Measurement of the Branching Fraction, and Bounds on the CP-Violating Asymmetries, of Neutral B Decays to $D^{*\pm}D^{\mp}$

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We present measurements of the branching fraction and CP-violating asymmetries for neutral B decays to $D^{*\pm}D^{\mp}$. The measurement uses a data sample of approximately 88×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the SLAC PEP-II asymmetric-energy e^+-e^- collider. By fully reconstructing the $D^{*\pm}D^{\mp}$ decay products, we measure the branching fraction to be $(8.8 \pm 1.0 \pm 1.3) \times 10^{-4}$ and the time-integrated CP-violating asymmetry between the rates to $D^{*-}D^{+}$ and $D^{*+}D^{-}$ to be $\mathcal{A} = -0.03 \pm 0.11 \pm 0.05$. We also measure the time-dependent CP-violating asymmetry parameters to be $S_{-+} = -0.24 \pm 0.69 \pm 0.12$, $C_{-+} = -0.22 \pm 0.37 \pm 0.10$ for $B \to D^{*-}D^{+}$ and $S_{+-} = -0.82 \pm 0.75 \pm 0.14$, $C_{+-} = -0.47 \pm 0.40 \pm 0.12$ for $B \to D^{*+}D^{-}$. In each case, the first error is statistical and the second error is systematic.

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Within the standard model (SM) of electroweak interactions, CP violation is the result of a complex phase in V, the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. In the SM, the time-dependent CP-violating asymmetries in $B \to D^{*\pm}D^{\mp}$ decays are related to the angle $\beta \equiv \arg[-V_{cd}V^*_{cb}/V_{td}V^*_{tb}]$. We present a measurement of the branching fraction and a first measurement of CP-violating asymmetries in $B \to D^{*\pm}D^{\mp}$ decays using a sample of $(87.9 \pm 1.0) \times 10^6$ $B\overline{B}$ decays.

As recent measurements of the parameter $\sin 2\beta$ using the quark process $b \to c\bar{c}s$ have shown, CP is violated in the neutral B-meson system [2,3]. The measured asymmetries are currently consistent with the SM expectation [4]. In order to search for additional sources of CP violation from new physics processes, different quark decays such as $b \to c\bar{c}d$ must be examined.

In $b \to c\bar{c}d$ processes (for example, $B \to D^{*\pm}D^{\mp}$ decays; see Fig. 1), penguin contributions containing a different weak phase than the tree are not expected to be as highly suppressed as in $b \to c\bar{c}s$ decays; thus the relation of the time-dependent CP-violating asymmetries in $b \to c\bar{c}d$ decays to β is less exact than in decays such as $B^0 \to J/\psi K^0_S$. However, the contribution from additional weak phases in time-dependent asymmetries in $b \to c\bar{c}d$ due to purely SM processes is still expected to be fairly small, of order $\Delta\beta = 0.1$ in a simplified model [5,6]. A variety of beyond-SM processes, which can provide additional sources of CP violation, can greatly increase this contribution, up to $\Delta\beta \approx 0.6$ in some models [5].

CP-violating asymmetries in $B \to D^{*\pm}D^{\mp}$ are due to interference between the decay amplitudes and the $B^0\overline{B}^0$ mixing amplitude, as well as interference between tree and penguin decay amplitudes. The decay rate distributions $f^{\pm}$, where the superscript $+(-)$ refers to whether the tagging meson, $B_{\rm tag}$, was B^0 $(\overline{B}^0)$, are given by

$$f^{\pm} = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \tag{1}$$

where τ is the mean B^0 lifetime, Δm_d is the $B^0\overline{B}^0$ mixing frequency, and $\Delta t = t_{\rm reco} - t_{\rm tag}$ is the time elapsed between the B decay to $D^{*\pm}D^{\mp}$ and the decay of $B_{\rm tag}$.

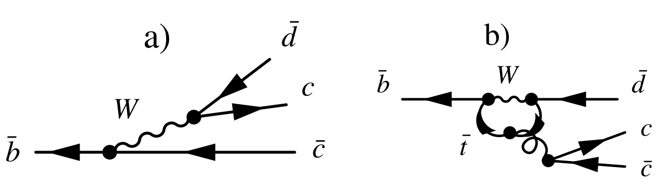

FIG. 1. The leading-order Feynman graphs for $B^0 \to D^{*\pm}D^{\mp}$ decay: (a) tree diagram and (b) penguin diagram.

Separate S and C parameters are fitted for the two decays $D^{*-}D^{+}$ and $D^{*+}D^{-}$, resulting in the four fitted CP-violation parameters $\{S_{-+}, C_{-+}, S_{+-}, C_{+-}\}$. The time-integrated asymmetry $\mathcal{A}$ between the rates to $D^{*-}D^{+}$ and $D^{*+}D^{-}$ is defined as

$$\mathcal{A} = \frac{N_{D^{*+}D^{-}} - N_{D^{*-}D^{+}}}{N_{D^{*+}D^{-}} + N_{D^{*-}D^{+}}}. \tag{2}$$

The states $D^{*-}D^{+}$ and $D^{*+}D^{-}$ are not CP eigenstates. The formalism of time evolution for non-CP eigenstate vector-pseudoscalar decays is given in Ref. [7]. In the case of equal amplitudes for $B \to D^{*-}D^{+}$ and $B \to D^{*+}D^{-}$, one expects that at tree level $C_{-+} = C_{+-} = 0$ and $S_{-+} = S_{+-} = -\sin 2\beta$.

A detailed description of the *BABAR* detector is presented in Ref. [8]. Charged-particle momenta are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer hexagonal-cell wire drift chamber (DCH) filled with a gas mixture of helium and isobutane. The SVT and DCH operate within a 1.5 T solenoidal field. Photons are detected and their energies are measured in a CsI(Tl) electromagnetic calorimeter. Muons are identified in the instrumented flux return, composed of resistive plate chambers and layers of iron that return the magnetic flux of the solenoid. A detector of internally reflected Cherenkov light (DIRC) is used for particle identification.

We select hadronic events using track multiplicity and event topology criteria. At least three reconstructed tracks, each with transverse momentum greater than 100 MeV$/c$, are required in the laboratory polar angle region $0.41 < \theta_{\rm lab} < 2.54$, where $\theta_{\rm lab} = 0$ is the e^--beam direction. The event must have a total measured energy in the laboratory frame greater than 4.5 GeV. In order to help reject non-$B\overline{B}$ background, the ratio of Fox-Wolfram moments H_2/H_0 is required to be less than 0.5 [9].

For reconstruction of $B \to D^{*\pm}D^{\mp}$ decays, all daughter tracks are required to pass within 10 cm in z and 1.5 cm in $r - \phi$ of the center of the beam crossing region. A track is identified as a charged kaon candidate using the Cherenkov angle measured in the DIRC and energy loss information (dE/dx) from the DCH and SVT.

Neutral pion candidates are composed of pairs of photons in the EMC. The photons must each have energy above 30 MeV, and their energy must sum to greater than 200 MeV. The π^0 candidates must have an invariant mass between 115 and 150 MeV$/c^2$. A mass-constrained fit is imposed on π^0 candidates, in order to improve resolution on the energy of reconstructed B candidates.

We require $K^0_S \to \pi^+\pi^-$ candidates to have an invariant mass within 15 MeV$/c^2$ of the nominal K^0_S mass [10]. The transverse flight distance of the K^0_S from the primary event vertex is required to be greater than 2 mm.

To form D candidates, kaon candidates are combined with other tracks, assumed to be pions, and π^0 candidates in the event. We reconstruct D^0 candidates in the four modes $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, and $K^0_S\pi^+\pi^-$, and D^+ candidates in the modes $K^-\pi^+\pi^+$ and $K^0_S\pi^+$. We require D^0 and D^+ 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. Mass-constrained fits are applied to D^0 and D^+ candidates in order to improve the measurement of the momentum of each D. The D^{*+} is then reconstructed in its decay to $D^0\pi^+$.

To select neutral B candidates from pairs of well-reconstructed $D^{*\pm}$ and $D^\mp$ candidates, we form a likelihood that includes all measured D^* and D masses:

$$\mathcal{L} = G(m_{D^\mp}, \sigma_{m_{D^\mp}}) \cdot G(m_{D^0}, \sigma_{m_{D^0}}) \cdot H(\delta m_{D^{*\pm}}, \sigma^{\rm core}_{\delta m_{D^{*\pm}}}, \sigma^{\rm tail}_{\delta m_{D^{*\pm}}}, f_{\rm core}), \qquad (3)$$

where the $D^{*\pm}$-D^0 mass difference is denoted by δm_{D^*}. Each G represents a Gaussian distribution, and H is the sum of two Gaussian distributions, for the core and tail of the $\delta m_{D^{*\pm}}$ distribution, respectively. For σ_{m_D}, we use values individually computed for each D candidate, while for $\sigma_{\delta m_{D^*}}$ we use values obtained from an inclusive D^* data sample: 0.35 MeV$/c^2$ for the core Gaussian distribution and 1.27 MeV$/c^2$ for the tail, and a core fraction ($f_{\rm core}$) of 51%. Likelihood cuts are set individually for each combination of $D^{*\pm}$ and $D^\mp$ decay modes, using a detailed Monte Carlo simulation, in order to maximize the expected signal sensitivity. In events with more than one B^0 candidate, we choose the candidate with the highest likelihood value.

A $B \to D^{*\pm}D^\mp$ candidate is characterized by two kinematic variables: the beam-energy substituted mass, $m_{\rm ES} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$, and the difference of the B candidate's measured energy from the beam energy, $\Delta E \equiv E_B^* - (\sqrt{s}/2)$. E_B^* (p_B^*) is the energy (momentum) of the B candidate in the e^+e^- center-of-mass frame and $\sqrt{s}$ is the total center-of-mass energy. The signal region in ΔE is defined to be $|\Delta E| < 18$ MeV. According to Monte Carlo simulations, the width of this region corresponds to approximately twice the signal resolution in ΔE.

The $B \to D^{*\pm}D^\mp$ decay candidates in the region $5.27 < m_{\rm ES} < 5.30\,{\rm GeV}/c^2$ and $|\Delta E| < 18\,$MeV are used to extract CP-violating asymmetries. A sideband, defined as $5.20 < m_{\rm ES} < 5.27\,{\rm GeV}/c^2$ and $|\Delta E| < 18\,$MeV, and a "large sideband," defined as $5.20 < m_{\rm ES} < 5.27\,{\rm GeV}/c^2$ and $|\Delta E| < 200\,$MeV, are used to extract various background parameters. The total numbers of selected events in the signal region, the sideband, and the large sideband are 197, 461, and 5187, respectively.

To extract the number of signal events above background, as well as the time-integrated CP asymmetry $\mathcal{A}$ [see Eq. (2)], we use an unbinned extended maximum likelihood fit to the $m_{\rm ES}$ distribution of the $D^{*\pm}D^\mp$ candidates, including the sideband. The $m_{\rm ES}$ distribution for the simultaneous fit to all the selected events is described by Gaussian distributions for the $D^{*+}D^-$ and $D^{*-}D^+$ signals, an ARGUS threshold function [11], and a Gaussian distribution to describe a small potential "peaking" background contribution (due to B decays such as $B^0 \to D^{*-}D_s^+$ that are similar to the signal modes). The end point of the ARGUS function is fixed to the average beam energy. From studies performed with both data and Monte Carlo simulations, the peaking contribution is estimated to be 12 ± 8 events. There are a total of four free parameters in the nominal fit: the shape and normalization of the background ARGUS function (2), the total $B \to D^{*\pm}D^\mp$ signal yield (1), and the CP asymmetry $\mathcal{A}$ (1). The total $B \to D^{*\pm}D^\mp$ signal yield is determined to be 113 ± 13 events. Figure 2 shows the $m_{\rm ES}$ distributions for $B \to D^{*-}D^+$ and $D^{*+}D^-$ candidates.

We use a Monte Carlo simulation of the *BABAR* detector to determine the efficiency for reconstructing the $B \to D^{*\pm}D^\mp$ signal. The efficiencies range from 6% to 18%, depending on the D decay modes. From these efficiencies and the total number of recorded $B\overline{B}$ pairs, and assuming the $\Upsilon(4S) \to B^0\overline{B}^0$ branching fraction to be 50%, we determine the branching fraction for neutral B to $D^{*\pm}D^\mp$ to be

$$\mathcal{B}(B \to D^{*\pm}D^\mp) = [8.8 \pm 1.0({\rm stat.}) \pm 1.3({\rm syst.})] \times 10^{-4}.$$

Systematic uncertainties on the branching fraction are dominated by uncertainty on the charged-particle tracking efficiency (8.9%), uncertainties on the branching fractions of the D decay modes (7.4%) [10], and the uncertainty on the amount of peaking background (6.8%). The total systematic uncertainty from all considered sources is 14.5%. The result is consistent with Ref. [12].

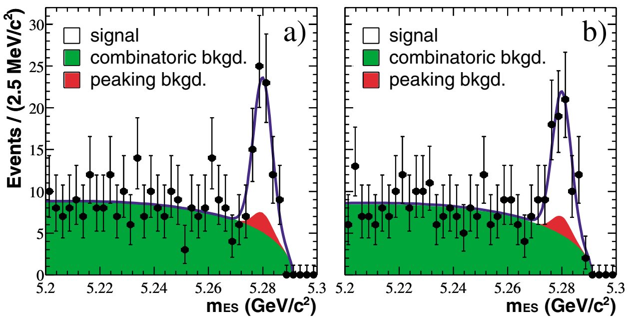

FIG. 2 (color). The $m_{\rm ES}$ distributions of (a) $B \to D^{*-}D^+$ and (b) $B \to D^{*+}D^-$ candidates with $|\Delta E| < 18$ MeV. The fit includes Gaussian distributions to model the signal and a small peaking background component, and an ARGUS function [11] to model the combinatoric background shape.

The fitted value for $\mathcal{A}$ is

$$\mathcal{A} = -0.03 \pm 0.11(\text{stat.}) \pm 0.05(\text{syst.}).$$

Systematic uncertainties on $\mathcal{A}$ are dominated by potential differences in the reconstruction efficiencies of positively and negatively charged tracks (0.04), and by uncertainty in the m_{ES} resolution for $B \to D^{*\pm}D^{\mp}$ signal events (0.03).

The method for extracting time-dependent CP asymmetries shares many of the techniques that are used for the measurement of $\sin 2\beta$ in charmonium decays in *BABAR* [2]. We use the same algorithms for determination of the flavor of the tagging B in the event, for determining the distance Δz between the $B \to D^{*\pm}D^{\mp}$ and tagging B decay vertices, and for performing the maximum likelihood fit. We also use the same data sample, B_{flav}, of fully reconstructed B decays to $D^{(*)\pm}(\pi^{\mp}, \rho^{\mp}, a_1^{\mp})$ to measure tagging performance and Δz resolution.

The B flavor-tagging algorithm relies on the correlation between the flavor of the b quark and the particle types, momenta, and charges of the remaining tracks in the event. A multivariate algorithm is used to separate events into four tagging categories and to determine tag flavor, the details of which are given in Ref. [2].

The elapsed time Δt between the $B \to D^{*\pm}D^{\mp}$ and tagging B decays is determined from the measured distance Δz between the z positions of the two B decay vertices and from the known boost of the e^+e^- system. A detailed description of the algorithm is given in Ref. [13]. We accept events with $\sigma_{\Delta t} < 2.5$ ps and $|\Delta t| < 20$ ps, where $\sigma_{\Delta t}$ is the error on Δt. We find that 93% of signal candidates satisfy these requirements.

We determine the time-dependent CP asymmetry parameters using a simultaneous unbinned maximum likelihood fit to the Δt distributions of the $D^{*\pm}D^{\mp}$ and B_{flav} candidates, including m_{ES} sideband samples for background parametrization. The Δt distribution for $D^{*\pm}D^{\mp}$ signal events is described by Eq. (1). The Δt distribution of B_{flav} events is also described by Eq. (1) with $C = 1$ and $S = 0$, where the superscript $+(-)$ refers to opposite (same) flavor events, comparing the reconstructed and tag B mesons. The mistag fraction w reduces the measured S and C coefficients by a factor of $1 - 2w$; this fraction is measured within the fit for each tagging category, utilizing the large B_{flav} sample. We convolve the Δt distribution with a resolution function modeled by the sum of three Gaussian distributions. The Δt resolution is dominated by the tag vertex z-position resolution and is parametrized in the same way as for the charmonium $\sin 2\beta$ measurement; this is described in detail in Ref. [13]. Both continuum and $B\overline{B}$ backgrounds are incorporated, each with a Δt distribution that is determined within the fit, using the m_{ES} sideband.

There are 37 fitted parameters in the combined fit for time-dependent CP asymmetries: the CP asymmetry parameters S_{-+}, C_{-+}, S_{+-}, and C_{+-} (4); the average mistag fractions w_i (4), and the differences Δw_i between B^0 and $\overline{B}^0$ mistag fractions (4), where i is one of the four tagging categories; parameters for the signal Δt resolution function (8); and parameters for background time dependence (6), Δt resolution (3), and mistag fractions (8). The B_{flav} sample constrains all parameters except the CP asymmetries. In the nominal fit, we fix $\tau_{B^0} = 1.542$ ps and $\Delta m_d = 0.489\ \mathrm{ps}^{-1}$ [10].

The time-dependent CP asymmetry fit to the $B \to D^{*\pm}D^{\mp}$ and B_{flav} samples yields

$$S_{-+} = -0.24 \pm 0.69(\text{stat.}) \pm 0.12(\text{syst.}), \qquad C_{-+} = -0.22 \pm 0.37(\text{stat.}) \pm 0.10(\text{syst.}),$$
$$S_{+-} = -0.82 \pm 0.75(\text{stat.}) \pm 0.14(\text{syst.}), \qquad C_{+-} = -0.47 \pm 0.40(\text{stat.}) \pm 0.12(\text{syst.}).$$

The correlation between S_{-+} and C_{-+} is 0.16, and between S_{+-} and C_{+-} is -0.01. Besides these correlations, the magnitudes of all correlations of the S and C parameters with any other free parameter are each less than 0.04. Figure 3 shows the Δt distributions and asymmetries in yields between B^0 and $\overline{B}^0$ tags for the $D^{*-}D^{+}$ and $D^{*+}D^{-}$ samples, each overlaid with a projection of the fit result.

Systematic uncertainties on the time-dependent CP asymmetry parameters are dominated by uncertainties in the amount, composition, and CP asymmetry of the background in the selected $D^{*\pm}D^{\mp}$ events (resulting in errors on the parameters ranging from 0.07–0.10); the parametrization of the Δt resolution function (0.01–0.06); possible differences between the B_{flav} and $D^{*\pm}D^{\mp}$ mistag fractions (0.01–0.04); the error on a small correction to the fitted asymmetries due to the limited size of the $D^{*\pm}D^{\mp}$ sample (0.01–0.02); and the potential presence of a small amount of CP-violating interference between leading order and doubly CKM-suppressed decay channels of the tagging B meson (0.01–0.03).

In summary, we have measured the branching fraction and CP-violating asymmetries for $B \to D^{*\pm}D^{\mp}$ decays. The small size of the $D^{*\pm}D^{\mp}$ sample currently precludes the observation of CP violation in this first measurement in this channel; however, with the addition of more data, future results may provide important information about sources of CP violation in the B-meson system.

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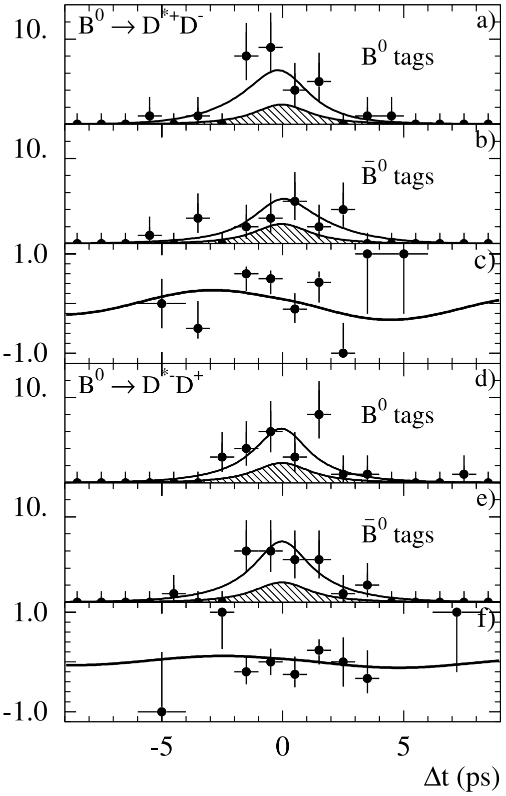

FIG. 3. Distributions of Δt for $B \to D^{*+}D^-$ candidates in the signal region with (a) a B^0 tag (N_{B^0}), (b) with a $\overline{B}^0$ tag ($N_{\overline{B}^0}$), and (c) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$. The solid curves are the fit projections in Δt. The shaded regions represent the background contributions. Figures (d), (e), and (f) contain the corresponding information for $D^{*-}D^+$.

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