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Observation of $B^- \to D_s^{(*)+} K^- \pi^-$ and $\overline{B}^0 \to D_s^+ K_S^0 \pi^-$ and Search for $\overline{B}^0 \to D_s^{*+} K_S^0 \pi^-$ and $B^- \to D_s^{(*)+} K^- K^-$

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We report on our search for $B^- \to D_s^{(*)+}K^-\pi^-$, $\overline{B}^0 \to D_s^{(*)+}K_S^0\pi^-$, and $B^- \to D_s^{(*)+}K^-K^-$ decays in 383 million $\Upsilon(4S) \to B\overline{B}$ events collected by the *BABAR* detector at the PEP-II asymmetric-energy B-factory. The branching fractions are measured to be $\mathcal{B}(B^- \to D_s^+K^-\pi^-) = (2.02 \pm 0.13_{stat} \pm 0.38_{syst}) \times 10^{-4}$, $\mathcal{B}(B^- \to D_s^{*+}K^-\pi^-) = (1.67 \pm 0.16_{stat} \pm 0.35_{syst}) \times 10^{-4}$, $\mathcal{B}(\overline{B}^0 \to D_s^+K_S^0\pi^-) = (0.55 \pm 0.13_{stat} \pm 0.10_{syst}) \times 10^{-4}$, and $\mathcal{B}(B^- \to D_s^+K^-K^-) = (0.11 \pm 0.04_{stat} \pm 0.02_{syst}) \times 10^{-4}$. Upper limits at the 90% C.L. are set on $\mathcal{B}(\overline{B}^0 \to D_s^{*+}K_S^0\pi^-) < 0.55 \times 10^{-4}$ and $\mathcal{B}(B^- \to D_s^{*+}K^-K^-) < 0.15 \times 10^{-4}$.

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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]. Along with $B^- \to D_s^{*+}X$ decays, these decays are mediated by a $b \to c$ quark transition and require at least three final state particles, including the production of an $s\bar{s}$ pair from the vacuum via radiative gluon pair production. Examples for three-body B^- decays with a $D_s^{(*)+}$ in the final state are $B^- \to D_s^{(*)+}K^-\pi^-$. The Feynman diagram for $B^- \to D_s^{(*)+}K^-\pi^-$ decays is shown in Figure 1. The corresponding $\bar{B}^0$ decays are $\bar{B}^0 \to D_s^{(*)+}\bar{K}^0\pi^-$. By replacing the π^- in Figure 1 with a K^-, we get the Cabibbo-suppressed decays $B^- \to D_s^{(*)+}K^-K^-$.

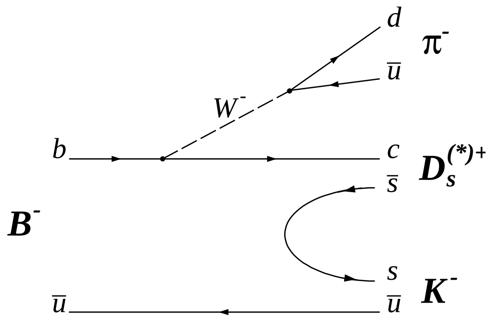

FIG. 1: Feynman diagram for $B^- \to D_s^{(*)+}K^-\pi^-$.

In addition to the dominant diagram shown in Figure 1, $B^- \to D_s^{(*)+}K^-\pi^-$ can occur via a color-suppressed diagram with the same $b \to c\bar{u}d$ vertices where the $\bar{u}$ from the W^- is now the constituent of the K^- instead of the π^-. Although a color-suppressed contribution does not exist for $\bar{B}^0 \to D_s^{(*)+}\bar{K}^0\pi^-$, a sub-dominant 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 of $B^- \to D_s^{(*)+}K^-\pi^-$ to $\overline{B}^0 \to D_s^{(*)+}K_S^0\pi^-$ branching fractions.

The $D_s^{(*)}$-K pair could 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].

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

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

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 verify that MC simulations correctly describe the data.

Candidates for D_s^+ mesons are reconstructed in the modes $D_s^+ \to \phi\pi^+$, $\overline{K}^{*0}K^+$, and $K_S^0K^+$, with $\phi \to K^+K^-$, $\overline{K}^{*0} \to K^-\pi^+$ and $K_S^0 \to \pi^+\pi^-$. The K_S^0 candidates are reconstructed from two oppositely-charged tracks that come 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 [7], depending on momentum and polar angle, and have a pion misidentification rate at the 5% level. The $\phi \to K^+K^-$, $\overline{K}^{*0} \to K^-\pi^+$ and $K_S^0 \to \pi^+\pi^-$ candidates are required to have invariant masses within ± 15 MeV/c^2, ± 50 MeV/c^2 and ± 10 MeV/c^2 of their nominal masses, respectively [8]. Fully polarized $\overline{K}^{*0}$ and ϕ mesons from the D_s^+ decays are employed 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 $\overline{K}^{*0}$ or ϕ rest frame. The $\overline{K}^{*0}$ and ϕ candidates are required to have $|\cos\theta_H|$ greater than 0.5.

TABLE I: Summary of results for the total detection efficiencies ε excluding the subsequent branching fractions of $D_s^{(*)}$ decay modes ($D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to \phi\pi^+$, $\overline{K}^{*0}K^+$, $K_S^0K^+$), expected peaking background events $n_{\rm peaking}$ with statistical uncertainties from fits of the m_{ES} distributions obtained using the D_s^+ invariant mass sidebands, final signal yields n_{sig} with statistical uncertainties from m_{ES} fits adjusted to account 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 UL on the branching fractions for $\overline{B}^0 \to D_s^{*+}K_S^0\pi^-$ and $B^- \to D_s^{*+}K^-K^-$.

Mode	$\varepsilon_{(D_s\to\phi\pi)}$	$\varepsilon_{(D_s\to\bar{K}^*K)}$	$\varepsilon_{(D_s\to K_S^0K)}$	$n_{\rm peaking}$	n_{sig}	$\mathcal{B}\times10^{-4}$	$s(\sigma)$	UL (90% C.L.)
$B^- \to D_s^+K^-\pi^-$	11.1%	6.8%	9.6%	41 ± 9	430 ± 29	$2.02\pm0.13\pm0.38$	21	—
$B^- \to D_s^{*+}K^-\pi^-$	5.9%	3.6%	5.1%	4 ± 5	178 ± 18	$1.67\pm0.16\pm0.35$	14	—
$\overline{B}^0 \to D_s^+K_S^0\pi^-$	8.8%	5.3%	7.6%	28 ± 6	61.8 ± 14.4	$0.55\pm0.13\pm0.10$	5.2	—
$\overline{B}^0 \to D_s^{*+}K_S^0\pi^-$	3.8%	2.3%	3.4%	-1.1 ± 2.7	13.6 ± 8.4	$0.29\pm0.18\pm0.073$	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	$0.11\pm0.04\pm0.02$	3.3	—
$B^- \to D_s^{*+}K^-K^-$	3.8%	2.4%	3.5%	-1.7 ± 1.3	4.7 ± 4.0	$0.07\pm0.06\pm0.02$	1.3	0.15×10^{-4}

The D_s^{*+} candidates are reconstructed in the mode $D_s^{*+} \to D_s^+\gamma$. The photons are accepted if their energy is greater than 100 MeV. Photons from D_s^{*+} candidates 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 D_s^+ nominal 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 $\overline{B}^0 \to D_s^{(*)+}D^-$, $D^- \to K_S^0\pi^-$ events from the $\overline{B}^0 \to D_s^{(*)+}K_S^0\pi^-$ samples, the invariant mass of the K_S^0 and π^- 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 $D_s^{*+}K^-K^-$.

The 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 [9]) and L_2/L_0 (the ratio of the second and zeroth angular moments of the energy flow about the B thrust axis [10]), are combined in a Fisher discriminant ($\mathcal{F}$) to effectively 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 $m_{\rm ES} \equiv \sqrt{E_{\rm b}^{*2} - (\sum_i \mathbf{p}_i^*)^2}$ and the energy difference $\Delta E \equiv \sum_i \sqrt{m_i^2 + \mathbf{p}_i^{*2}} - E_{\rm b}^*$, where $E_{\rm b}^*$ 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. The estimated B reconstruction efficiencies, excluding the subsequent branching fractions, 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 [11]:

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

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 set of particles as signal in the final state. The peaking contribution is evaluated using the 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 revealed that constraining the D_s^+ mass did not significantly affect the resolutions of m_{ES} and ΔE distributions. Table I shows the fit yields of the peaking background contribution under the m_{ES} peak 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_{ES} spectra of the reconstructed B candidates. For each mode, we perform an extended unbinned maximum likelihood (ML) fit to the m_{ES} distributions using the candidates from all D_s^+ decay modes combined. The m_{ES} distributions are fit with the sum of two functions: $f(m_{\mathrm{ES}})$ characterizing the combinatorial background and a Gaussian function to describe the signal. The likelihood function is given by:

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

where P_i^{sig} and P_i^{bkg} are the probability density functions for the 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

The final signal yields 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 since these values are consistent with zero although their errors are still propagated. The final values are given in the n_{sig} column of Table I. The total signal yield in each B decay mode is related to the B branching fraction $\mathcal{B}$ using the following expression:

$$\mathcal{B} = n_{sig}/(N_{B\bar{B}} \cdot \sum_i \mathcal{B}_i \cdot \varepsilon_i),$$

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 ($i = \phi\pi^+$, $\overline{K}^{*0}K^+$, $K_S^0K^+$). As an input to the calculations, we used branching fraction numbers from [8]. The results of these calculations are summarized in Table I.

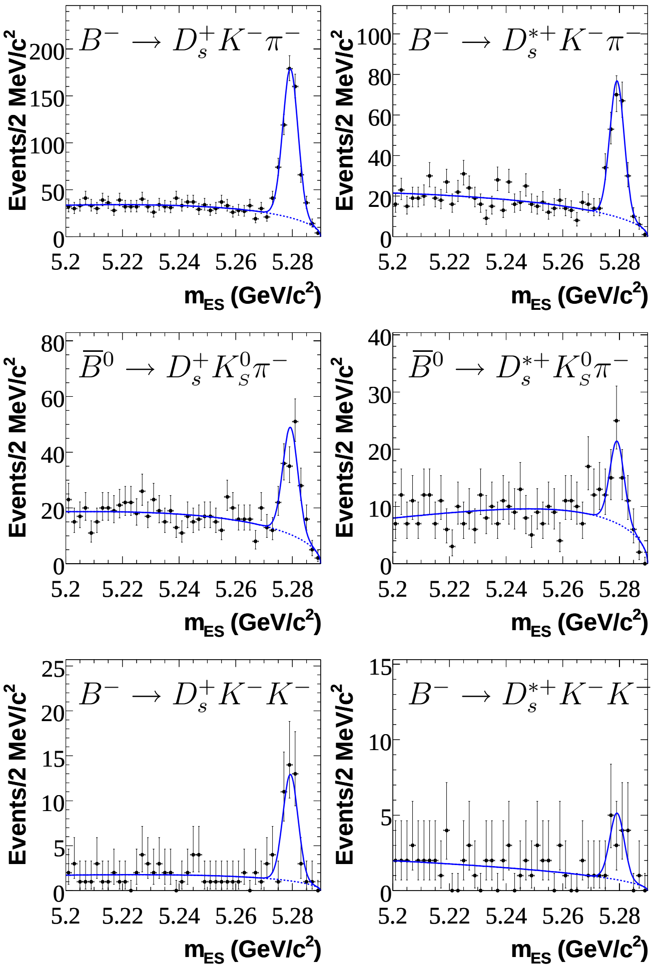

FIG. 2: m_{ES} spectra for the $B^- \to D_s^+K^-\pi^-$ (top left), $B^- \to D_s^{*+}K^-\pi^-$ (top right), $\overline{B}^0 \to D_s^+K_S^0\pi^-$ (middle left), $\overline{B}^0 \to D_s^{*+}K_S^0\pi^-$ (middle right), $B^- \to D_s^+K^-K^-$ (bottom left), and $B^- \to D_s^{*+}K^-K^-$ (bottom right). Solid curves show the fit results, as explained in the text. Dashed lines in the signal regions correspond to the non-peaking background components of the fit. The data are the points with error bars.

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 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 ($D_s^{*+}K_S^0\pi^-$ and $D_s^{*+}K^-K^-$) 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 entries in the cross-feed matrix affecting the $D_s^{(*)+}K^-K^-$ modes vary by 8%(5%) when they are calculated with MC events weighted according to the observed spectra of the $D_s^{(*)+}K^-$ invariant mass.

For the $\overline{B}^0 \to D_s^{*+}K_S^0\pi^-$ and $B^- \to D_s^{*+}K^-K^-$ decay modes, the upper limits are set using a frequentist approach [8] and taking into account the systematic uncertainties. The upper limits are summarized in Table I.

Studies of the invariant mass spectra of the $D_s^{(*)+}K^-$ system in $B^- \to D_s^{(*)+}K^-\pi^-$ modes reveal distributions incompatible with those of three-body phase space. As shown in Figure 3, there are enhancements in the number of events at the lower ends of the $m(D_s^{(*)+}K^-)$ spectra. These enhancements suggest 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 $\overline{B}^0 \to D_s^+K_S^0\pi^-$ decays are observed for the first time each with significance greater than 5σ. Evidence for $B^- \to D_s^+K^-K^-$ was found with a significance slightly greater than 3σ. Upper limits are set on the branching fractions of the two decay modes with significances lower than 2σ: $\overline{B}^0 \to D_s^{*+}K_S^0\pi^-$ and $B^- \to D_s^{*+}K^-K^-$.

The ratios of $\mathcal{B}(D_s^{(*)+}K^-K^-)$ to $\mathcal{B}(B^- \to D_s^{(*)+}K^-\pi^-)$ are consistent with the expected Cabibbo suppression. The branching fraction of $\overline{B}^0 \to D_s^+K_S^0\pi^-$ is less than half that of $B^- \to D_s^+K^-\pi^-$; this may be due to the W-exchange diagram correction to the neutral mode and the color-suppressed contribution to the charged mode.

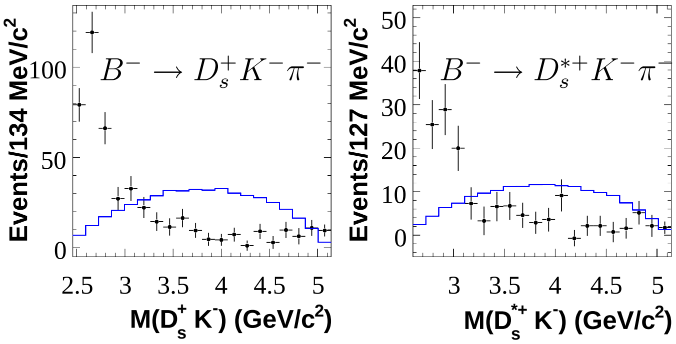

FIG. 3: $D_s^{(*)+}K^-$ invariant mass spectra for the $B^- \to D_s^+K^-\pi^-$ (left) and $B^- \to D_s^{*+}K^-\pi^-$ (right) decay modes using the data. A requirement of $m_{ES} > 5.270$ GeV/c^2 is applied to the events shown in the figure, in addition to the signal selection described in the text. Combinatoric background is approximated and then subtracted using events outside the $m_{\rm ES}$ signal region ($m_{ES} < 5.265$ GeV/c^2). The histogram shows the non-resonant signal MC events distribution, scaled to the number of events in the data signal region.

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