Evidence for the Rare Decay $B^+ \to D_s^+ \pi^0$

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We have searched for the rare decay $B^+ \to D_s^+ \pi^0$. The analysis is based on a sample of 232×10^6 $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector at the SLAC PEP-II e^+e^- storage ring. We find

19.6 signal events, corresponding to a significance of 4.7σ. The extracted signal yield including statistical and systematic uncertainties is $20.1^{+6.8+0.4}_{-6.0-1.5}$, and we measure $\mathcal{B}(B^+ \to D_s^+ \pi^0) = (1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.2) \times 10^{-5}$, where the first uncertainty is statistical, the second is systematic, and the last is due to the uncertainty on the D_s^+ decay and its daughter decay branching fractions.

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Significant *CP* violation in the standard model (SM) of particle physics is induced by the 3×3 unitary Cabibbo-Kobayashi-Maskawa (CKM) quark flavor mixing matrix V [1] but is considered too small to produce the observed matter-antimatter asymmetry in the Universe. Hence, New Physics contributions are searched for by testing unitarity conditions for V in a variety of processes. In these tests the parameter $\gamma = \arctan(\bar{\eta}/\bar{\rho})$, where $\bar{\rho} + i \cdot \bar{\eta} \equiv -V_{ud}V_{ub}^*/V_{cd}V_{cb}^*$, plays a crucial role as it is extracted from processes dominated by SM tree amplitudes and can be compared with γ obtained from constraints dominated by loop amplitudes which are mutually sensitive to New Physics. Constraints on $\sin(2\beta + \gamma)$ ($\beta = \arctan[\bar{\eta}/(1 - \bar{\rho})]$) can be obtained from the measurement of time-dependent decay rates in B^0, $\bar{B}^0 \to D^- \pi^+$, or $D^{*-}\pi^+$ [2], where CKM-favored ($\propto V_{cb}^* V_{ud}$) and CKM-suppressed ($\propto V_{ub}^* V_{cd}$) processes interfere [3]. First measurements have been recently published [4].

The ratio $r = |A(B^0 \to D^+\pi^-)/A(B^0 \to D^-\pi^+)|$ of decay amplitudes is required in order to constrain $\sin(2\beta + \gamma)$ from $B^0 \to D^{\mp}\pi^{\pm}$. The amplitude $A(B^0 \to D^-\pi^+)$ is well known from the precisely measured branching fraction $\mathcal{B}(B^0 \to D^-\pi^+)$ [5]. With the currently available data samples the measurement of the CKM-suppressed decay $B^0 \to D^+\pi^-$ is not feasible due to the presence of a very large background from the CKM-favored decay $\bar{B}^0 \to D^+\pi^-$. This problem could be avoided with the measurement of the isospin related decay $B^+ \to D^+\pi^0$ which is currently out of reach due to its small branching fraction ($<10^{-6}$). However, r can be related to $\mathcal{B}(B^0 \to D_s^+\pi^-)$ [3] as well as to $\mathcal{B}(B^+ \to D_s^+\pi^0)$ with the use of SU(3) flavor symmetry. Tree and W-exchange amplitudes contribute to $B^0 \to D^+\pi^-$, whereas only a tree amplitude contributes to $B^{0(+)} \to D_s^+\pi^{-(0)}$. The exchange amplitude is expected to be small and has been estimated at 10%–15% of the total decay amplitude [6]. This estimate uses $\mathcal{B}(B^0 \to D_s^- K^+)$ [7] and neglects final-state rescattering interactions. Nonfactorizable SU(3)-breaking effects are hard to quantify and often assumed to not exceed the 30% level [4] consistent with the spread of theoretical estimates of r [8].

The branching fraction $\mathcal{B}(B^0 \to D_s^+\pi^-)$ has been measured by the Belle and *BABAR* Collaborations [7]. The decay $B^+ \to D_s^+\pi^0$ provides an independent estimate of r, though not as precise as the one from $B^0 \to D_s^+\pi^-$ due to the smaller branching fraction and reconstruction efficiency. It also represents a significant background source for analyses of other decays related to the extraction of $\sin(2\beta + \gamma)$, such as $B^+ \to D^+\pi^0$, $D_s^{*+}\pi^0$, or $B^0 \to D_s^+\rho^-$. For $\mathcal{B}(B^+ \to D_s^+\pi^0)$ only an upper limit of 2×10^{-4} at 90% confidence level [9] has been established so far. Here, we present evidence for the decay $B^+ \to D_s^+\pi^0$ and a measurement of its branching fraction.

The analysis uses a sample of 232×10^6 $\Upsilon(4S)$ decays into $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy B factory. The *BABAR* detector is described in detail elsewhere [10]. We use the GEANT4 [11] Monte Carlo (MC) software to simulate interactions of particles traversing the *BABAR* detector.

We select events with a minimum of three reconstructed tracks. To reject $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum events, the ratio of the second and zeroth order Fox-Wolfram moments [12], determined from all clusters in the electromagnetic calorimeter with an energy above 30 MeV and all tracks, must be less than 0.5.

We reconstruct D_s^+-meson candidates in the decay modes $D_s^+ \to \phi\pi^+$, $K_S^0 K^+$, and $\bar{K}^{*0}K^+$, with $\phi \to K^+K^-$, $K_S^0 \to \pi^+\pi^-$, and $\bar{K}^{*0} \to K^-\pi^+$. Charged kaon (pion) candidates are required to fulfill kaon (pion) selection criteria with high efficiency (80%–95%) and small misidentification probability (1%–10%) depending on the selector used [10,13]. K_S^0 candidates, reconstructed from two oppositely charged tracks, are required to have a measured flight distance from the primary interaction point that is at least 3 times the measurement error and an invariant $\pi^+\pi^-$ mass of $\pm 15~\text{MeV}/c^2$ around the Particle Data Group (PDG) mass [5]. ϕ ($\bar{K}^{*0}$) candidates are required to have an invariant K^+K^- ($K^-\pi^+$) mass of ± 30 (± 75) MeV/c^2 around the PDG mass [5]. D_s^+ candidates are required to have invariant masses $m_{D_s^+}$ within $60~\text{MeV}/c^2$ around $m_{D_s^+}^{\text{PDG}} = 1968.3~\text{MeV}/c^2$ [5]. We further define a signal region by requiring $|m_{D_s^+} - m_{D_s^+}^{\text{PDG}}| \lesssim 2\sigma$, where σ has been determined from the MC simulation and found to be 4.7 (5.0) MeV/c^2 for $D_s^+ \to \phi\pi^+$ ($\bar{K}^{*0}K^+$) and $6.0~\text{MeV}/c^2$ for $K_S^0 K^+$. For background studies, sidebands are defined by $|m_{D_s^+} - m_{D_s^+}^{\text{PDG}}| \gtrsim 3\sigma$. To suppress background from $B^+ \to D_s^*\pi^0$ events we restrict the D_s^+ momentum in the $\Upsilon(4S)$ system to lie within $[2.073, 2.550]~\text{GeV}/c$. Decay daughters from $\bar{K}^{*0}$, K_S^0, D_s^+, and B^+ candidates are constrained to a geometric vertex.

Neutral pions are reconstructed in $\pi^0 \to \gamma\gamma$ requiring a π^0 laboratory energy above 200 MeV and an invariant mass $m_{\gamma\gamma} \in [115, 150]~\text{MeV}/c^2$. To improve the momentum resolution a kinematic fit is applied to the daughter photons constraining $m_{\gamma\gamma}$ to the PDG π^0 mass [5].

Charged B-meson candidates are obtained by combining D_s^+ and π^0 candidates and are identified by two kinematic variables. The first is the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(\frac{s/2+\mathbf{p}_0\cdot\mathbf{p}_B}{E_0})^2 - \mathbf{p}_B^2}$, where E_0 and $\mathbf{p}_0$ are the energy, respectively, the momentum of the e^+e^- system, $\mathbf{p}_B$ the B^+ candidates momentum, and $\sqrt{s}$ the e^+e^- center-of-momentum (c.m.) energy. The second variable is $\Delta E = E_B^* - \sqrt{s}/2$, where E_B^* is the B^+ candidate's c.m. energy. For signal events the $m_{\rm ES}$ distribution is centered at the B-meson mass with a resolution of about 2.5 MeV$/c^2$, and the ΔE distribution has a maximum close to zero with a resolution of about 50 MeV. The $m_{\rm ES}$ and ΔE signal distributions are both asymmetric with a tail towards smaller values due to energy leakage in the electromagnetic calorimeter when reconstructing $\pi^0 \to \gamma\gamma$. The signal region is defined by $m_{\rm ES} \in [5.2, 5.3]$ GeV$/c^2$ and $|\Delta E| < 0.2$ GeV. In a small fraction of events (<5%) multiple signal candidates are found. In this case, the candidate with the smallest deviation of $m_{\gamma\gamma}$ from the PDG π^0 mass [5] is retained. If multiple candidates still remain, the final candidate is selected randomly.

A neural network (NN) [14] built from event topology and invariant mass variables is used to suppress continuum background, mainly coming from $e^+e^- \to c\bar{c}$. The NN variables are: (1) thrust [15] and (2) sphericity [16], both calculated from all tracks and neutral candidates in the event; (3) the cosine of the angle between the thrust axis of the B^+ candidate and the thrust axis calculated from all tracks and neutral candidates not belonging to the B^+ candidate; (4) the energy flow moments L_0 and L_2 [17]; (5) the cosine of the angle between the thrust axis of the B^+ candidate in the $\Upsilon(4S)$ system and the beam axis; (6) the cosine of the angle between the B^+ momentum vector in the $\Upsilon(4S)$ system and the beam axis; (7) the invariant mass of the corresponding ϕ, K_S^0, and $\bar{K}^{*0}$ candidate; (8) the cosine of the helicity angle between the ϕ ($\bar{K}^{*0}$) momentum in the D_s^+ rest frame and the momentum vector of the ϕ ($\bar{K}^{*0}$) decay daughter in the ϕ ($\bar{K}^{*0}$) rest system. The NN has been trained on simulated $B^+ \to D_s^+\pi^0$ and simulated continuum events. With an optimized NN cut, signal events are retained with an efficiency of order 60%, while about 96% (70%) of continuum events (nonsignal B decays) are rejected.

We extract the signal yield with a two-dimensional extended unbinned maximum likelihood fit in the variables $m_{\rm ES}$ and ΔE where we combine the three D_s^+ modes. The extended log-likelihood function used is given by

$$\ln\mathcal{L} = -\sum_{j=1}^{3} n_j + \sum_{i=1}^{N} \ln\sum_{j=1}^{3} n_j P_j(\mathbf{x}_i),$$

where the sum is over $i = 1, \ldots, N = 154$ selected events inside the signal region and the n_j represent the three yields after the aforementioned selection: (1) signal (SIG), (2) combinatorial background (CBG) that comes from random combinations of tracks and π^0 candidates, mainly from continuum events, and (3) B background peaking at $m_{\rm ES}$ values close to the nominal B-meson mass and at negative ΔE values (PBG) mostly due to $B^+ \to D_s^*\pi^0$. $P_j(\mathbf{x}_i)$ is the product of probability density functions (PDF's) of candidate i in the variables $\mathbf{x}_i = (m_{\rm ES}, \Delta E)_i$: $P_j(\mathbf{x}_i) = P_{j,1}(m_{{\rm ES}i})P_{j,2}(\Delta E_i)$. To take into account correlations observed in the simulation we allow in some cases for a functional dependence of the PDF parameters of $P_{j,1}(m_{\rm ES})$ on ΔE, or of $P_{j,2}(\Delta E)$ on $m_{\rm ES}$.

The signal PDF has been determined from the MC simulation. The $m_{\rm ES}$ PDF is described by an asymmetric Gaussian $G(m_{\rm ES}, \mu, \sigma)$ with $\sigma = \sigma_L(\sigma_R)$ for $x - \mu < 0(\geq 0)$. The parameters μ, σ_L, and σ_R are given by second order polynomials in ΔE in order to take into account a nonlinear correlation between ΔE and $m_{\rm ES}$ observed in the MC simulation. The ΔE signal PDF is described by a Crystal Ball function [18].

The CBG PDF in $m_{\rm ES}$ is parametrized by $f(m_{\rm ES}) = m_{\rm ES}\sqrt{1 - (\frac{m_{\rm ES}}{m_{\rm ES}^{\rm max}})^2}\exp(\xi[1 - (\frac{m_{\rm ES}}{m_{\rm ES}^{\rm max}})^2])$ [19], where $m_{\rm ES}^{\rm max}$ is the kinematic limit $\sqrt{s}/2$ fixed at 5.2895 GeV$/c^2$. The CBG PDF in ΔE is described by a second order polynomial ${\rm Pol}(\Delta E) = 1 + p_1\Delta E + p_2(m_{\rm ES})\Delta E^2$. To take into account a possible correlation between ΔE and $m_{\rm ES}$ of order 5%, the parameter p_2 depends linearly on $m_{\rm ES}$. The parameters ξ, p_1, and p_2 are determined from the likelihood fit on data.

The PBG component is modeled by simulated $B^+ \to D_s^*\pi^0$ MC events. The ΔE PDF is described by a Gaussian. As in the case for the signal, the $m_{\rm ES}$ PDF is described by an asymmetric Gaussian, and its parameters μ, σ_L, and σ_R are given by second order polynomials in ΔE. Additional backgrounds that peak at negative ΔE values are due to B-meson decays such as $B^0 \to D^{(*)-}\rho^+$ with a similar decay topology and kinematics as the signal decay. This kind of background is found to be well described by the $B^+ \to D_s^*\pi^0$ PDF. Another sizeable background source from the decay $B^0 \to D_s^+\rho^-$ is not well described by the $B^+ \to D_s^*\pi^0$ PDF. However, the expected number of $B^0 \to D_s^+\rho^-$ events estimated from Ref. [20] is small compared to the other peaking background sources. As a consequence, we do not introduce an additional PDF and estimate the fit bias introduced in this way from a dedicated MC simulation study.

The fit has been validated on samples using signal and peaking background events from the full MC simulation. From the likelihood fit we find the yield estimators $\hat{n}_{\rm SIG} = 19.6^{+6.8}_{-6.0}$, $\hat{n}_{\rm CBG} = 116.7 \pm 12.5$, and $\hat{n}_{\rm PBG} = 17.7 \pm 6.9$, the latter being consistent with the expectation from the MC simulation. The signal significance is determined from a MC simulation containing no signal events, where we use the background yields and the CBG parameters as measured by the fit on data. We include the statistical uncertainties on the CBG PDF parameters and the uncertainties on the background yields and find a probability to observe at least $\hat{n}_{\rm SIG}$ events of 1.5×10^{-6} corresponding to a 4.7σ significance. Fit projections for ΔE and $m_{\rm ES}$ are shown in

Fig. 1 where background contributions are suppressed by a cut on the signal-to-background likelihood ratio where the cut values are determined from MC calculations by maximizing the ratio $\hat{n}_{\rm SIG}/\sqrt{\hat{n}_{\rm SIG} + \hat{n}_{\rm CBG} + \hat{n}_{\rm PBG}}$.

We assume $\mathcal{B}(\Upsilon(4S) \to B^+B^-) = \mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)$ and calculate the branching fraction from $\mathcal{B}(B^+ \to D_s^+\pi^0) = \hat{n}_{\rm SIG}/(N_{B\bar{B}}\sum_k \varepsilon_k \mathcal{B}_k)$, where $N_{B\bar{B}}$ is the number of charged and neutral B-meson pairs, ε_k is the signal efficiency, and $\mathcal{B}_k$ is the branching fraction of D_s^+ decay mode k ($k = \phi\pi^+, K_S^0K^+, \bar{K}^{*0}K^+$) including their daughter decay modes taken from Ref. [5] and scaled to the recent result [21] for $D_s^+ \to \phi\pi^+$ ($\mathcal{B}_{\phi\pi^+} = 2.3\%$, $\mathcal{B}_{K_S^0K^+} = 1.7\%$, $\mathcal{B}_{\bar{K}^{*0}K^+} = 2.9\%$). Signal efficiencies ($\varepsilon_{\phi\pi^+} = 9.7\%$, $\varepsilon_{K_S^0K^+} = 9.1\%$, $\varepsilon_{\bar{K}^{*0}K^+} = 7.1\%$) are estimated from the MC simulation and are corrected for differences between data and simulation using high statistics control samples of high purity. The result is

$$\mathcal{B}(B^+ \to D_s^+\pi^0) = (1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.2) \times 10^{-5},$$

where the first uncertainty is statistical, the second systematic (Table I), and the third due to the branching fraction uncertainties of the D_s^+ [21] and its daughter decays (Table I and Ref. [5]). We also quote the product $\mathcal{B}(B^+ \to D_s^+\pi^0)\mathcal{B}(D_s^+ \to \phi\pi^+) = (7.0^{+2.4+0.5}_{-2.1-0.7} \pm 0.4) \times 10^{-7}$.

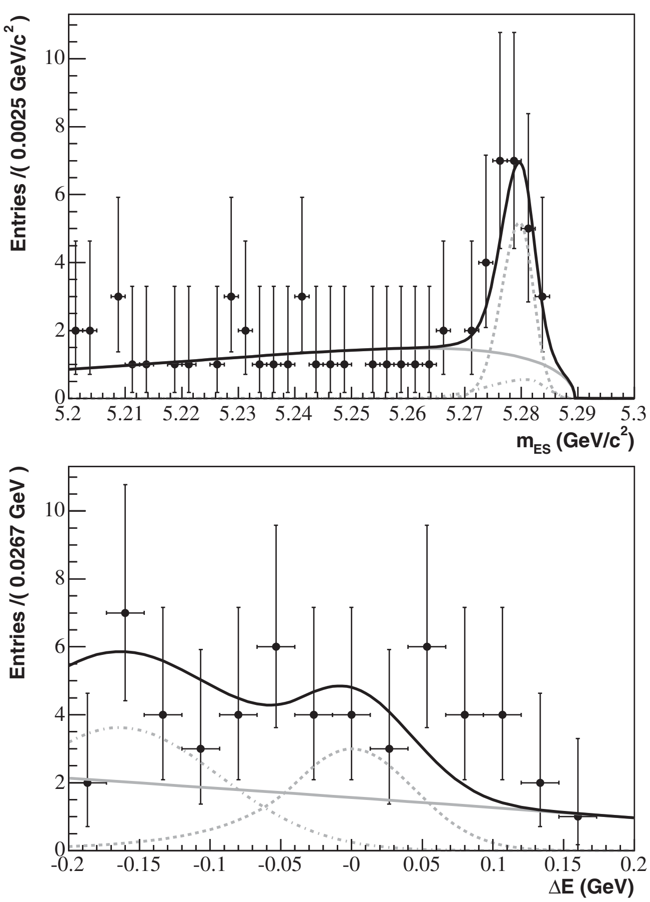

FIG. 1. Likelihood projections on $m_{\rm ES}$ and ΔE after a cut on the signal-to-background likelihood ratio. Points with error bars: data; black solid line: result of the full fit; gray dashed curve: signal; gray dash-dotted curve: peaking background; gray solid curve: combinatorial background.

Several systematic uncertainties on the signal yield have been considered. Background from B decays into charmless final states (CPBG, e.g., $B^+ \to \phi\rho^+$) peaking in the same region in $m_{\rm ES}$ and ΔE as $B^+ \to D_s^+\pi^0$ has been estimated from a fit in the D_s^+ mass sidebands. Scaled to the D_s^+ mass signal region we find $\hat{n}_{\rm CPBG}^{\rm scaled} = -1.4 \pm 1.4$ and assign the statistical error as a one-sided systematic error. The background peaking at negative ΔE values found in this fit is consistent with the MC expectation. MC studies with many samples of the same size as the data sample indicate a small negative fit bias. We correct for this bias (+0.5 events) and assign the statistical uncertainty as a systematic error (± 0.3 events). The PDF parameters for signal and peaking background have been varied within their errors as found in the fit on MC data resulting in a variation of ± 0.20 events in the signal yield. The change in the signal yield when $m_{\rm ES}^{\rm max}$ is free to vary is +0.16 events and is assigned as a systematic error. The possible bias in $\hat{n}_{\rm SIG}$ due to the presence of $B^0 \to D_s^+\rho^-$ events is estimated to be -0.18 events where the upper limit at 90% confidence level [20], $\mathcal{B}(B^0 \to D_s^+\rho^-) < 1.9 \times 10^{-5}$, has been assumed, and is assigned as a systematic uncertainty. We obtain a total systematic uncertainty on the signal yield of $^{+0.4}_{-1.5}$ events.

Other systematic uncertainties on the branching fraction are due to the uncertainty on $N_{B\bar{B}}$, the statistical uncertainty on the MC samples used, and possible differences in detection and reconstruction efficiencies between data and MC simulation for: NN and $m_{D_s^+}$ selection requirements

TABLE I. Contributions to the relative systematic uncertainty (in %) on the branching fraction $\mathcal{B}(B^+ \to D_s^+\pi^0)$ coming from the signal efficiency subdivided in the reconstructed D_s^+ modes, the signal yield, and the number of $B\bar{B}$ pairs. Also shown is the total relative systematic uncertainty and the uncertainty due to the individual $\mathcal{B}_k$ (both in %).

Uncertainty in $D_s^+ \to$	$\phi\pi^+$	$K_S^0K^+$	$\bar{K}^{*0}K^+$
NN cut efficiency	+4.5, −5.2	+6.1, −7.0	+4.1, −4.7
m_{D_s} cut efficiency	+1.6, −2.0	+2.2, −3.1	+4.6, −6.6
Tracking efficiency	±3.9	±1.3	±3.9
K_S^0 efficiency	—	±3.1	—
π^0 efficiency		±3.2	
PID efficiency	±2.5	±1.6	±2.5
MC statistics	±1.1	±1.1	±1.4
Total efficiency error	+7.5, −8.0	+8.2, −9.2	+8.5, −10.0
Signal Yield		+2.3, −7.5	
$N_{B\bar{B}}$		±1.1	
Total systematic error		+6.9, −9.6	
$\mathcal{B}_k$	±13	±21	±17

estimated with a high-purity control sample of $B^+ \to D_s^+ \bar{D}^0$ ($\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^+\pi^-$) events, charged particle tracking, K_S^0 and π^0 reconstruction, and charged particle identification (PID).

In summary, we measure $\mathcal{B}(B^+ \to D_s^+\pi^0) = (1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.2) \times 10^{-5}$ and translate the result into a $\mathcal{B}(B^0 \to D_s^+\pi^-)$ value with the use of isospin symmetry and B-meson lifetime values from Ref. [5]. The result, $\mathcal{B}(B^0 \to D_s^+\pi^-) = (2.7^{+0.9+0.2}_{-0.8-0.3} \pm 0.4) \times 10^{-5}$, is consistent with the ones given in Ref. [7] but is less precise.

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