Measurement of Time-Dependent $CP$ Asymmetries and the $CP$-Odd Fraction in the Decay $B^0 \to D^+ D^-$

We present a measurement of time-dependent CP-odd fraction in the decay $B^0 \rightarrow D^{*-}D^+$ using a data sample of $88 \times 10^6 \bar{B}B$ pairs collected by the BABAR detector at the PEP-II $B$ Factory at SLAC. We determine the $CP$-odd fraction to be $0.063 \pm 0.055^{\text{(stat)}} \pm 0.009^{\text{(syst)}}$. The time-dependent $CP$ asymmetry parameters $\text{Im}(\lambda_s)$ and $|\lambda_s|$ are determined to be $0.05 \pm 0.29^{\text{(stat)}} \pm 0.10^{\text{(syst)}}$ and $0.75 \pm 0.19^{\text{(stat)}} \pm 0.02^{\text{(syst)}}$, respectively. The standard model predicts these parameters to be $-\sin2\beta$ and 1, respectively, in the absence of penguin diagram contributions.

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The symmetry for combined charge conjugation (C) and parity (P) transformations is violated in B decays. Measurements of CP asymmetries by the BABAR [1] and BELLE [2] Collaborations established this effect and are compatible with the standard model expectation based on the current knowledge of the Cabibbo-Kobayashi-Maskawa [3] quark-mixing matrix. As a result of the interference between direct B decay and decay after flavor change, a CP-violating asymmetry is expected in the time evolution of the decays \( B^0 \to D^{*+} D^{*-} [4] \) within the framework of the standard model [5]. This CP asymmetry is related to \( \sin 2\beta \) when corrections due to theoretically uncertain penguin diagram contributions are neglected [6,7].

Penguin-induced corrections are predicted to be small in models based on the factorization approximation and heavy-quark symmetry; an effect of about 2% is predicted by Ref. [8]. A comparison of measurements of \( \sin 2\beta \) from \( b \to c\bar{s}s \) modes such as \( B^0 \to J/\psi K_S^0 [9] \) with that obtained in \( B^0 \to D^{*+} D^{*-} \) is an important test of these models and the standard model.

The \( B^0 \to D^{*+} D^{*-} \) mode is a pseudoscalar decay to a vector-vector final state, with contributions from three partial waves with different CP parities: even for the S and D waves, odd for the P wave. The CP-odd contribution is predicted to be about 6% in Refs. [10,11]. We present an updated [12] determination of the CP-odd fraction, \( R_\perp \), based on a one-dimensional time-integrated angular analysis. We also present a measurement of the time-dependent CP asymmetry, obtained from a combined analysis of the time dependence of flavor-tagged decays and the one-dimensional angular distribution of the decay products. The data used in this analysis were collected with the BABAR detector at the PEP-II storage ring. The BABAR detector is described in detail elsewhere [13]. The data sample corresponds to about \( 8.8 \times 10^6 e^+ e^- \to Y(4S) \to BB \) events.

\( B^0 \) mesons are exclusively reconstructed by combining two charged \( D^* \) candidates reconstructed in the modes \( D^{*+} \to D^0 \pi^+ \) and \( D^{*+} \to D^+ \pi^0 \). We include the \( D^{*+} D^{*-} \) combinations \( (D^0 \pi^+, D^0 \pi^-) \) and \( (D^0 \pi^+, D^- \pi^0) \), but not \( (D^+ \pi^0, D^- \pi^0) \) due to the smaller branching fraction and larger backgrounds. Prior to forming a \( B^0 \), the \( D^* \) candidates are subjected to a mass-constrained fit and vertex fit that includes the position of the beam spot.

The reconstructed \( D^0 \) and \( D^+ \) modes are \( D^0 \to K^- \pi^+ \), \( K^- \pi^+ \pi^0 \), \( K^- \pi^+ \pi^0 \), \( K^0_S \pi^+ \pi^0 \), and \( D^+ \to K^- \pi^+ \pi^0 \), \( K^0_S \pi^+ \pi^0 \), \( K^0_S \pi^+ \pi^0 \). The reconstructed mass of the \( D^0 \) (\( D^+ \)) candidates is required to be within 20 MeV/c\(^2\) of the nominal \( D^0 \) (\( D^+ \)) mass [14], except for \( D^0 \to K^- \pi^+ \pi^0 \), which has a looser requirement of 35 MeV/c\(^2\). The \( D \) candidates are subjected to a mass-constrained fit prior to forming \( D^* \) candidates.

Charged kaon candidates are required to be inconsistent with the pion hypothesis, as inferred from the Cherenkov angle measured by the Cherenkov detector and the specific ionization measured by the charged-particle tracking system. No particle identification requirements are made for the kaon from the decay \( D^0 \to K^- \pi^+ \). The reconstructed mass of \( K_S^0 \to \pi^+ \pi^- \) candidates is required to be within 25 MeV/c\(^2\) of the nominal \( K_S^0 \) mass. The angle between the flight direction and the momentum vector of the \( K_S^0 \) is required to be less than 200 mrad, and the transverse flight distance from the primary event vertex must be greater than 2 mm. A mass-constrained fit is applied to each \( K_S^0 \) candidate. Neutral pion candidates are formed from two photons detected in the electromagnetic calorimeter, each with energy above 30 MeV; the mass of the pair must be within 20 MeV/c\(^2\) of the nominal \( \pi^0 \) mass, and their summed energy must be greater than 200 MeV. A mass-constrained fit is applied to these \( \pi^0 \) candidates. The mass of the \( \pi^0 \) from \( D^{*+} \to D^+ \pi^0 \), however, is required to be within 35 MeV/c\(^2\) of the nominal \( \pi^0 \) mass, and the momentum in the Y(4S) frame in the interval \( |p^*| < 450 \text{ MeV}/c \), with no requirement on the photon energy sum.

We construct a mass likelihood \( \mathcal{L}_{\text{Mass}} \) that includes the mass and mass uncertainty of the \( D \) and \( D^* \) candidates. The \( D \) mass resolution is modeled by a Gaussian whose variance is determined on a candidate-by-candidate basis. The \( D^- \cdot D \) mass difference resolution is modeled by a double-Gaussian distribution whose parameters are determined from simulated events. The value of \( \mathcal{L}_{\text{Mass}} \) is used to select \( B^0 \) candidates, with a different requirement used for each \( D \) mode combination. In an event where more than one \( B^0 \) candidate is reconstructed, the candidate with the largest \( \mathcal{L}_{\text{Mass}} \) value is chosen.

The primary variables used to distinguish signal from background are the energy-substituted mass, \( m_{ES} = \sqrt{E_{\text{Beam}}^2 - p_B^2} \), and the difference of the \( B \) candidate energy from the beam energy, \( \Delta E = E_B - E_{\text{Beam}} \), where all variables are evaluated in the \( Y(4S) \) center-of-mass frame. The \( B^0 \) candidates are required to have \( -39 < \Delta E < 31 \text{ MeV} \) and \( m_{ES} > 5.2 \text{ GeV}/c^2 \).

To reject backgrounds from the \( e^+ e^- \to e\tau \) continuum process, events are required to have a ratio of second to zeroth Fox-Wolfram moments [15] of less than 0.6. We also require that the cosine of the angle between the thrust axis of the reconstructed \( B \) and the thrust axis of the rest of the event be less than 0.9.

After all selection criteria have been applied, a fit to the \( m_{ES} \) distribution using a Gaussian and an ARGUS function [16] for the signal and background, respectively, results in a signal yield of 156 ± 14(stat) events. In the region \( m_{ES} > 5.27 \text{ GeV}/c^2 \), the signal purity is 73%.

We perform a one-dimensional angular analysis to determine the fraction, \( R_\perp \), of the \( P \) wave, CP-odd component of the \( B^0 \to D^{*+} D^{*-} \) decay. In the transversity basis [5], the following three angles are defined: the angle \( \theta_1 \) between the momentum of the slow pion from the \( D^{*+} \) in the \( D^{*-} \) rest frame and the direction of flight of the \( D^{*-} \) in the \( B \) rest frame; the polar angle \( \theta_2 \) between the
normal to the $D^{*-}$ decay plane and the direction of flight of the slow pion from the $D^{*+}$ in the $D^{*+}$ rest frame; and the corresponding azimuthal angle $\phi_{tr}$. The time-dependent angular distribution of the decay products is given in Ref. [17].

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{tr}} = \frac{9}{32\pi} \left[ (1 - R_{\perp}) \sin^2\theta_{tr} \left( \frac{1 + \alpha}{2} I_0(\cos\theta_{tr}) + \frac{1 - \alpha}{2} I_0(\cos\theta_{tr}) + 2R_{\perp} \cos^2\theta_{tr} \times I_1(\cos\theta_{tr}) \right) \right],$$

where $R_{\perp} = M_0^2/(M_0^2 + M_1^2 + M_2^2)$, $\alpha = (M_0^2 - M_1^2)/(M_0^2 + M_2^2)$, and $(M_0, M_1, M_2)$ are the magnitudes of the amplitudes in the transversity basis. The three efficiency moments, $I_k$ ($k = 0, 1, \perp$), are defined as

$$I_k(\cos\theta_{tr}) = \int d\cos\theta_{t} d\phi_{tr} g_k(\theta_{t}, \phi_{tr}) \epsilon(\theta_{t}, \theta_{tr}, \phi_{tr}).$$

where $g_0 = 4\cos^2\theta_{t}\cos^2\phi_{tr}$, $g_1 = 2\sin\theta_{t}\sin^2\phi_{tr}$, $g_2 = \sin^2\theta_{t}$, and $\epsilon$ is the detector efficiency. The efficiency moments are determined using simulated events. The efficiency moments are fit to second-order even polynomials in $\cos\theta_{tr}$, the parameters of which are fixed in the subsequent likelihood fit to the $\cos\theta_{tr}$ distribution.

The measurement of $R_{\perp}$ is based on a combined unbinned maximum likelihood fit of the $\cos\theta_{tr}$ and $m_{ES}$ distributions. The probability density function (pdf) for the $m_{ES}$ distribution is given by the sum of ARGUS and Gaussian functions. The background shape is modeled by an even second-order polynomial in $\cos\theta_{tr}$. The pdf used for signal events is given by Eq. (1). The experimental resolution of $\theta_{tr}$ is not negligible and is accounted for by convolving the signal pdf with a double Gaussian. Also, the resolution of $\theta_{tr}$ has significant tails caused by misreconstructed events. The effect of these tails is accounted for by an additional term in the signal pdf. The parametrization of the $\theta_{tr}$ resolution is determined from simulations.

We categorize our events in three types: $D^{*+}D^{*-} \rightarrow (D^0\pi^+ + D^0\pi^-)$, $(D^0\pi^+ + D^0\pi^0)$, and $(D^0\pi^0, D^0\pi^-)$ because events with a neutral slow pion and events with a charged slow pion have different background levels, detection efficiencies, and $\cos\theta_{tr}$ resolutions. Thus, the parameters determined in the likelihood fit are three signal fractions, the $\cos\theta_{tr}$ background shape parameter, three $m_{ES}$ parameters ($\sigma$ and mean of the Gaussian, and $\kappa$ from the ARGUS function), and $R_{\perp}$. The fit to the data set yields a value of

$$R_{\perp} = 0.063 \pm 0.055{\text{(stat)}} \pm 0.009{\text{(syst)}}.$$  

(3)

The dependence of the detector efficiency on the decay angles can introduce a bias in the measured value of $R_{\perp}$. Including the efficiency explicitly in the time-dependent measurement of the characteristic decay rate: $\cos\theta_{tr}$ and then integrating over time and the angles $\theta_{t}$ and $\phi_{tr}$ results in the one-dimensional differential decay rate:

$$F_{\pm}(\Delta t) = e^{-\Delta t/\tau_{B^0}} \left\{ G \left( 1 - \frac{1}{2} \Delta D \right) + D \Sigma \sin(\Delta m_d \Delta t) + C \cos(\Delta m_d \Delta t) \right\},$$

where $\Delta t = t_{rec} - t_{tag}$ is the difference between the proper decay time of the reconstructed $B$ meson ($t_{rec}$) and of the tagging $B$ meson ($t_{tag}$), $\tau_{B^0}$ is the $B^0$ lifetime, and $\Delta m_d$ is the mass difference determined from the $B^0\rightarrow\bar{B}^0$ oscillation frequency. The dilution factor, $D = 1 - 2\omega$, where

![FIG. 1 (color online). Measured distribution of $\cos\theta_{tr}$ and fit results. The data points are from the region $m_{ES} > 5.27$ GeV/c$^2$ and the solid line is the projection of the fit result in the same region. The dotted line represents the background component.](131801-5)
\( \omega \) is the average mistag fraction, describes the effect of incorrect tags, and \( \Delta D \) accounts for possible differences in the mistag probabilities for \( B^0 \) and \( \bar{B}^0 \). The \( G, C, \) and \( S \) coefficients are defined as

\[
G = \frac{3}{4} \left[ (1 - R_\perp) \sin^2 \theta_\text{tr} + 2 R_\perp \cos^2 \theta_\text{tr} \right], \quad C = \frac{3}{4} \left[ (1 - R_\perp) \frac{1 - |\lambda_+|^2}{1 + |\lambda_+|^2} \sin^2 \theta_\text{tr} + 2 R_\perp \frac{1 - |\lambda_+|^2}{1 + |\lambda_+|^2} \cos^2 \theta_\text{tr} \right], \quad S = -\frac{3}{4} \left[ (1 - R_\perp) \frac{2 \text{Im}(\lambda_+)}{1 + |\lambda_+|^2} \sin^2 \theta_\text{tr} - 2 R_\perp \frac{2 \text{Im}(\lambda_+)}{1 + |\lambda_+|^2} \cos^2 \theta_\text{tr} \right].
\]

(5)

Because the two \( CP \)-even transversity amplitudes produce the same distribution in \( \cos \theta_\text{tr} \), we are sensitive only to \( \lambda_+ \), the appropriate average of \( \lambda_0 \) and \( \lambda_+ \):

\[
\text{Im}(\lambda_+) \left\{ \frac{\text{Im}(\lambda_+)}{1 + |\lambda_+|^2} M_\|^2 + \frac{\text{Im}(\lambda_0)}{1 + |\lambda_0|^2} M_0^2}{M_\|^2 + M_0^2} \right\},
\]

\[
1 - |\lambda_+|^2 \left\{ \frac{1 - |\lambda_0|^2}{1 + |\lambda_0|^2} M_\|^2 + \frac{1 - |\lambda_0|^2}{1 + |\lambda_0|^2} M_0^2}{M_\|^2 + M_0^2} \right\}, \quad (6)
\]

If angular acceptance effects are not taken into account and the \( CP \)-odd fraction is allowed to float in the fit, then no bias is seen in the resulting value of \( \lambda_+ \) based on simulations. Hence, a dedicated method to correct for detector efficiency is not required. The value of \( R_\perp \) obtained is therefore an effective value, which is not identical to the acceptance-corrected value from the time-integrated measurement.

The time interval \( \Delta t \) is calculated from the measured separation \( \Delta z \) between the decay vertex of the reconstructed \( B \) meson and the vertex of the flavor-tagging \( B \) meson along the collision axis. Events with a \( \Delta t \) uncertainty <2.5 ps and a measured \( |\Delta t| < 20 \) ps are accepted. The mistag fractions and \( \Delta t \) resolution functions are determined from a sample of neutral \( B \) decays to flavor eigenstates, \( B_{\text{flav}} \), as in the \( \sin 2 \beta \) measurement using charmonium decays [9]. Vertex reconstruction, the determination of \( \Delta t \), and the algorithms used for the determination of the flavor of \( B_{\text{tag}} \) are described in Refs. [9,18].

We determine the parameters \( \text{Im}(\lambda_+) \) and \( |\lambda_+| \) with a simultaneous unbinned maximum likelihood fit to the \( \Delta t \) distributions of the \( B_{\text{rec}} \) and \( B_{\text{flav}} \) tagged samples (Fig. 2). The \( \Delta t \) distribution of the \( B_{\text{flav}} \) sample evolves according to the known frequency for flavor oscillations in neutral \( B \) mesons. The observed magnitude of the \( CP \) asymmetry in the \( B_{\text{rec}} \) sample and the flavor oscillation in the \( B_{\text{flav}} \) sample are reduced by the same factor \( D \) due to flavor mistags. The \( \Delta t \) distributions for the \( B_{\text{rec}} \) and \( B_{\text{flav}} \) samples are both convolved with a common \( \Delta t \) resolution function. The \( \theta_\text{tr} \) angular resolution is accounted for in the same way as described previously. Events are assigned signal and background probabilities based on their \( m_{\text{ES}} \) values. Backgrounds are incorporated with an empirical description of their \( \Delta t \) distributions, containing prompt (zero lifetime) and nonprompt components convolved with a separate resolution function [9].

FIG. 2. From top to bottom: Number \( N_{B^0} \) (\( N_{\bar{B}^0} \)) of candidate events in the region \( m_{\text{ES}} > 5.27 \) GeV/\( c^2 \) with a \( B^0 \) (\( \bar{B}^0 \)) tag, and the raw asymmetry \( (N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0}) \), as functions of \( \Delta t \). The solid curves represent the result of the combined fit to the full sample. The shaded regions represent the background contributions.
\[ \text{Im}(\lambda_+) = 0.05 \pm 0.29(\text{stat}) \pm 0.10(\text{syst}). \] (7)

\[ |\lambda_+| = 0.75 \pm 0.19(\text{stat}) \pm 0.02(\text{syst}). \] (8)

The dominant sources of systematic uncertainty come from the variation of the value of \( |\lambda_+| \) [0.056 and 0.008, respectively, for \( \text{Im}(\lambda_+) \) and \( |\lambda_+| \)], and the level, composition, and \( CP \) asymmetry of the background (0.078 and 0.005).

If the \( B \to D^{*+}D^{*-} \) transition proceeds only through the \( b \to c\bar{d} \) tree amplitude, we expect that \( \text{Im}(\lambda_+) = -\sin2\beta \) and \( |\lambda_+| = 1 \). To test this hypothesis, we fix \( \text{Im}(\lambda_+) = -0.741 \) [9] and \( |\lambda_+| = 1 \) and repeat the fit. The observed change in the likelihood corresponds to 2.5 standard deviations (statistical uncertainty only).

In summary, we have reported a measurement of the \( CP \)-odd fraction and measurements of time-dependent \( CP \) asymmetries for the decay \( B^0 \to D^{*+}D^{*-} \). The measurement of \( R_{\perp} \) supersedes the previous BABAR result [12], with a factor of 3 reduction in the statistical uncertainty, and indicates that \( B^0 \to D^{*+}D^{*-} \) is mostly \( CP \) even. The time-dependent asymmetries are found to differ slightly from standard model predictions with penguin amplitudes ignored.

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*Also with Università di Perugia, Perugia, Italy.
†Also with Università della Basilicata, Potenza, Italy.
‡Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain.
§Deceased.

[4] Throughout this paper, flavor-eigenstate decay modes also imply their charge conjugate.
[16] Defined as \( A = \sqrt{x} \times \exp(\alpha x) \) where \( x = 1 - (m_{ES}^2/m_0)^2 \); \( m_{ES}^2 < m_0 \). The value of \( m_0 \) is fixed to 5.291 GeV/c^2. H. Albrecht et al., Z. Phys. C 48, 543 (1990).