Observation of Tree-Level B Decays with $s\bar{s}$ Production from Gluon Radiation

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We report on our search for decays proceeding via a tree-level $b \to c$ quark transition in which a gluon radiates into an $s\bar{s}$ pair. We present observations of the decays $B^- \to D_s^{(*)+} K^- \pi^-$ and $\bar{B}^0 \to D_s^+ K_S^0 \pi^-$ and evidence for $B^- \to D_s^+ K^- K^-$ and set upper limits on the branching fractions for $\bar{B}^0 \to D_s^{*+} K_S^0 \pi^-$ and $B^- \to D_s^{*+} K^- K^-$ using 383×10^6 $\Upsilon(4S) \to B\bar{B}$ events collected by the *BABAR* detector at SLAC. We present evidence that the invariant mass distributions of $D_s^{(*)+} K^-$ pairs from $B^- \to D_s^{(*)+} K^- \pi^-$

decays are inconsistent with the phase-space model, suggesting the presence of charm resonances lying below the $D_s^{(*)+}K^-$ threshold.

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Evidence for inclusive flavor correlated production of D_s^+ in B^- decays was reported recently [1] with a branching fraction of $\mathcal{B}(B^- \to D_s^+ X) = (1.2 \pm 0.4)\%$ [2]. These decays, along with $B^- \to D_s^{*+} X$, are mediated by a $b \to c$ quark transition and the production of an $s\bar{s}$ pair from the vacuum via radiative gluon pair production resulting in at least three final state particles. Examples for three-body B^- decays with a $D_s^{(*)+}$ in the final state are $B^- \to D_s^{(*)+}K^-\pi^-$. The dominant Feynman diagram for these decays is shown in Fig. 1. The corresponding $\bar{B}^0$ decays are $\bar{B}^0 \to D_s^{(*)+}\bar{K}^0\pi^-$. By replacing the π^- in Fig. 1 with a K^-, we get the Cabibbo-suppressed decays $B^- \to D_s^{(*)+}K^-K^-$.

Besides the dominant diagram, $B^- \to D_s^{(*)+}K^-\pi^-$ can occur via the color-suppressed diagram where the constituent $\bar{u}$'s of the K^- and π^- are switched. Although a color-suppressed contribution does not exist for $\bar{B}^0 \to D_s^{(*)+}\bar{K}^0\pi^-$, a subdominant contribution from a W-exchange diagram with $s\bar{s}$ and $d\bar{d}$ popping may exist instead. Either of these contributions could cause a deviation from the naive expectation of two for the ratio $\mathcal{B}(B^- \to D_s^{(*)+}K^-\pi^-)/\mathcal{B}(\bar{B}^0 \to D_s^{(*)+}K_S^0\pi^-)$.

The $D_s^{(*)}K$ can come from intermediate charm resonances instead of directly from the B. It has been proposed that these resonances can play a significant role in $B^- \to D_s^+K^-\pi^-$ decays [3] despite their masses lying below the $m(D_sK)$ production threshold [4]. In this case, it may be possible to measure the parameters of the resonances such as their masses and widths, complementary to the analysis using $B \to \bar{D}\pi\pi$ decays [4].

No exclusive decays proceeding via radiative gluon $s\bar{s}$ pair production at the tree level have hitherto been observed. Upper limits on $\mathcal{B}(B^- \to D_s^{(*)+}K^-\pi^-)$ and $\mathcal{B}(\bar{B}^0 \to D_s^{(*)+}K_S^0\pi^-)$ have been placed by ARGUS [5]. In this Letter we report first observations of the decay modes $B^- \to D_s^{(*)+}K^-\pi^-$ and $\bar{B}^0 \to D_s^+K_S^0\pi^-$, evidence for $B^- \to D_s^+K^-K^-$, and limits on $\mathcal{B}(\bar{B}^0 \to D_s^{*+}K_S^0\pi^-)$

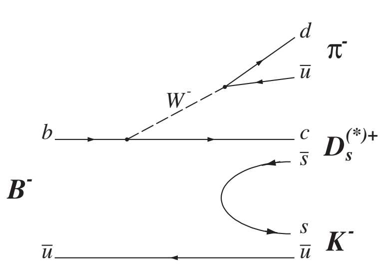

FIG. 1. Feynman diagram for $B^- \to D_s^{(*)+}K^-\pi^-$.

and $\mathcal{B}(B^- \to D_s^{*+}K^-K^-)$. We also present $D_s^{(*)+}K^-$ invariant mass distributions from $B^- \to D_s^{(*)+}K^-\pi^-$ decays and compare them to the spectra obtained from a phase-space model.

The analysis uses approximately 383×10^6 $\Upsilon(4S) \to B\bar{B}$ events created by the PEP-II e^+e^- collider and collected by the *BABAR* detector. The *BABAR* detector is described elsewhere [6].

Optimal selection criteria and probability density functions of selection variables are determined by an analysis based on Monte Carlo (MC) simulation of both signal and background events. We use GEANT4 [7] software to simulate interactions of particles traversing the *BABAR* detector, taking into account the varying detector conditions and beam backgrounds. We verify with MC simulation that resolutions and background levels correctly describe the data.

Candidate D_s^+ mesons are reconstructed in the modes $D_s^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K_S^0K^+$, with $\phi \to K^+K^-$, $\bar{K}^{*0} \to K^-\pi^+$, and $K_S^0 \to \pi^+\pi^-$. The K_S^0 candidates are reconstructed from two oppositely charged tracks coming from a common vertex displaced from the e^+e^- interaction point. We require the significance of this displacement (the measured K_S^0 flight distance divided by its estimated error) to exceed 2. All other tracks are required to originate less than 1.5 cm away from the e^+e^- interaction point in the transverse plane and less than 10 cm along the beam axis. Charged kaon candidates must satisfy identification criteria that are typically around 92% efficient [8], depending on momentum and polar angle, and have a pion misidentification rate at the 5% level. The $\phi \to K^+K^-$, $\bar{K}^{*0} \to K^-\pi^+$, and $K_S^0 \to \pi^+\pi^-$ candidates are required to have invariant masses within ± 15, ± 50, and ± 10 MeV$/c^2$ of their nominal masses, respectively [9].

The full polarization of the $\bar{K}^{*0}$ and ϕ mesons from the D_s^+ decays is exploited to reject backgrounds through the use of the helicity angle θ_H, defined as the angle between the K^- momentum vector and the direction of flight of the D_s^+ in the $\bar{K}^{*0}$ or ϕ rest frame. The $\bar{K}^{*0}$ and ϕ candidates are required to have $|\cos\theta_H| > 0.5$.

The D_s^{*+} candidates are reconstructed in the mode $D_s^{*+} \to D_s^+\gamma$. Photons from D_s^{*+} candidates are accepted if their energy is greater than 100 MeV. They are rejected if, when combined with any other photon having an energy greater than 150 MeV, they belong to a photon pair whose invariant mass lies within ± 10 MeV$/c^2$ of the π^0 mass. The D_s^+ candidates are required to have invariant masses in the interval ± 10 MeV$/c^2$ of the nominal D_s^+ mass while the invariant masses of D_s^{*+} candidates lie in the range from $m(D_s^{*+}) - 15$ MeV$/c^2$ to $m(D_s^{*+}) + 10$ MeV$/c^2$.

All D_s^+ candidates are subjected to a mass-constrained fit after selection. The invariant mass of the D_s^{*+} is calculated after the mass constraint on the daughter D_s^+ has been applied. Subsequently, all D_s^{*+} candidates are subjected to mass-constrained fits. To eliminate $\bar{B}^0 \to D_s^{(*)+} D^-$, $D^- \to K_S^0 \pi^-$ events from the $\bar{B}^0 \to D_s^{(*)+} K_S^0 \pi^-$ samples, the $K_S^0 \pi^-$ invariant mass must be outside a 40 MeV$/c^2$ window around the D^- mass.

Finally, the B meson candidates are formed using the reconstructed combinations of $D_s^+ K^- \pi^-$, $D_s^{*+} K^- \pi^-$, $D_s^+ K_S^0 \pi^-$, $D_s^{*+} K_S^0 \pi^-$, $D_s^+ K^- K^-$, and $D_s^{*+} K^- K^-$.

Background from continuum $q\bar{q}$ production (where $q = u, d, s, c$) is suppressed based on the event topology. The event shape variables, R_2 (the ratio of the second to zeroth Fox-Wolfram moments [10]) and L_2/L_0 (the ratio of the second and zeroth angular moments of the energy flow about the B thrust axis [11]), are combined in a Fisher discriminant ($\mathcal{F}$) to exploit the difference between the shapes of $e^+e^- \to B\bar{B}$ and $e^+e^- \to q\bar{q}$ events. A selection is applied to $\mathcal{F}$ such that 80% of continuum background is rejected while maintaining 80% signal efficiency.

The signals are extracted using the energy-substituted mass $m_{\rm ES} \equiv \sqrt{E_b^{*2} - (\sum_i \mathbf{p}_i^*)^2}$ and the energy difference $\Delta E \equiv \sum_i \sqrt{m_i^2 + \mathbf{p}_i^{*2}} - E_b^*$, where E_b^* is the beam energy in the laboratory frame, $\mathbf{p}_i^*$ is the momentum of the daughter particle i of the B meson candidate also in the laboratory frame, and m_i is the mass hypothesis for particle i. For signal events, $m_{\rm ES}$ peaks at the B meson mass with a resolution of about 2.6 MeV$/c^2$ and ΔE peaks near zero with a resolution of 13 MeV. The B candidates are required to have $|\Delta E| < 25$ MeV and $m_{\rm ES} > 5.2$ GeV$/c^2$. After all selection criteria are applied, we find the fraction of events containing more than one B candidate to be between 3% and 11% depending on the decay mode. In these instances, the B candidate with ΔE closest to zero is chosen. Estimated B reconstruction efficiencies are shown in Table I.

Background events that pass these selection criteria are represented by approximately equal amounts of $q\bar{q}$ continuum and $B\bar{B}$ events. We parametrize their $m_{\rm ES}$ distributions by a threshold function [12]:

$$f(m_{\rm ES}) \sim m_{\rm ES}\sqrt{1 - x^2}\exp[-\xi(1 - x^2)],$$

where $x = 2m_{\rm ES}/\sqrt{s}$, $\sqrt{s}$ is the total energy of the beams in their center of mass frame, and ξ is a fit parameter.

A study using simulated B decays reveals significant numbers of background events peaking in the regions of $5.272 < m_{\rm ES} < 5.288$ GeV$/c^2$ and $|\Delta E| < 25$ MeV similar to the reconstructed signal candidates. This peaking background is due to charmless and charmonium B decays with the same sets of final state particles as signal. The peaking contribution is evaluated using data by reconstructing $D_s^{(*)+} K^- \pi^-$, $D_s^{(*)+} K_S^0 \pi^-$, and $D_s^{(*)+} K^- K^-$ combinations, where "D_s^+" candidates are selected from 25–40 MeV$/c^2$ sidebands around the D_s^+ nominal mass. In this procedure, we use the same selection requirements as for the signal except that "D_s^+" candidates are not mass constrained. Studies reveal that constraining the D_s^+ mass does not significantly affect the resolutions of $m_{\rm ES}$ and ΔE distributions and that events in the D_s^+ mass sidebands are good representations of the background under the D_s^+ peak. Table I shows the fit yields of peaking background contributions under the $m_{\rm ES}$ peaks for each mode.

A matrix is constructed to study the cross feed between the signal modes. Its elements describe the contributions of each mode according to the levels seen in MC samples. No off-diagonal element of the cross-feed matrix exceeds 2%; this near-diagonal structure indicates effective suppression of the cross-feed contributions by application of the selection criteria.

Figure 2 shows the $m_{\rm ES}$ spectra of the reconstructed B candidates. For each mode, we perform an extended unbinned maximum likelihood fit to the $m_{\rm ES}$ distributions using candidates from all D_s^+ decay modes combined. The distributions are then fit with the sum of two functions:

TABLE I. Summary of results for the total detection efficiencies ε excluding subsequent branching fractions of $D_s^{(*)}$ decay modes ($D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0 K^+$), expected peaking background $n_{\rm peaking}$ with statistical uncertainties from fits of the $m_{\rm ES}$ distributions obtained using D_s^+ mass sidebands, final signal $n_{\rm sig}$ and background $n_{\rm bkg}$ yields with statistical uncertainties from $m_{\rm ES}$ fits adjusted for estimated peaking backgrounds and cross-feed contributions, branching fractions $\mathcal{B}$ with statistical and systematic uncertainties, significances $s(\sigma)$ calculated by comparing the likelihood maximum of the nominal fit to that of the fit with the signal yield fixed to the difference between the raw and corrected signal yields, and upper limits on $\mathcal{B}(\bar{B}^0 \to D_s^{*+} K_S^0 \pi^-)$ and $\mathcal{B}(B^- \to D_s^{*+} K^- K^-)$. Background yields $n_{\rm bkg}$ are selected in the region 5.27–5.29 GeV$/c^2$.

Mode	$\varepsilon_{\phi\pi}$	$\varepsilon_{\bar{K}^*K}$	$\varepsilon_{K_S^0 K}$	$n_{\rm peaking}$	$n_{\rm sig}$	$n_{\rm bkg}$	$\mathcal{B} \times 10^{-4}$	$s(\sigma)$	Upper limits (90% C.L.)
$B^- \to D_s^+ K^- \pi^-$	11.1%	6.8%	9.6%	41 ± 9	430 ± 29	182 ± 6	$2.02 \pm 0.13 \pm 0.38$	21	—
$B^- \to D_s^{*+} K^- \pi^-$	5.9%	3.6%	5.1%	4 ± 5	178 ± 18	87.1 ± 3.5	$1.67 \pm 0.16 \pm 0.35$	14	—
$\bar{B}^0 \to D_s^+ K_S^0 \pi^-$	8.8%	5.3%	7.6%	28 ± 6	61.8 ± 14.4	94.5 ± 5.5	$0.55 \pm 0.13 \pm 0.10$	5.2	—
$\bar{B}^0 \to D_s^{*+} K_S^0 \pi^-$	3.8%	2.3%	3.4%	-1.1 ± 2.7	13.6 ± 8.4	62.8 ± 3.4	$0.29 \pm 0.18 \pm 0.07$	1.8	0.55×10^{-4}
$B^- \to D_s^+ K^- K^-$	7.1%	4.3%	6.3%	-0.3 ± 1.9	14.4 ± 5.6	9.8 ± 1.3	$0.11 \pm 0.04 \pm 0.02$	3.3	—
$B^- \to D_s^{*+} K^- K^-$	3.8%	2.4%	3.5%	-1.7 ± 1.3	4.7 ± 4.0	6.5 ± 0.9	$0.07 \pm 0.06 \pm 0.02$	1.3	0.15×10^{-4}

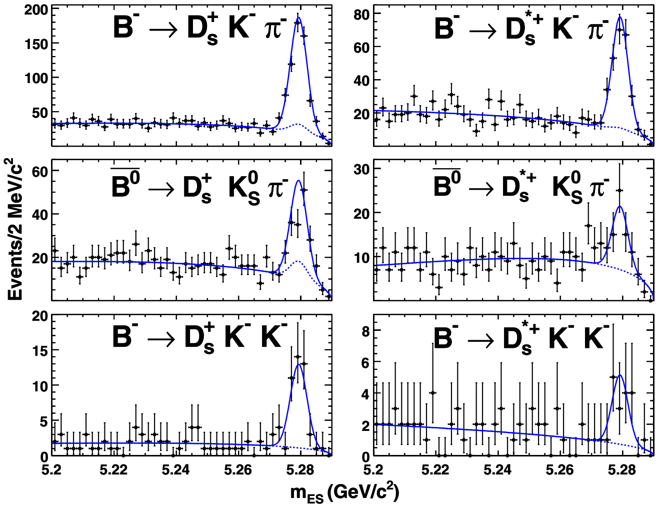

FIG. 2 (color online). m_{ES} spectra for all modes as labeled. Solid curves show the fits described in the text. Dashed lines in the signal regions correspond to the peaking and nonpeaking background components of the fit. The data are the points with error bars.

$f(m_{\mathrm{ES}})$ characterizing the combinatorial background and a Gaussian function to describe the signal. The likelihood function is given by

$$\mathcal{L} = \frac{e^{-(n_{\mathrm{sig}}+n_{\mathrm{bkg}})}}{N!}\prod_{i=1}^{N}(n_{\mathrm{sig}}P_i^{\mathrm{sig}} + n_{\mathrm{bkg}}P_i^{\mathrm{bkg}}),$$

where P_i^{sig} and P_i^{bkg} are the probability density functions for signal and background, n_{sig} and n_{bkg} are the number of signal and background events, and N is the total number of events in the fit.

Final signal yields (column n_{sig} of Table I) are obtained by subtracting the estimated peaking background and cross-feed contributions from the yields of the m_{ES} fits described in the preceding paragraph. No peaking background is subtracted from modes that have n_{peaking} less than zero in Table I because these values are consistent with zero. However, their errors are still propagated. The total signal yield in each B decay mode is related to the B branching fraction by $\mathcal{B} = n_{\mathrm{sig}}/(N_{B\bar{B}} \cdot \sum_i \mathcal{B}_i \cdot \varepsilon_i)$, where $N_{B\bar{B}}$ is the number of produced $B\bar{B}$ pairs, $\mathcal{B}_i$ is the product of the intermediate branching ratios, ε_i is the reconstruction efficiency (from Table I), and the sum is over D_s^+ modes ($i = \phi\pi^+,\ \bar{K}^{*0}K^+,\ K_S^0K^+$). As an input to the calculations, we used branching fraction numbers from [9]. Results are summarized in Table I.

The total relative systematic uncertainty in the B branching fractions is estimated to be approximately 19%–25% depending on the decay mode. The largest contribution, an uncertainty of 15%, comes from the D_s^+ branching fractions. The differences between selection efficiencies in MC simulation and in the data (estimated using the control mode $B^- \to D_s^- D^0$, $D^0 \to K^-\pi^+$) contribute to the systematic uncertainty (5%–10%) as does the efficiency dependence on the $D_s^{(*)+}K^-$ invariant mass spectrum (7%–9%). In the m_{ES} fits of the lower statistics modes ($D_s^{*+}K_S^0\pi^-$, $D_s^{*+}K^-K^-$) the signal Gaussian parameters and $\sqrt{s}$ in $f(m_{\mathrm{ES}})$ are fixed to ensure fit convergence. The associated systematic uncertainties are 14% and 9%, respectively. The cross-feed matrix elements affecting the $D_s^{(*)+}K^-K^-$ modes vary by 8% (5%) when estimated with MC events weighted according to the observed spectra of the $D_s^{(*)+}K^-$ invariant mass.

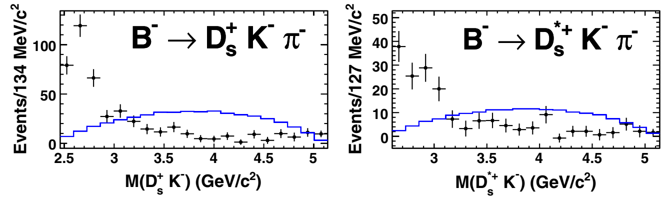

FIG. 3 (color online). $D_s^{(*)+}K^-$ invariant mass spectra using data (points with error bars) and nonresonant signal MC events scaled to the number of events in data (solid curves) subjected to signal selection described in the text and $m_{\mathrm{ES}} > 5.270\ \mathrm{GeV}/c^2$. Combinatorial background is approximated and then subtracted using events outside the signal region ($m_{\mathrm{ES}} < 5.265\ \mathrm{GeV}/c^2$).

The invariant mass spectra of the $D_s^{(*)+}K^-$ system in $B^- \to D_s^{(*)+}K^-\pi^-$ reveal distributions incompatible with those of three-body phase space. As shown in Fig. 3, there are enhancements in the number of events at the lower ends of the $m(D_s^{(*)+}K^-)$ spectra, suggesting the presence of charm resonances lying below the $D_s^{(*)+}K^-$ threshold [3].

In summary, $B^- \to D_s^+K^-\pi^-$, $B^- \to D_s^{*+}K^-\pi^-$, and $\bar{B}^0 \to D_s^+K_S^0\pi^-$ decays are observed for the first time each with a significance greater than 5σ. Evidence for $B^- \to D_s^+K^-K^-$ is found with a significance slightly greater than 3σ. For channels with significances lower than 2σ, upper limits are set on $\mathcal{B}(\bar{B}^0 \to D_s^{*+}K_S^0\pi^-)$ and $\mathcal{B}(\bar{B}^0 \to D_s^{*+}K_S^0\pi^-)$ using a frequentist approach [9] and taking into account the systematic uncertainties. The ratios $\mathcal{B}(B^- \to D_s^{(*)+}K^-K^-)/\mathcal{B}(B^- \to D_s^{(*)+}K^-\pi^-)$ are consistent with the expected Cabibbo suppression. That $\mathcal{B}(\bar{B}^0 \to D_s^+K_S^0\pi^-)$ is less than half of $\mathcal{B}(B^- \to D_s^+K^-\pi^-)$ may be due to the W-exchange diagram correction to the neutral mode and the color-suppressed contribution to the charged mode.

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