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# Observation of the decays $B^- \to D_s^{(*)+} K^- \pi^-$

The *BABAR* Collaboration

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**Abstract**

We report first observations of the decays $B^- \to D_s^{(*)+} K^- \pi^-$, using 292 $\text{fb}^{-1}$ of data collected at the $\Upsilon(4S)$ resonance energy by the *BABAR* detector at the PEP-II $e^+e^-$ collider. The branching fractions are measured to be $\mathcal{B}(B^- \to D_s^+ K^- \pi^-) = (1.88 \pm 0.13 \pm 0.41) \cdot 10^{-4}$ and $\mathcal{B}(B^- \to D_s^{*+} K^- \pi^-) = (1.84 \pm 0.19 \pm 0.40) \cdot 10^{-4}$.

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# 1 INTRODUCTION

First evidence for so-called 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 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 ( $s\bar{s}$ "popping"). An example for a three-body $B^-$ decay with a $D_s^+$ in the final state is $B^- \to D_s^+ K^- \pi^-$. The corresponding $\bar{B}^0$ decay is $\bar{B}^0 \to D_s^+ \bar{K}^0 \pi^-$. The Feynman diagram for $B^- \to D_s^{(*)+} K^- \pi^-$ decays is shown in Fig. 1. In case of $\bar{B}^0 \to D_s^+ \bar{K}^0 \pi^-$, an additonal contribution from a $W$-exchange diagram with $s\bar{s}$ and $d\bar{d}$ popping may exist. If we

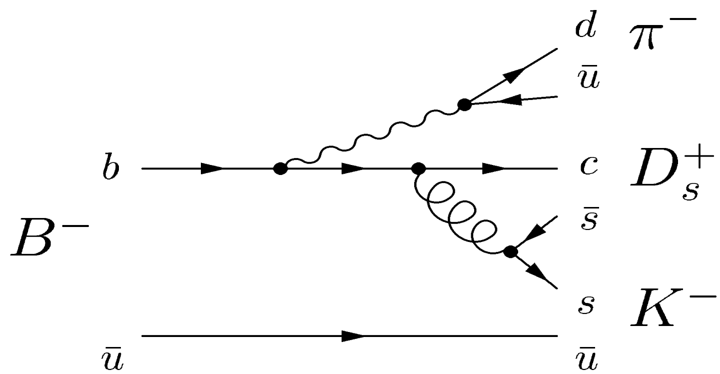


Figure 1: Feynman diagram for $B^- \to D_s^+ K^- \pi^-$.

replace the $\pi^-$ in Fig. 1, which comes from the hadronization of the $W^-$ boson with a $K^-$, we get the Cabibbo-suppressed decays $B^- \to D_s^+ K^- K^-$ and $\bar{B}^0 \to D_s^+ \bar{K}^0 K^-$. It is interesting to note that the final state $D_s^+ \bar{K}^0 K^-$ can also be reached from a $B^0$ decay. In this case the decay is mediated by a $b \to u$ quark transition, but the $W$ hadronization is not Cabibbo-suppressed. Thus a $\bar{B}^0$ can either decay directly to $D_s^+ \bar{K}^0 K^-$ or via $B^0\bar{B}^0$ mixing followed by $B^0 \to D_s^+ \bar{K}^0 K^-$. The interference between the two decay amplitudes for decay with and without $B^0\bar{B}^0$ mixing leads to a time-dependent *CP*-asymmetry that is sensitive to $\sin(2\beta + \gamma)$. In case the contribution from the higher $D^{**}$ resonances decaying into $D_s^+ \bar{K}$ turns out to be large, it may also be interesting to measure the resonant parameters independently from the analysis using $B \to \bar{D}\pi\pi$ decays [3].

No exclusive $B^- \to D_s^{(*)+} X$ or $\bar{B}^0 \to D_s^{(*)+} X$ decay mode has hitherto been observed. Limits on the branching fractions from the analyses by other experiments are listed in Table 1. In this paper we report the first measurement of the decay modes $B^- \to D_s^{(*)+} K^- \pi^-$.

# 2 THE *BABAR* DETECTOR AND DATASET

The analysis uses a sample of approximately 292 $\mathrm{fb}^{-1}$, which corresponds to about 324 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II [4] asymmetric-energy $B$-factory. The *BABAR* detector is described elsewhere [5] and only the components crucial to this analysis are summarized here. Charged particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification,

Table 1: Upper limits from ARGUS [6] and CLEO [7] on $B^- \to D_s^{(*)+} K^- \pi^-$ branching fractions.

| Experiment | Decay Mode | Upper limit (@90% $C.L.$) |
|---|---|---|
| ARGUS | $B^- \to D_s^+ K^- \pi^-$ | $8 \times 10^{-4}$ |
| | $B^- \to D_s^{*+} K^- \pi^-$ | $12 \times 10^{-4}$ |
| CLEO | $B^- \to D_s^+ K^- \pi^-$ | $5 \times 10^{-4}$ |
| | $B^- \to D_s^{*+} K^- \pi^-$ | $6.8 \times 10^{-4}$ |

ionization energy loss ($dE/dx$) in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device are used. Photons are identified and measured using a thallium-doped CsI-crystal electromagnetic calorimeter. These systems are located inside a 1.5 T solenoidal superconducting magnet. We use GEANT4 [8] software to simulate interactions of particles traversing the *BABAR* detector, taking into account the varying detector conditions and beam backgrounds.

# 3 ANALYSIS METHOD

The optimal selection criteria as well as the probability density distributions of selection variables are determined by a blind analysis based on Monte Carlo (MC) simulation of both signal and background. For the calculation of the expected signal yield we assume $\mathcal{B}(B^- \to D_s^{(*)+} K^- \pi^-)$ to be $10^{-4}$ (*i.e.* about 10% of the measured $\mathcal{B}(B^- \to D^+ \pi^- \pi^-)$ [3]). We use MC samples of our signal modes and, to simulate background, inclusive samples of $B^+B^-$ (784 fb$^{-1}$), $B^0\overline{B}^0$ (774 fb$^{-1}$), $c\bar{c}$ (247 fb$^{-1}$), and $q\bar{q},\ q = u, d, s$ (246 fb$^{-1}$). In addition, we use large samples of simulated events of rare background modes which have final states similar to the signal. We have verified that our MC correctly describes the data by comparing distributions of various selection variables.

Candidates for $D_s^+$ mesons are reconstructed in the modes $D_s^+ \to \phi\pi^+$, $\overline{K}^{*0}K^+$, and $K_S^0 K^+$, 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 (measured flight distance divided by an 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 kaon identification criteria that are typically around 92% efficient, 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 close to their nominal masses (we require the absolute differences between their measured masses and the nominal values [9] to be in the range $\pm 15$ MeV, $\pm 50$ MeV and $\pm 10$ MeV, respectively). The polarizations of the $\overline{K}^{*0}$ and $\phi$ mesons in the $D_s^+$ decays are employed to reject backgrounds through the use of the helicity angle $\theta_H$, defined as the angle between the $K^-$ momentum vector and the direction of flight of the $D_s^+$ in the $\overline{K}^{*0}$ or $\phi$ rest frame. The $\overline{K}^{*0}$ and $\phi$ candidates are required to have $|\cos\theta_H|$ greater than 0.5.

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. The $D_s^+$ and $D_s^{*+}$ candidates are required to have invariant masses in the interval $[-10, 10]$ MeV/$c^2$ (for $D_s^+$) and $[-15, 10]$ MeV/$c^2$ (for $D_s^{*+}$) from their nominal values [9] (the $D_s^+$ mass resolution is around 6 MeV/$c^2$, and the asymmetric mass cut on $D_s^{*+}$ has an efficiency of about 90%). All $D_s^+$ candidates are mass-constrained. The invariant mass of the $D_s^{*+}$ is calculated after a mass constraint on the daughter $D_s^+$ has been applied. Subsequently, all $D_s^{*+}$ candidates are subjected to a mass-constrained fit.

We also require that photons from $D_s^{*+}$ are inconsistent with $\pi^0$ hypothesis when combined with any other photon having an energy greater than 150 MeV in the event (the $\pi^0$ veto window is $\pm 10$ MeV/$c^2$). Finally, the $B^-$ meson candidates are formed using the reconstructed combinations of $D_s^+K^-\pi^-$ and $D_s^{*+}K^-\pi^-$.

The background from continuum $q\bar{q}$ production (where $q = u, d, s, c$) is suppressed based on the event topology. We calculate the angle ($\theta_T$) between the thrust axis of the $B$ meson candidate and the thrust axis of all other particles in the event in the center-of-mass frame (c.m.). In this frame, $B\overline{B}$ pairs are produced approximately at rest and have a uniform $\cos\theta_T$ distribution. In contrast, $q\bar{q}$ pairs are produced in the c.m. frame with high momenta, which results in a $|\cos\theta_T|$ distribution peaking at 1. $|\cos\theta_T|$ is required to be smaller than 0.8. In addition, the ratio of the second and zeroth order Fox-Wolfram moments [10] must be less than 0.3.

We extract the signal using the kinematical variables $m_{\rm ES} = \sqrt{E_{\rm b}^{*2} - (\sum_i \mathbf{p}_i^*)^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + \mathbf{p}_i^{*2}} - E_{\rm b}^*$, where $E_{\rm b}^*$ is the beam energy in the c.m. frame, $\mathbf{p}_i^*$ is the c.m. momentum of the daughter particle $i$ of the $B^-$ meson candidate, 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 $\Delta E$ peaks near zero with a resolution of 13 MeV, indicating that the $B^-$ candidate has a total energy consistent with the beam energy in the c.m. frame. The $B^-$ candidates are required to have $|\Delta E| < 25$ MeV (around $2\sigma$ of the signal $\Delta E$ resolution) and $m_{\rm ES} > 5.2$ GeV/$c^2$.

The fraction of events with multiple $B^-$ candidates is estimated using the MC simulation and found to be around 3% for $D_s^+K^-\pi^-$ and 9% for $D_s^{*+}K^-\pi^-$ combinations. In each event with more than one $B^-$ candidate that passes the selection requirements, we select the one with the lowest $|\Delta E|$ value.

After all selection criteria are applied, we estimate the $B^-$ reconstruction efficiencies, excluding the subsequent branching fractions (see Table 2).

Table 2: Reconstruction efficiencies for $B^- \to D_s^{(*)+}K^-\pi^-$ decays (excluding the subsequent branching fractions).

| Decay mode | $D_s^+ \to \phi\pi^+$ | $D_s^+ \to \overline{K}^{*0}K^+$ | $D_s^+ \to K_S^0K^+$ |
|---|---|---|---|
| $B^- \to D_s^+K^-\pi^-$ | 11.0% | 7.0% | 10.0% |
| $B^- \to D_s^{*+}K^-\pi^-$ | 5.3% | 3.4% | 4.8% |

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 $m_{\rm ES}$ distribution 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 $\xi$ is the fit parameter.

A study using simulated $B^0$ and $B^+$ decays shows that some background events with distributions in $m_{\rm ES}$ and in $\Delta E$ peaking near the signal region are expected in reconstructed $B^- \to D_s^+ K^- \pi^-$ candidates due to charmless and charmonium $B^-$ decays with the same set of particles in the final state. For $B^- \to D_s^{*+} K^- \pi^-$, no background of this kind is expected, due to the presence of the $\gamma$, which suppresses charmless and charmonium decay contributions. The peaking contribution is evaluated using the data by reconstructing "$D_s^{(*)+}$" $K^-\pi^-$ combinations, where "$D_s^+$" candidates are selected from $[\pm 40, \pm 25]$ MeV 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. The resulting $m_{\rm ES}$ spectra are shown in Figure 2. We fit the distributions using an extended unbinned maximum likelihood (ML) fit with a sum of a Gaussian (with a width and central value fixed from the MC simulation) and a threshold function $f(m_{\rm ES})$ with the floating shape and normalization (see detailed expression of the likelihood function is Section 5). The fit yields $34 \pm 12$ events in the "signal" $m_{\rm ES}$ peak for "$D_s^+$"$K^-\pi^-$ and $3 \pm 7$ for "$D_s^{*+}$"$K^-\pi^-$. Since the sideband interval is 1.5 times larger than the $D_s^+$ mass region used for signal selection, this translates into $23 \pm 8$ peaking background events expected in $B^- \to D_s^+ K^- \pi^-$.

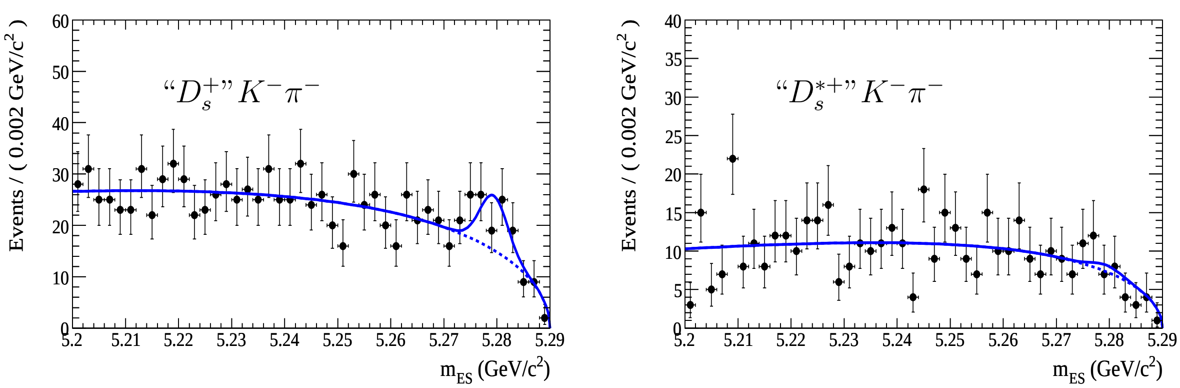


Figure 2: $m_{ES}$ spectra for the data "$D_s^+$"$K^-\pi^-$ (left) and "$D_s^{*+}$"$K^-\pi^-$ (right) combinations with no mass constraint applied on "$D_s^+$" candidates, using $D_s^+$ mass sidebands $[\pm 25, \pm 40]$ MeV (1.5 times the signal interval).

We also study cross-feed between the signal modes and other decays with final states similar to our signal modes, including $D_s^{(*)+} K^- K^-$. The cut on $\Delta E$ of the $B^-$ candidates effectively suppresses the cross-feed contributions, which do not exceed 2% of the reconstructed signal after all the selection criteria are applied.

# 4 SYSTEMATIC STUDIES

The summary of the systematic uncertainties is presented in Table 3. The total relative systematic error is estimated to be 22% for each $B^-$ decay mode, with the largest contribution coming from the $D_s^+$ branching fractions uncertainty (15%). Other significant sources of systematic errors are found to be due to the difference between the selection efficiency in MC events and in the data (estimated using the control mode $B^- \to D_s^- D^0,\ D^0 \to K^- \pi^+$), and also due to the efficiency dependence on the $D_s^{(*)+} K^-$ invariant mass and its potential effect if the resonant contribution is present.

Table 3: Summary of relative systematic errors (in %) for $B^- \to D_s^{(*)+} K^- \pi^-$ decays.

| Source | $B^- \to D_s^+ K^- \pi^-$ | $B^- \to D_s^{*+} K^- \pi^-$ |
|---|---|---|
| $B$ counting | 1.1 | 1.1 |
| MC statistics | 0.8 | 1.4 |
| Tracking | 5 | 5 |
| Particle identification efficiency | 4 | 4 |
| $K_S^0$ efficiency | 0.5 | 0.5 |
| $\gamma$ (from $D_s^{*+} \to D_s^+ \gamma$) efficiency | – | 2 |
| $\mathcal{B}$ of sub-decays | 15 | 15 |
| Peaking background contribution | 6 | 3 |
| Cross-feed contribution | 1 | 2 |
| Selection efficiency, Data/MC | 12 | 12 |
| Signal and background shape uncertainty | 3 | 3 |
| $M(D_s^{(*)-} K^+)$ efficiency dependence | 7 | 9 |
| Total | 22 | 22 |

# 5 RESULTS

Figure 3 shows the $m_{\rm ES}$ distributions for the reconstructed candidates $B^- \to D_s^+ K^- \pi^-$ and $B^- \to D_s^{*+} K^- \pi^-$. For each mode, we perform an extended unbinned ML fit to the $m_{\rm ES}$ distributions using the candidates from all $D_s^+$ decay modes combined. We fit the $m_{\rm ES}$ distributions with the sum of the function $f(m_{\rm ES})$ characterizing the combinatorial background and a Gaussian function to describe the signal. The mean and width of the Gaussian function, the threshold shape parameter $\xi$, and the numbers of signal ($n_{sig}$) and background ($n_{bkg}$) events are free parameters of the fit. 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, $N$ is the total number of events in the fit and $i$ is the index over all events in the fit.

The fit yields $393 \pm 25$ events in the $B^- \to D_s^+ K^- \pi^-$ mode. Taking into acccount the estimated peaking background contribution, we obtain $370 \pm 26$ signal events for $B^- \to D_s^+ K^- \pi^-$. The

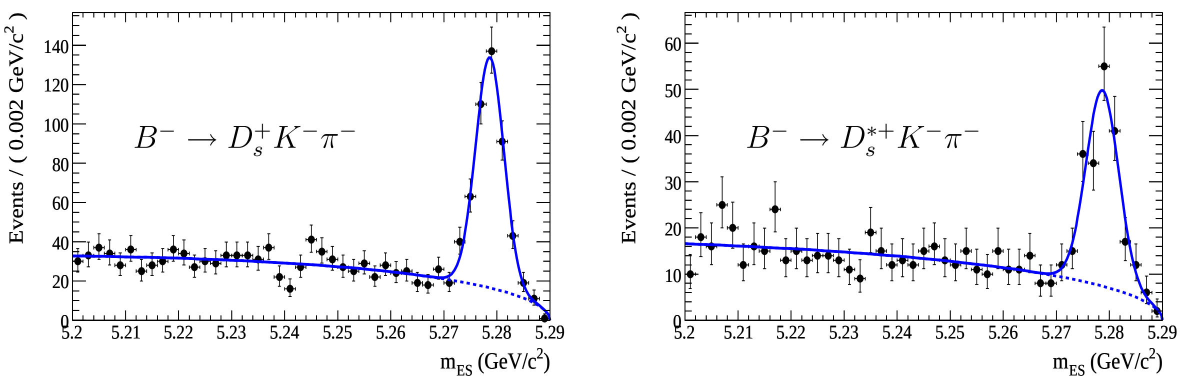


Figure 3: $m_{ES}$ spectra for the $B^- \to D_s^+ K^- \pi^-$ (left) and $B^- \to D_s^{*+} K^- \pi^-$ (right) using the data. Solid curves show the fit results, as explained in the text. Dashed lines in the signal regions correspond to the background components of the fit.

number of $B^- \to D_s^{*+} K^- \pi^-$ signal events from the fit is $164 \pm 17$ (no peaking contribution is subtracted in this mode as it was estimated to be consistent with 0). We also fit signal yields in each of the $D_s^+$ modes, fixing the width and central values of the signal Gaussians to that of the combined fit, letting the background level and shape float. The ratio of the signal yields between submodes is consistent with the expectations from MC.

The total signal yield in each $B^-$ decay mode is calculated as a sum over $D_s^+$ modes ($i = \phi\pi^+$, $\overline{K}^{*0} K^+$, $K_S^0 K^+$) and is related to the $B^-$ branching fraction $\mathcal{B}$ using the following expression:

$$n_{sig} = \mathcal{B} \cdot N_{B\bar{B}} \cdot \sum_i \mathcal{B}_i \cdot \epsilon_i,$$

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 and $\epsilon_i$ is the reconstruction efficiency (from Table 2). As an input to the calculation, we used branching fraction numbers from [9] and [12]. The relative systematic uncertainties are converted into absolute numbers using the measured central values. The results are:

$$\mathcal{B}(B^- \to D_s^+ K^- \pi^-) = (1.88 \pm 0.13 \pm 0.41) \cdot 10^{-4}$$

$$\mathcal{B}(B^- \to D_s^{*+} K^- \pi^-) = (1.84 \pm 0.19 \pm 0.40) \cdot 10^{-4}$$

In summary, two decay modes of charged $B$ mesons are observed for the first time. The significance of the observation is $14.2\sigma$ for $B^- \to D_s^+ K^- \pi^-$ and $9.6\sigma$ for $B^- \to D_s^{*+} K^- \pi^-$.

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