Observation of $\overline{B}^0 \to D_{sJ}^*(2317)^+ K^-$ Decay

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The decays $\overline{B}^0 \to D_{sJ}^+ K^-$ and $\overline{B}^0 \to D_{sJ}^- \pi^+$ are studied for the first time. A significant signal is observed in the $\overline{B}^0 \to D_{sJ}^*(2317)^+ K^-$ decay channel with $\mathcal{B}(\overline{B}^0 \to D_{sJ}^*(2317)^+ K^-) \times \mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+ \pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \times 10^{-5}$. No signals are observed in the $\overline{B}^0 \to D_{sJ}^*(2317)^- \pi^+$, $\overline{B}^0 \to D_{sJ}(2460)^+ K^-$, and $\overline{B}^0 \to D_{sJ}(2460)^- \pi^+$ decay modes, and upper limits are obtained. The analysis is based on a data set of 140 fb^{-1} collected by the Belle experiment at the asymmetric e^+e^- collider KEKB.

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Two narrow resonances denoted as $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ have been observed recently in e^+e^- continuum interactions [1–4]. These resonances were initially seen in the $D_{sJ}^*(2317)^+ \to D_s^+ \pi^0$, $D_{sJ}(2460)^+ \to D_s^+ \gamma$, and $D_{sJ}(2460)^+ \to D_s^{*+} \pi^0$ decay modes [5], and their quantum numbers were tentatively classified as $J^P = 0^+$ for $D_{sJ}^*(2317)^+$ and $J^P = 1^+$ for $D_{sJ}(2460)^+$. However, the measured masses are significantly lower than the values predicted within potential models for 0^+ and 1^+ states [6]. The D_{sJ} mesons were also observed in $B \to \overline{D} D_{sJ}$ decay modes with branching fractions an order of magnitude less than those for $B \to \overline{D} D_s$ decay modes with a pseudoscalar D_s [7]. Angular analysis of $B \to \overline{D} D_{sJ}(2460)^+$ favors a spin 1 assignment for $D_{sJ}(2460)^+$. There has been a significant effort to explain the surprising D_{sJ} masses [6], and some authors have discussed the possibility of four-quark content in the D_{sJ}^+ [8–12].

In this Letter we report the results from a search for $\overline{B}^0 \to D_{sJ}^+ K^-$ and $\overline{B}^0 \to D_{sJ}^- \pi^+$ decays, where D_{sJ}^+ mesons are reconstructed in the modes $D_{sJ}^*(2317)^+ \to D_s^+ \pi^0$ and $D_{sJ}(2460)^+ \to D_s^+ \gamma$. Measurements of the corresponding decays $\overline{B}^0 \to D_s^+ K^-$ and $\overline{B}^0 \to D_s^- \pi^+$ have been reported recently by Belle [13] and *BABAR* [14].

The decay mode $\overline{B}^0 \to D_{s(J)}^- \pi^+$ can be described by a $b \to u$ tree diagram. Within the factorization approach [15], the branching fraction ratio $R_{\pi^+/D^+} = \mathcal{B}(\overline{B}^0 \to D_s^- \pi^+)/\mathcal{B}(\overline{B}^0 \to D_s^- D^+)$ is predicted to be $(0.424 \pm 0.041) \times |V_{ub}/V_{cb}|^2$ and can be used to obtain the ratio of Cabibbo-Kobayashi-Maskawa matrix elements $|V_{ub}/V_{cb}|$. Assuming similar ratios R_{π^+/D^+} for D_s and D_{sJ} mesons, only a few $\overline{B}^0 \to D_{sJ}^- \pi^+$ events would be observed in the current Belle data sample.

The decays $\overline{B}^0 \to D_{s(J)}^+ K^-$ are of special interest because the quark content of the initial $\overline{B}^0$ meson ($b\bar{d}$) is completely different from that of the $D_{s(J)}^+ K^-$ final state ($cs\bar{s}\bar{u}$), indicating an unusual configuration with both initial quarks involved in the weak decay. Branching fractions for the pseudoscalar D_s^+ meson $\mathcal{B}(\overline{B}^0 \to D_s^+ K^-) = (4.6^{+1.2}_{-1.1} \pm 1.3) \times 10^{-5}$ and $(3.2 \pm 1.0 \pm 1.0) \times 10^{-5}$ were measured by the Belle [13] and *BABAR* [14] Collaborations, respectively. Predictions for this branching fraction have been obtained assuming a dominant contribution from a perturbative QCD factorization W exchange process [Fig. 1(a)] [16,17] or, alternatively, from final state

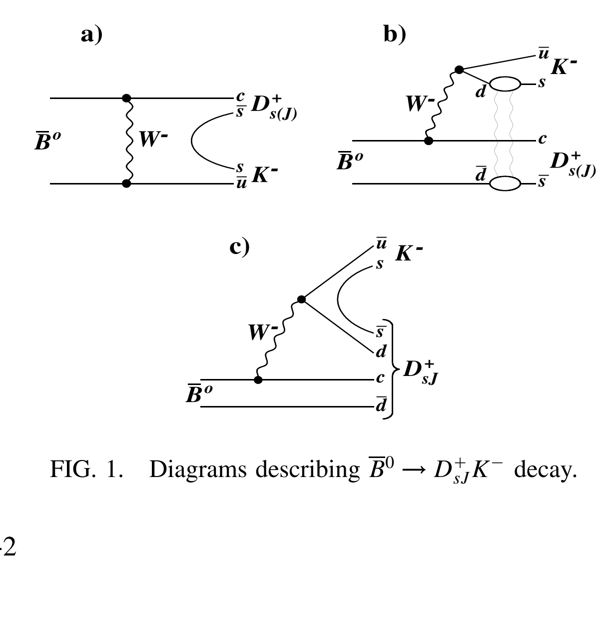

FIG. 1. Diagrams describing $\overline{B}^0 \to D_{sJ}^+ K^-$ decay.

interactions [Fig. 1(b)] [18,19], and cover the range from a few units times 10^{-6} to 10^{-4}. If the D_{sJ} mesons have a four-quark component, then the tree diagram with $s\bar{s}$ pair creation [shown in Fig. 1(c)] may also contribute.

The analysis was performed using a 140 fb^{-1} data sample containing $(152.0 \pm 0.7) \times 10^6$ $B\bar{B}$ pairs. The data were collected with the Belle detector at KEKB [20], an asymmetric energy double storage ring collider with 8 GeV electrons and 3.5 GeV positrons. Belle is a general-purpose large-solid-angle detector that consists of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel Čerenkov counters (ACC), a time of flight counter system (TOF), and a CsI(Tl) electromagnetic calorimeter (ECL) located inside a superconducting solenoidal coil with a 1.5 T magnetic field. The detector is described in detail elsewhere [21].

Charged tracks are required to have momentum $p > 100\ \mathrm{MeV}/c$ [22] and impact parameters less than 2 cm radially and 5 cm in the z direction [23] with respect to the interaction point. Kaon and pion mass hypotheses are assigned using a likelihood ratio $\mathcal{L}_{K/\pi} = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, obtained by combining information from the CDC (dE/dx), ACC, and TOF systems. We require $\mathcal{L}_{K/\pi} > 0.6$ ($\mathcal{L}_{K/\pi} < 0.6$) for kaon (pion) candidates [21]. With these requirements the identification efficiency for particles used in this analysis varies from 91% to 86% for kaons and from 98% to 94% for pions, decreasing as the momentum increases.

ECL clusters with a photonlike shape and energy larger than 50 MeV that are not associated with charged tracks are accepted as photon candidates. Photon pairs of invariant mass within $\pm 12\ \mathrm{MeV}/c^2$ ($\sim 3\sigma$ in the π^0 mass resolution) of the π^0 mass are considered π^0 candidates; the π^0 momentum is required to be larger than $100\ \mathrm{MeV}/c$.

K_S^0 candidates are formed from $\pi^+\pi^-$ pairs with an invariant mass within $\pm 10\ \mathrm{MeV}/c^2$ ($\sim 3\sigma$) of the nominal K_S^0 mass and a common vertex displaced from the interaction point by more than 0.2 cm in the plane perpendicular to the beam direction. A common vertex for the two tracks in the plane perpendicular to the beam direction was found; the difference in z coordinates of the measured pion tracks at this point was required to be less than 2 cm. The angle α between the K_S^0 flight and momentum directions is required to satisfy $\cos\alpha > 0.8$.

Invariant masses of $K^{*0} \to K^+\pi^-$ candidates are required to be within $\pm 50\ \mathrm{MeV}/c^2$ of the nominal K^{*0} mass, and those of $\phi \to K^+K^-$ candidates, within $\pm 12\ \mathrm{MeV}/c^2$ of the ϕ mass. D_s^+ mesons are reconstructed in the $\phi\pi^+$, $\bar{K}^{*0}K^+$, and $K_S^0K^+$ decay channels; a mass window of $\pm 12\ \mathrm{MeV}/c^2$ ($\sim 2.5\sigma$) is imposed in each case.

The D_{sJ} mesons are reconstructed in the $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ and $D_{sJ}(2460)^+ \to D_s^+\gamma$ decay modes. To select a $D_{sJ}^*(2317)^+$, the candidate mass difference $\Delta M(D_{sJ}^*(2317)^+) \equiv M(D_s^+\pi^0) - M(D_s^+)$ is required to lie within $\pm 20\ \mathrm{MeV}/c^2$ of $348.6\ \mathrm{MeV}/c^2$ ($\sim 3.0\sigma$). To select a $D_{sJ}(2460)^+$, we require $\Delta M(D_{sJ}(2460)^+) \equiv M(D_s^+\gamma) - M(D_s^+)$ within $\pm 30\ \mathrm{MeV}/c^2$ of $487.9\ \mathrm{MeV}/c^2$ ($\sim 2.5\sigma$). The D_{sJ} and D_s mass differences were taken from [3].

We then form $\bar{B}^0 \to D_{sJ}^+K^-$ and $D_{sJ}^-\pi^+$ candidates and extract the signal using the energy difference $\Delta E = E_B^{\mathrm{c.m.}} - E_{\mathrm{beam}}^{\mathrm{c.m.}}$ and beam-constrained mass $M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{beam}}^{\mathrm{c.m.}})^2 - (p_B^{\mathrm{c.m.}})^2}$; $E_B^{\mathrm{c.m.}}$ and $p_B^{\mathrm{c.m.}}$ are the energy and momentum of the B candidate in the center-of-mass (c.m.) system and $E_{\mathrm{beam}}^{\mathrm{c.m.}}$ is the c.m. beam energy. Only events within the intervals $M_{\mathrm{bc}} > 5.2\ \mathrm{GeV}/c^2$ and $|\Delta E| < 0.2$ GeV are used in this analysis. The B meson signal region is defined by $|\Delta E| < 0.04$ GeV and $5.272 < M_{\mathrm{bc}} < 5.288\ \mathrm{GeV}/c^2$.

Combinatorial background for channels involving the $D_{sJ}(2460)^+$ was further suppressed by requiring $\cos\theta_{D_s\gamma} < 0.7$. The helicity angle $\theta_{D_s\gamma}$ is defined as the angle between the direction opposite the B momentum and the D_s^+ momentum in the $D_s^+\gamma$ rest frame. This requirement rejects 49% of background events and only 6% of signal events, assuming $J^P = 1^+$ for the $D_{sJ}(2460)^+$. The uncertainty due to this assumption is included in the systematic error.

For events with two or more B candidates, the D_s^+ and π^0 candidates with invariant masses closest to their nominal values and the B daughter K^+ or π^- candidate with the best $\mathcal{L}_{K/\pi}$ value are chosen. With these requirements no multiple entries are allowed for the $D_{sJ}^*(2317)^+$ channels and, according to the Monte Carlo (MC) simulation, less than 1% of selected events will have two B candidates in channels with $D_{sJ}(2460)^+$. No multiple entries are found in the data.

After this selection the principal background is from $e^+e^- \to q\bar{q}$ continuum events ($q = u, d, s$, or c). We exploit the event topology to separate $B\bar{B}$ events (spherical) from the continuum background (jetlike). The ratio of the second and zeroth Fox-Wolfram moments [24] of all particles in the event is required to be less than 0.5. For such events, we form a Fisher discriminant from six modified Fox-Wolfram moments [25]. A signal (background) likelihood $\mathcal{L}_S$ ($\mathcal{L}_{BG}$) is obtained using signal MC (sideband) data from the product of probability density functions for the Fisher discriminant and $\cos\theta_B$, where θ_B is the B flight direction in the c.m. system with respect to the z axis. We require $\mathcal{R} = \mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{BG}) > 0.4$ for $D_s^+ \to \bar{K}^{*0}K^+$ and $\mathcal{R} > 0.25$ for the other D_s^+ decay modes, which have lower backgrounds. For the $\bar{B}^0 \to D_{sJ}^*(2317)^+K^-$ mode these requirements retain 92%, 85%, and 95% of signal events while removing 47%, 67%, and 64% of continuum events, for $D_s^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K_S^0K^+$, respectively. The fractions retained (or removed) for the other B decay modes are similar, varying by a few percent.

The ΔE and $\Delta M(D_{sJ})$ distributions for the various $D_{sJ}^+K^-$ and $D_{sJ}^-\pi^+$ combinations are shown in Fig. 2 for

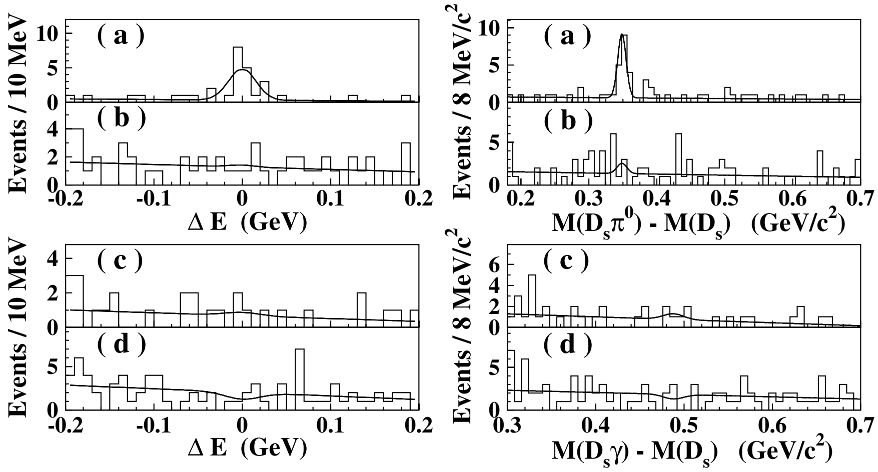

FIG. 2. ΔE (left) and $\Delta M(D_{sJ})$ (right) distributions for $\overline{B}^0$ decays to (a) $D_{sJ}^*(2317)^+K^-$, (b) $D_{sJ}^*(2317)^-\pi^+$, (c) $D_{sJ}(2460)^+K^-$, and (d) $D_{sJ}(2460)^-\pi^+$. Tight requirements on $M_{\rm bc}$ and $\Delta M(D_{sJ})$ (left) or ΔE (right) are applied; see the text.

the range $5.272 < M_{\rm bc} < 5.288$ GeV/c^2. To obtain the $\Delta M(D_{sJ})$ distributions we relax the $\Delta M(D_{sJ})$ requirements and apply a tight selection on ΔE. Each ΔE distribution is fitted by a Gaussian with zero mean and a width fixed from MC data to describe the signal, and a linear background function. The $\Delta M(D_{sJ})$ distributions are described by signal Gaussians with width fixed from MC data and mass differences fixed to 348.6 MeV/c^2 or 487.9 MeV/c^2, and linear backgrounds. A clear $\overline{B}^0 \to D_{sJ}^*(2317)^+K^-$ signal is observed; no significant signals are observed in the remaining modes (Fig. 2). The $\overline{B}^0$ yields, based on fits to histograms combining all three D_s^+ decay modes, are listed in the last four lines of Table I.

Various studies are performed to confirm the $\overline{B}^0 \to D_{sJ}^*(2317)^+K^-$ signal. The parameters of the signal peak are allowed to float in the $\Delta M(D_{sJ})$ fit: a mean (351.2 ± 1.6) MeV/c^2 and a width (6.0 ± 1.2) MeV/c^2 are obtained, in good agreement with the MC expectations, (348.5 ± 0.3) MeV/c^2 and (6.1 ± 0.2) MeV/c^2. [The mass of 2317.5 MeV/c^2 and the zero width are used in the MC simulation of the $D_{sJ}^*(2317)^+$ signal.] Good agreement is also obtained for the signal position and width in ΔE and $M_{\rm bc}$.

To check for a possible background contribution due to a random combination of a $D_{sJ}^*(2317)^+$ meson and a kaon, $\Delta M(D_{sJ}^*(2317)^+)$ distributions are obtained for events from the ΔE sideband $0.05 < |\Delta E| < 0.2$ GeV and the $M_{\rm bc}$ sideband $5.2 < M_{\rm bc} < 5.26$ GeV/c^2. After rescaling the fit results to the B signal region, the background contribution is estimated to be -0.8 ± 0.7 (1.1 ± 0.9) events using the ΔE ($M_{\rm bc}$) sideband. As both ΔE and $M_{\rm bc}$ requirements are applied in the $\Delta M(D_{sJ}^*(2317))$ fit, this background contribution is estimated to be less than one event, and treated as a source of systematic error.

The shape of the background-subtracted and efficiency-corrected $\cos\theta_{D_s\pi}$ distribution for $\overline{B}^0 \to D_{sJ}^*(2317)^+K^-$ decay is compared with those predicted for possible $D_{sJ}^*(2317)^+$ quantum number hypotheses. (The helicity angle $\theta_{D_s\pi}$ is defined as for $\theta_{D_s\gamma}$, with π^0 substituted for γ.) The distribution is expected to be flat if the $D_{sJ}^*(2317)^+$

TABLE I. Signal yields, efficiencies, product branching fractions (or limits), and significances for the $\overline{B}^0 \to D_{sJ}^+K^-$ and $D_{sJ}^-\pi^+$ decay modes. Only statistical errors are shown. Product branching fractions are obtained from $\Delta M(D_{sJ})$ fits: see the text.

Decay mode		Yield $\Delta M(D_{sJ})$	Yield ΔE	Efficiency (10^{-4})	Product $\mathcal{B}(\overline{B}^0 \to D_{sJ}h)\times$ $\mathcal{B}(D_{sJ} \to D_s\pi^0(\gamma))(10^{-5})$	Significance σ
$\overline{B}^0 \to D_{sJ}^*(2317)^+K^-$,	$D_s \to \phi\pi$	$7.5^{+3.1}_{-2.5}$		8.8 ± 0.6	$5.6^{+2.4}_{-1.9}$	4.6
	$D_s \to \overline{K}^{*0}K$	$3.3^{+2.6}_{-1.8}$		7.1 ± 0.5	$3.1^{+2.3}_{-1.7}$	2.3
	$D_s \to K_S^0K$	$5.7^{+2.8}_{-2.1}$		5.8 ± 0.5	$6.6^{+3.2}_{-2.4}$	4.1
	Simultaneous fit				$5.3^{+1.5}_{-1.3}$	6.7
	Sum of three modes	$16.6^{+4.6}_{-4.1}$	17.6 ± 4.5			
$\overline{B}^0 \to D_{sJ}^*(2317)^-\pi^+$		$2.9^{+3.3}_{-2.8}$	0.5 ± 3.3	27.6 ± 1.3	<2.5 (90% C.L.)	
$\overline{B}^0 \to D_{sJ}(2460)^+K^-$		$2.0^{+2.9}_{-2.2}$	1.0 ± 2.9	56.5 ± 2.4	<0.94 (90% C.L.)	
$\overline{B}^0 \to D_{sJ}(2460)^-\pi^+$		$-1.9^{+3.1}_{-2.6}$	-3.9 ± 4.1	65.6 ± 2.6	<0.40 (90% C.L.)	

has $J^P = 0^+$, or to have the form $\cos^2\theta_{D_s\pi}$ in the 1^- case; within large errors, it is consistent with a constant. A fit gives $\chi^2 = 1.44$ for a constant and $\chi^2 = 4.72$ for $\cos^2\theta_{D_s\pi}$, for 4 degrees of freedom. A larger data sample is required for a statistically significant separation of the two hypotheses.

Signal yields, efficiencies, branching fractions, and significances for the studied decay channels are shown in Table I. The $\overline{B}^0 \to D_{sJ}^*(2317)^+K^-$ branching fraction is obtained using a simultaneous fit to the $\Delta M(D_{sJ}^*(2317))$ distributions for the three D_s^+ decay channels, with independent background descriptions, but common values for the signal width (fixed from MC data) and peak position (allowed to float). The branching fraction thus obtained is in good agreement with the values from the ΔE and $M_{\rm bc}$ fits. Efficiencies include all intermediate resonance branching fractions [26] and were obtained from the MC simulation, assuming $J^P = 0^+$ for $D_{sJ}^*(2317)$ and $J^P = 1^+$ for $D_{sJ}(2460)$. We assume equal production of neutral and charged B mesons. The significance is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ and $\mathcal{L}_0$ are likelihoods (corrected for the number of degrees of freedom) for the best fit and zero signal yields, respectively. The upper limits are obtained using fits to $\Delta M(D_{sJ})$ distributions, with fixed signal positions and widths. We use the Feldman-Cousins method [27], assuming a Gaussian distribution for the statistical error. The upper limit is then increased by 29% (the sum in quadrature of the experimental systematic error and the uncertainty in the D_s^+ branching fraction scale). The systematic error is treated in a conservative way in order to avoid Bayesian assumptions about its probability distributions. Other methods for upper limit determinations agree with the values obtained here within 5% for the first two upper limits (that have positive signals) and within 15% for the last upper limit.

The main result of this study is the measurement of the product branching fraction $\mathcal{B}(\overline{B}^0 \to D_{sJ}^*(2317)^+K^-) \times \mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \times 10^{-5}$. The three error terms are the statistical uncertainty, the total systematic error, and the uncertainty due to D_s^+ branching fractions; this last term is dominated by the ~25% uncertainty in $\mathcal{B}(D_s^+ \to \phi\pi^+)$ [26].

The major sources contributing to the systematic error are uncertainties in efficiencies of charged track reconstruction ($1\% \times N_{\rm tracks}$), particle identification for charged pions ($2\% \times N_\pi$) and kaons [$(2\%–3\%) \times N_K$], the photon and π^0 reconstruction efficiencies and energy scale (5%), the K_S^0 vertex reconstruction (3%), the efficiency of the ΔE (2%) and topological likelihood ratio ($\mathcal{R}$) selections (3%), the background and signal shape definition for the B signal (3%), the background subtraction (6%), the change in reconstruction efficiency for the different D_{sJ}^+ quantum number assumptions (4%), the statistical uncertainty of the MC sample used to determine efficiency (4%), and the uncertainty on the number of $B\overline{B}$ pairs (0.5%). These uncertainties were added in quadrature to obtain a total systematic error of 13%.

In conclusion, the $\overline{B}^0 \to D_{sJ}^+K^-$ and $D_{sJ}^-\pi^+$ decay modes were studied for the first time. The $\overline{B}^0 \to D_{sJ}^*(2317)^+K^-$ mode was observed, with a product branching fraction $\mathcal{B}(\overline{B}^0 \to D_{sJ}^*(2317)^+K^-) \times \mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \times 10^{-5}$. Recent measurements imply that the $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ channel is dominant and the $D_{sJ}(2460)^+ \to D_s^+\gamma$ fraction is around 30%. Taking into account these approximate values, we can conclude that $\mathcal{B}(\overline{B}^0 \to D_{sJ}^*(2317)^+K^-)$ is of the same order of magnitude as $\mathcal{B}(\overline{B}^0 \to D_s^+K^-)$ and at least a factor of 2 larger than the $\overline{B}^0 \to D_{sJ}(2460)^+K^-$ branching fraction, in contrast to the naïve expectation that decays with the same spin-doublet $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons would have similar rates. No significant signals for $\overline{B}^0 \to D_{sJ}^-\pi^+$ decays were seen.

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