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Permalink

<https://escholarship.org/uc/item/8km7d9d7>

Journal

Physical Review D, 74(9)

ISSN

2470-0010

Authors

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Publication Date

2006-11-01

DOI

10.1103/physrevd.74.091101

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Peer reviewed

Measurement of the branching fraction and time-dependent CP asymmetry in the decay $B^0 \rightarrow D^{*+} D^{*-} K_S^0$

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(Received 7 August 2006; published 1 November 2006)

We study the decay $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ using $(230 \pm 2) \times 10^6 B\bar{B}$ pairs collected by the BABAR detector at the PEP-II B factory. We measure a branching fraction $\mathcal{B}(B^0 \rightarrow D^{*+}D^{*-}K_S^0) = (4.4 \pm 0.4 \pm 0.7) \times 10^{-3}$ and find evidence for the decay $B^0 \rightarrow D^{*-}D_{s1}^+(2536)$ with a significance of 4.6σ . A time-dependent CP asymmetry analysis is also performed to study the possible resonant contributions to $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ and the sign of $\cos 2\beta$. Our measurement indicates that there is a sizable resonant contribution to the decay $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ from an unknown D_{s1}^+ state with large width, and that $\cos 2\beta$ is positive at the 94% confidence level under certain theoretical assumptions.

DOI: 10.1103/PhysRevD.74.091101

PACS numbers: 13.25.Hw, 11.30.Er, 12.15.Hh

In the standard model framework, CP violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]. Measurements of CP asymmetries by the BABAR [2] and Belle [3] collaborations have firmly established this effect in the decay $B^0 \rightarrow J/\psi K_S^0$ [4] and related modes that are governed by the $b \rightarrow c\bar{c}s$ transition. Since both B^0 and \bar{B}^0 mesons can decay to the final state $D^{*+}D^{*-}K_S^0$ and this process is dominated by a single weak phase, W -emission $b \rightarrow c\bar{c}s$ transition, a time-dependent CP violating asymmetry is expected.

In the approximation of neglecting penguin contributions for the decay $B^0 \rightarrow D^{*+}D^{*-}K_S^0$, there is no direct CP violation. The time-dependent decay rate asymmetry of $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ in the half Dalitz space $s^+ \leq s^-$ or $s^+ \geq s^-$ can be written as [5]

$$A(t) \equiv \frac{\Gamma_{\bar{B}^0} - \Gamma_{B^0}}{\Gamma_{\bar{B}^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0} \cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0} \sin 2\beta + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \times \sin(\Delta m_d t), \quad (1)$$

where $s^+ \equiv m^2(D^{*+}K_S^0)$ and $s^- \equiv m^2(D^{*-}K_S^0)$, Γ_{B^0} ($\Gamma_{\bar{B}^0}$) is the decay rate for B^0 (\bar{B}^0) to $D^{*+}D^{*-}K_S^0$ at a proper time t after production, Δm_d is the mass difference between the two B^0 mass eigenstates, and $\eta_y = -1(+1)$ for $s^+ \leq s^-$ ($s^+ \geq s^-$). The parameters J_0 , J_c , J_{s1} , and J_{s2} are the integrals over the half Dalitz phase space with $s^+ < s^-$ of the functions $|a|^2 + |\bar{a}|^2$, $|a|^2 - |\bar{a}|^2$, $\text{Re}(\bar{a}a^*)$, and $\text{Im}(\bar{a}a^*)$, where a and \bar{a} are the decay amplitudes of $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ and $\bar{B}^0 \rightarrow D^{*+}D^{*-}K_S^0$, respectively.

If the decay $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ has only a nonresonant component, the parameter $J_{s2} = 0$ and J_c is at the few percent level [5]. The CP asymmetry can be extracted by fitting the B^0 time-dependent decay distribution. The measured CP asymmetry is $\sin 2\beta$ multiplied by a factor of $2J_{s1}/J_0$ because the final state is an admixture of CP eigenstates with different CP parities. In this case, the value of the dilution factor $2J_{s1}/J_0$ is estimated to be large [5], similar to the decay $B^0 \rightarrow D^{*+}D^{*-}$.

The situation is more complicated if intermediate resonances such as D_{s1}^+ are present. In this case, the parameter

J_{s2} is nonzero and J_c can be large. The resonant components are expected to be dominated by two P -wave excited D_{s1} states [5]. One such state is $D_{s1}^+(2536)$ that has a narrow width and does not contribute much to J_{s2} . It can be easily removed by imposing a mass window requirement. The other D_{s1}^+ resonant state is predicted in the quark model [6] to have a mass above the $D^{*+}K_S^0$ mass threshold with a large width. In this case, the J_{s2} can be large. Therefore by studying the time-dependent asymmetry of $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ in two different Dalitz regions, the sign of $\cos 2\beta$ can be determined for a sufficiently large data set using the method described in Refs. [5,7,8]. This would allow the resolution of the $\beta \rightarrow \pi/2 - \beta$ ambiguity despite the large theoretical uncertainty of $2J_{s2}/J_0$. However, if the unknown P -wave D_{s1}^+ is the newly discovered $D_{s1}^+(2317)$ or $D_{s1}^+(2460)$, both of which lie below the $D^{*+}K_S^0$ mass threshold, then it will not contribute to the decay $B^0 \rightarrow D^{*+}D^{*-}K_S^0$. As a result, the time-dependent analysis of $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ not only has a potential to measure the sign of $\cos 2\beta$, but also can help us to understand the possible structure of the excited charm meson spectrum.

In this paper, we present an improved measurement of the branching fraction of the decay $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ [9] and a search for intermediate resonant decays. We also perform a time-dependent CP asymmetry analysis to study the possible resonant contributions and the sign of $\cos 2\beta$.

The data used in this analysis comprise (230 ± 2) million $Y(4S) \rightarrow B\bar{B}$ decays collected with the BABAR detector at the PEP-II storage rings. The BABAR detector is described in detail elsewhere [10]. We use a Monte Carlo (MC) simulation based on GEANT4 [11] to validate the analysis procedure and to study the relevant backgrounds.

We select $B^0 \rightarrow D^{*+}D^{*-}K_S^0$ decays by combining two oppositely charged D^* candidates reconstructed in the modes $D^{*+} \rightarrow D^0\pi^+$ and $D^{*-} \rightarrow D^+\pi^0$ with a K_S^0 candidate. We include the $D^{*+}D^{*-}$ combinations $(D^0\pi^+, \bar{D}^0\pi^-)$ and $(D^0\pi^+, D^-\pi^0)$, but not $(D^+\pi^0, D^-\pi^0)$ because of the small branching fraction and large backgrounds. To suppress the $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, \text{ and } c$) continuum background, we require the ratio of the second and zeroth order Fox-Wolfram moments [12] to be less than 0.5.

Candidates for D^0 and D^+ mesons are reconstructed in the modes $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^+ \pi^-$, and $D^+ \rightarrow K^- \pi^+ \pi^+$, by selecting track combinations with invariant mass within $\pm 2\sigma$ of the nominal D masses [13]. The resolution σ is measured using a large data sample of inclusive D decays. It is equal to $7.0 \text{ MeV}/c^2$ for $D^0 \rightarrow K^- \pi^+$ decays, $13.5 \text{ MeV}/c^2$ for $D^0 \rightarrow K^- \pi^+ \pi^0$ decays, $5.7 \text{ MeV}/c^2$ for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays, and $5.6 \text{ MeV}/c^2$ for $D^+ \rightarrow K^- \pi^+ \pi^+$ decays.

The K_S^0 candidates are reconstructed from two oppositely charged tracks with an invariant mass within $15 \text{ MeV}/c^2$ of the nominal K_S^0 mass [13], which is equivalent to slightly less than 5σ of the measured K_S^0 mass resolution. The χ^2 probability of the $\pi^+ \pi^-$ vertex fit must be greater than 0.1%. To reduce combinatorial background, we require the measured proper decay time of the K_S^0 to be greater than 3 times its uncertainty. Charged kaon candidates, except for the one in the decay $D^0 \rightarrow K^- \pi^+$, are required to be inconsistent with the pion hypothesis, as inferred from the Cherenkov angle measured by the Cherenkov detector and the ionization energy loss measured by the charged-particle tracking system [10]. Neutral pion candidates are formed from pairs of photons detected in the electromagnetic calorimeter [10], each with energy above 30 MeV. The mass of the pair must be within $30 \text{ MeV}/c^2$ of the nominal π^0 mass, and their summed energy is required to be greater than 200 MeV. In addition, a mass-constrained fit is applied to the π^0 candidate.

The D^0 and D^+ candidates are subject to a mass-constrained fit prior to the formation of the D^{*+} candidates. The slow π^+ from the D^{*+} decay is required to have a momentum in the $Y(4S)$ center-of-mass (CM) frame less than $450 \text{ MeV}/c$. The slow π^0 from the D^{*+} must have a momentum between 70 and $450 \text{ MeV}/c$ in the CM frame. No requirement on the photon-energy sum is applied to the π^0 candidates from the D^{*+} decays. The D^{*+} mass is required to be within $4 \text{ MeV}/c^2$ of the nominal D^{*+} mass, corresponding to slightly more than 3σ of the measured D^{*+} mass resolution.

For each $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ candidate, we calculate the difference of the B^0 candidate energy E_B^* from the beam energy E_{Beam}^* , $\Delta E \equiv E_B^* - E_{\text{Beam}}^*$, in the CM frame. In order to reduce the combinatorial background further, $|\Delta E|$ is required to be less than 25 MeV, which is equivalent to 2.5σ of the measured ΔE resolution.

The beam energy-substituted mass, $m_{\text{ES}} = \sqrt{E_{\text{Beam}}^{*2} - p_B^{*2}}$, where p_B^* is the B^0 candidate momentum in the CM frame, is used to extract the signal yield from the events satisfying the aforementioned selection. We select B^0 candidates with $m_{\text{ES}} \geq 5.23 \text{ GeV}/c^2$. On average we have 1.25 B^0 candidates per event. If more than one candidate is selected in an event, we retain the one with the smallest $|\Delta E|$. Studies using MC samples show that this procedure results in the selection of the correct B^0 candidate more than 95% of the time.

The total probability density function (PDF) is the sum of the signal and background components. The signal m_{ES} PDF is modeled by a Gaussian function and the combinatorial background is described by an ARGUS [14] function. MC studies show that there is a small peaking background from $B^+ \rightarrow \bar{D}^{*0} D^{*+} K_S^0$ in which a \bar{D}^{*0} originating from a \bar{D}^{*0} decay is combined with a random soft π^- to form a D^{*-} candidate. The peaking background is described by the same PDF as the signal, its fraction with respect to the signal yield is fixed to be 1.4%, determined from the MC simulation. An unbinned maximum likelihood (ML) fit to the m_{ES} distribution yields $201 \pm 17(\text{stat})$ signal events, where the mean and width of the signal Gaussian, as well as the ARGUS shape parameters, are allowed to float in the fit. In the region of $m_{\text{ES}} > 5.27 \text{ GeV}/c^2$, the signal purity is approximately 79%. The fit result is shown in Fig. 1(a).

To correct for variations in signal efficiency across the $D^{*+} D^{*-} K_S^0$ Dalitz plane, we calculate the branching fraction using the *sPlots* method [15]:

$$\mathcal{B} = \sum_i \frac{w_{\text{sig}}(m_{\text{ES},i})}{N_{B\bar{B}} \cdot \epsilon_i \cdot \mathcal{B}_{\text{sub}}}, \quad (2)$$

where the sum is over all events i , ϵ_i is the efficiency estimated from the simulated events in the vicinity of each data point in the Dalitz plane, \mathcal{B}_{sub} is the product of the branching fractions of the subdecays, and w_{sig} is an event-dependent signal weight that is defined as [15]

$$w_{\text{sig}}(m_{\text{ES},i}) = \frac{\sum_{j=1}^{N_s} V_{\text{sig},j} P_j(m_{\text{ES},i})}{\sum_{j=1}^{N_s} N_j P_j(m_{\text{ES},i})}, \quad (3)$$

which is calculated from the yield N_j of the j th PDF component P_j in the fit, and the covariance matrix elements $V_{\text{sig},j}$ between the signal yield N_{sig} and N_j . The N_s is the number of PDF components in the fit.

We investigate the production of intermediate resonances by examining the invariant mass distribution of the $D^{*\pm}$ and K_S^0 combinations. Figure 1(b) shows the projected distribution of $m(D^{*\pm} K_S^0)$ from $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ signal events after efficiency correction using the *sPlots* technique. A peak is seen at the value of $D_{s1}^+(2536)$ mass. We do not observe evidence of the $D_{s2}^+(2573)$. The events tend to cluster toward lower values of $m(D^{*\pm} K_S^0)$ (below about $2.9 \text{ GeV}/c^2$), in contrast to the phase-space model, as shown in Fig. 1(b).

To extract the signal yield of $B^0 \rightarrow D^{*-} D_{s1}^+(2536)$, we perform an unbinned ML fit to the $\Delta m = m(D^{*\pm} K_S^0) - m(D^{*\pm}) - m(K_S^0)$ distribution in the region $m_{\text{ES}} > 5.27 \text{ GeV}/c^2$ with a PDF given by the sum of a Gaussian shape for the signal and a threshold function $\Delta m^a \exp(b\Delta m)$ for the background. The mean and width of the signal Gaussian, as well as the background PDF parameters a and b , are allowed to float in the fit. The fit yields $12.3 \pm 4.0(\text{stat})$ signal events, as shown in Fig. 1(c).

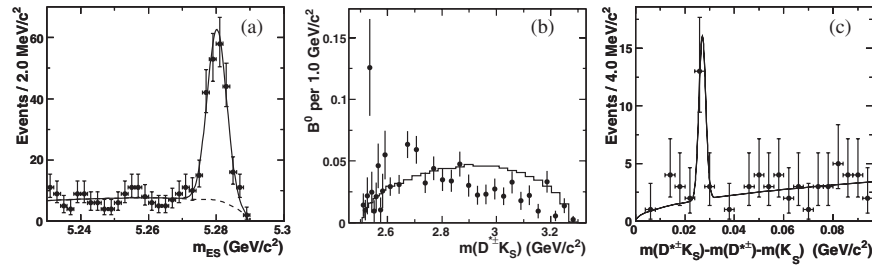


FIG. 1. (a) Measured distribution of m_{ES} . The solid line is the projection of the fit result. The dashed line represents the background components. (b) The efficiency-corrected yield of $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ signal events as a function of $m(D^{*\pm} K_S^0)$ in data (points) and in three-body phase-space signal MC (histogram) with an arbitrary normalization. Errors shown are statistical only. Note that the vertical axis shows events per unit $m(D^{*\pm} K_S^0)$, not the events in each bin. (c) Measured distribution of $m(D^{*+} K_S^0) - m(D^{*+}) - m(K_S^0)$ in the region $m_{ES} > 5.27 \text{ GeV}/c^2$. The solid line is the projection of the fit result.

The significance is estimated to be 4.6σ using the log-likelihood ratio between a fit with signal and another with none. The significance is dominated by the statistical uncertainty and has little contribution from the systematic uncertainty corresponding to the estimate of the signal yield. The fitted signal mean and width are consistent with the MC simulation. We repeat the fit in different Δm regions up to the kinematic limit, as well as using different background parametrizations. All of these give consistent signal yields of $D_{s1}^+(2536)$. We also examine the Δm distribution in the $m_{ES} \leq 5.27 \text{ GeV}/c^2$ region, and see no peaking structure.

The systematic uncertainties of the branching fraction measurements are dominated by the uncertainty of the charged track reconstruction efficiency (10.7%). Other sources also contribute to the systematic errors, such as the kaon particle identification efficiency (3.9%), π^0 reconstruction efficiency (3.5%), branching fractions of the D decays (5.8%), determination of the number of $B\bar{B}$ in the data sample (1.1%), event selection criteria (5.0%), and the estimate of the peaking background fraction (1.8%). The measured branching fraction is

$$\mathcal{B}(B^0 \rightarrow D^{*+} D^{*-} K_S^0) = (4.4 \pm 0.4 \pm 0.7) \times 10^{-3},$$

where the first uncertainty is the statistical and the second is systematic. Our result is in good agreement with the previous *BABAR* measurement [9]. We also measure the intermediate resonant decay branching fraction and find

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow D^{*-} D_{s1}^+(2536)) \times \mathcal{B}(D_{s1}^+(2536) \rightarrow D^{*+} K_S^0) \\ = (4.1 \pm 1.3 \pm 0.6) \times 10^{-4}. \end{aligned}$$

The fraction of the decay $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ through the intermediate $D_{s1}^+(2536)$ resonance is measured to be $0.092 \pm 0.024(\text{stat}) \pm 0.001(\text{syst})$.

We subsequently perform a time-dependent analysis using the event sample described previously. In the time-dependent analysis, we require that the invariant mass of the $D^{*\pm}$ and K_S^0 combination be larger than $2.55 \text{ GeV}/c^2$ in order to reject the narrow $D_{s1}^+(2536)$ resonant decays.

For the time-dependent CP analysis, we use information from the other B meson in the event to tag the initial flavor of the fully reconstructed $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ candidate. The decay rate $f_+(f_-)$ for a neutral B meson accompanied by a $B^0(\bar{B}^0)$ tag is given by

$$\begin{aligned} f_{\pm}(\Delta t) \propto e^{-|\Delta t|/\tau_{B^0}} \left\{ (1 \mp \Delta\omega) \pm (1 - 2\omega) \right. \\ \times \left[\eta_y \frac{J_c}{J_0} \cos(\Delta m_d \Delta t) - \left(\frac{2J_{s1}}{J_0} \sin 2\beta \right. \right. \\ \left. \left. + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \sin(\Delta m_d \Delta t) \right] \right\}, \end{aligned} \quad (4)$$

where $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the difference between the proper decay time of the reconstructed signal B meson (B_{rec}) and that of the tagging B meson (B_{tag}), τ_{B^0} is the B^0 lifetime, and Δm_d is the mass difference determined from the $B^0 - \bar{B}^0$ oscillation frequency [13]. The average mistag probability ω describes the effect of incorrect tags, and $\Delta\omega$ is the difference between the mistag rate for B^0 and \bar{B}^0 .

The technique used to measure the CP asymmetry is analogous to that used in previous *BABAR* measurements as described in Refs. [16,17]. We calculate the time interval Δt between the two B decays from the measured separation Δz between the decay vertices of B_{rec} and B_{tag} along the collision (z) axis [16]. The z position of the B_{rec} vertex is determined from the charged daughter tracks. The B_{tag} decay vertex is determined by fitting charged tracks not belonging to the B_{rec} candidate to a common vertex, employing constraints from the beam-spot location and the B_{rec} momentum [16]. Only events with a Δt uncertainty less than 2.5 ps and a measured $|\Delta t|$ less than 20 ps are accepted. We perform a simultaneous unbinned maximum likelihood fit to the Δt and m_{ES} distributions to extract the CP asymmetry. The signal PDF in Δt is given by Eq. (4) convolved with an empirical Δt resolution function [16]. Both the signal mistag probability and Δt resolution function are determined from a sample of neutral B decays to flavor eigenstates, B_{flav} .

The background Δt distributions are parametrized with an empirical description that includes zero and nonzero lifetime components [16]. We also allow the nonzero lifetime background to have effective CP asymmetries and let them float in the likelihood fit.

The fits to the data yield

$$\begin{aligned} \frac{J_c}{J_0} &= 0.76 \pm 0.18(\text{stat}) \pm 0.07(\text{syst}) \\ \frac{2J_{s1}}{J_0} \sin 2\beta &= 0.10 \pm 0.24(\text{stat}) \pm 0.06(\text{syst}) \\ \frac{2J_{s2}}{J_0} \cos 2\beta &= 0.38 \pm 0.24(\text{stat}) \pm 0.05(\text{syst}). \end{aligned} \quad (5)$$

Figure 2 shows the Δt distributions and asymmetries in yields between B^0 and \bar{B}^0 tags, overlaid with the projection of the likelihood fit result. The effective CP asymmetries in the background are found to be consistent with zero within statistical uncertainties. As a cross-check, we also repeat the fit by allowing the B^0 lifetime to float. The obtained B^0 lifetime is in a good agreement with its world average [13] within the statistical uncertainty.

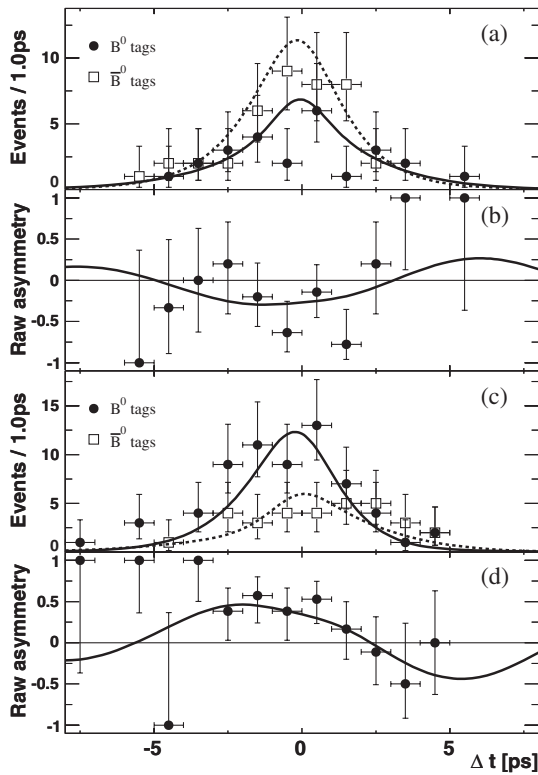


FIG. 2. (a) The distribution of Δt in the region $m_{ES} > 5.27 \text{ GeV}/c^2$ for B^0 (\bar{B}^0) tag candidates in the half Dalitz space $s^+ < s^-$ ($\eta_y = -1$). The solid (dashed) curve represents the fit projections in Δt for B^0 (\bar{B}^0) tags. (b) The raw asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of Δt , where N_{B^0} ($N_{\bar{B}^0}$) is the number of candidate with B^0 (\bar{B}^0) tag. (c) and (d) contain the corresponding information for the B^0 candidates in the other half Dalitz space $s^+ > s^-$ ($\eta_y = +1$).

The sources and estimates of systematic uncertainties are summarized in Table I. Since the signal reconstruction efficiency is not uniform over the entire Dalitz space, the different CP components may not have the same acceptance. Therefore the measured parameters will deviate slightly from their true values. We estimate the possible bias using the signal MC weighted according to the expected theoretical Dalitz distributions in Ref. [5]. Because of the lack of knowledge of the unknown D_{s1}^+ state, we vary its mass and width over a wide range. The largest bias of the measured parameters J_c/J_0 , $(2J_{s1}/J_0) \sin 2\beta$, and $(2J_{s2}/J_0) \cos 2\beta$ are taken as the corresponding systematic uncertainties on the acceptance effect.

The other systematic uncertainties arise from the possible backgrounds that tend to peak under the signal and their CP asymmetries, the assumed parametrization of the Δt resolution function, the possible differences between the B_{flav} and $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ tagging performances, knowledge of the event-by-event beam-spot position, and the possible interference between the suppressed $\bar{b} \rightarrow \bar{u} c \bar{d}$ amplitude and the favored $b \rightarrow c \bar{u} d$ amplitude for some tag-side decays [18]. They also include the systematic uncertainties from the finite MC sample used to verify the fitting method. All the systematic uncertainties are found to be much smaller than the statistical uncertainties.

In summary, we have reported an improved branching fraction measurement of the decay $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ that supersedes the previous *BABAR* result [9]. We also find evidence for the decay $B^0 \rightarrow D^{*-} D_{s1}^+(2536)$ with 4.6σ significance. A time-dependent CP asymmetry analysis has also been performed. The measured J_c/J_0 is significantly different from zero, which may indicate that there is a sizable resonant contribution to the decay $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ from a unknown D_{s1}^+ state with large width, according to Ref. [5]. We measure that $(2J_{s2}/J_0) \cos 2\beta = 0.38 \pm 0.24(\text{stat}) \pm 0.05(\text{syst})$. Under the assumption that there is a significant broad resonant contribution to the decay $B^0 \rightarrow D^{*+} D^{*-} K_S^0$, it implies that the sign of $\cos 2\beta$ is preferred to be positive at the 94% confidence level if the theoretical parameter J_{s2}/J_0 is positive, as predicted in Ref. [5].

TABLE I. Sources of systematic error on J_c/J_0 (column I), $(2J_{s1}/J_0) \sin 2\beta$ (column II), and $(2J_{s2}/J_0) \cos 2\beta$ (column III).

Source	I	II	III
Acceptance	0.060	0.040	0.030
Peaking backgrounds	0.009	0.016	0.002
Δt resolution function	0.015	0.006	0.008
Mistag fraction differences	0.016	0.015	0.015
Detector Alignment	0.005	0.015	0.015
$\Delta m_d, \tau_B$	0.001	0.001	0.001
MC statistics	0.021	0.032	0.032
Others	0.005	0.004	0.005
Total	0.068	0.058	0.050

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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 (U.S.A.), 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), Marie Curie EIF (European Union), the A.P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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