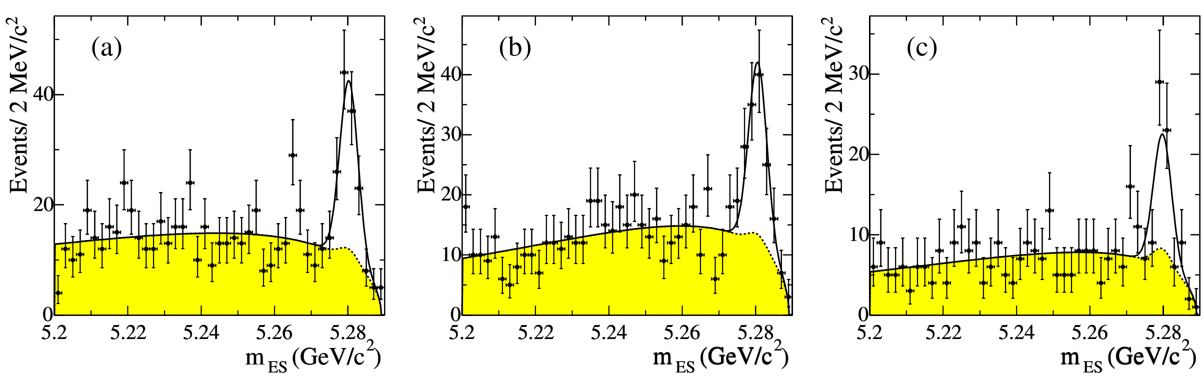

FIG. 1 (color online). Distribution of $m_{\rm ES}$ for (a) $\overset{(-)}{B}{}^0 \to D^{*+}D^-$, (b) $\overset{(-)}{B}{}^0 \to D^{*-}D^+$, and (c) $\overset{(-)}{B}{}^0 \to D^+D^-$ candidates. The shaded areas represent the contributions from background events. The dashed and solid curves describing the background and signal plus background distributions, respectively, are explained in the text.

TABLE I. Signal yield and purity for each of the samples. The purity is defined as the fraction of signal events $N_{\rm sig}/N_{\rm cand}$ in the region $m_{\rm ES} > 5.27\ {\rm GeV}/c^2$.

Sample	$N_{\rm cand}$	$N_{\rm sig}$	Purity
$\overset{(-)}{B}{}^0 \to D^{*-}D^+$	993	126 ± 16	0.49 ± 0.03
$\overset{(-)}{B}{}^0 \to D^{*+}D^-$	1038	145 ± 16	0.49 ± 0.03
$\overset{(-)}{B}{}^0 \to D^+D^-$	538	54 ± 11	0.37 ± 0.06

some background events to peak in the $m_{\rm ES}$ 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 $B^0 \to D^{*\pm}D^{\mp}$ and $(13.6 \pm 6.2)\%$ for $B^0 \to D^+D^-$.

The increase in statistics since our last measurement [11] for $B^0 \to D^{*\pm}D^{\mp}$ has allowed some refinements in the analysis. These include an improved treatment of signal probabilities as determined from the $m_{\rm ES}$ 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 Δt distributions. These are C_f and S_f for signal (2) and background (2), the average mistag fractions w_i and the differences Δw_i between B^0 and $\bar{B}^0$ mistag fractions for each tag category i (12), parameters for the signal Δt resolution (7), parameters for background Δt distribution (4) and resolution (3) of the $B_{\rm flav}$ and *CP* samples, and values for w_i and Δw_i for the prompt (12) and nonprompt (12) background of the $B_{\rm flav}$ sample.

The likelihood fits yield the following results:

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

Projections of the fit onto Δt for the three different *CP* samples are shown in Fig. 2, together with the raw *CP* asymmetry

$$A_{CP}^{\rm raw}(\Delta t) \equiv \frac{N_+(\Delta t) - N_-(\Delta t)}{N_+(\Delta t) + N_-(\Delta t)}, \quad (2)$$

where $N_+(\Delta t)$ $[N_-(\Delta t)]$ is the number of $B^0 \to D^{(*)\pm}D^{\mp}$ 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 Δt resolution function (0.01–0.03); and potential differences between the mistag fractions for the $B_{\rm flav}$ and B_{CP} samples (0.01–0.02). Further sources of systematic uncertainty include the shape of the $m_{\rm ES}$ distribution,

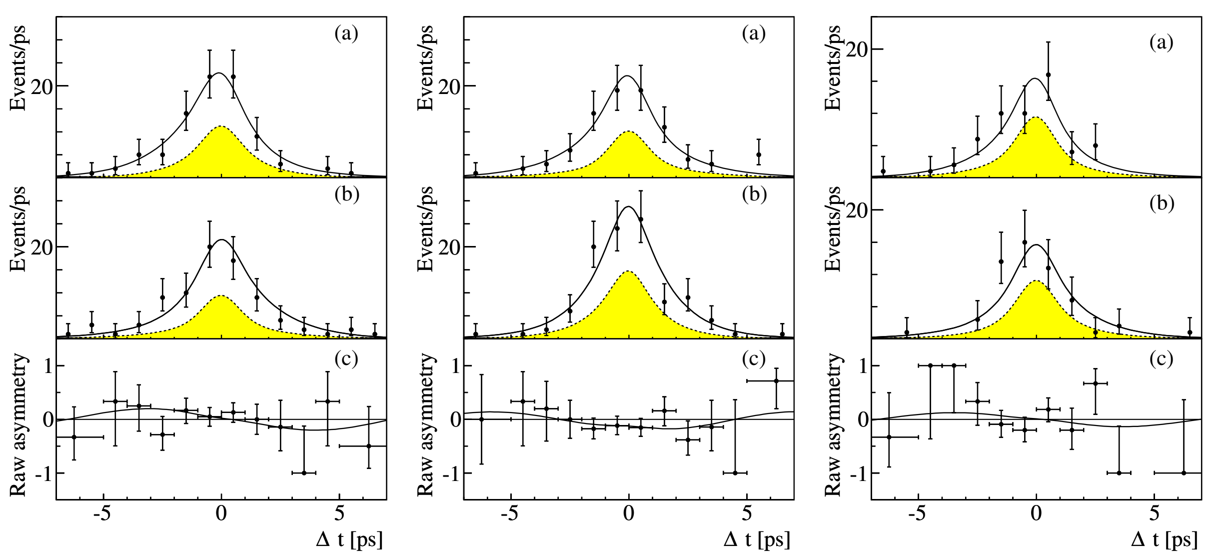

FIG. 2 (color online). Distribution of Δt and fit projections for $\overset{(-)}{B}{}^0 \to D^{*+}D^-$ (left), $\overset{(-)}{B}{}^0 \to D^{*-}D^+$ (middle), and $\overset{(-)}{B}{}^0 \to D^+D^-$ (right) candidates in the signal region $m_{\rm ES} > 5.27\ {\rm GeV}/c^2$ with a B^0 tag (a) or a $\bar{B}^0$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

detector misalignment, uncertainty in the beam energies, and the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the favored $b \to c\bar{u}d$ 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 $B^0 \to D^+D^-$. We have also updated our *CP* asymmetry measurements in $B^0 \to D^{*+}D^-$ and $B^0 \to D^{*-}D^+$, 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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