Observation of $\bar{B}^0 \rightarrow D_{sJ}^{+}(2317) \pi^-$ decay.

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(Dated: March 25, 2022)
Abstract

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

PACS numbers: 13.25.Hw, 14.40.Nd
Two narrow resonances denoted as \( D^*_s(2317)^+ \) and \( D_{sJ}(2460)^+ \) have been observed recently in \( e^+e^- \) continuum interactions \[1, 2, 3, 4\]. These resonances were initially seen in the \( D^*_{sJ}(2317)^+ \rightarrow D_s^+\pi^0 \), \( D_{sJ}(2460)^+ \rightarrow D_s^+\gamma \) and \( D_{sJ}(2460)^+ \rightarrow D_s^+\pi^0 \) 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 \( B \rightarrow D\bar{s}J \) decay modes with branching fractions an order of magnitude less than those for \( B \rightarrow D_s \) decay modes with a pseudoscalar \( D_s \) \[7\]. Angular analysis of \( B \rightarrow D\bar{s}J(2460)^+ \) favors a spin \( 1^+ \) assignment for \( D_{sJ}(2460)^+ \). There has been a significant effort to explain the surprising \( D_{sJ} \) masses \[8\], and some authors have discussed the possibility of four-quark content in the \( D_{sJ}^+ \) \[8, 9, 10, 11, 12\].

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

The decay mode \( B^0 \rightarrow D_{sJ}^+\pi^+ \) can be described by a \( b \rightarrow u \) tree diagram. Within the factorization approach \[15\], the branching fraction ratio \( R_{\pi^+}/D^+ = \mathcal{B}(B^0 \rightarrow D_s^-\pi^+)/\mathcal{B}(B^0 \rightarrow D_s^-D^+) \) is predicted to be \((0.424 \pm 0.041) \cdot |V_{ub}/V_{cb}|^2\) and can be used to obtain the ratio of Cabbibo-Kobayashi-Maskawa matrix elements \( |V_{ub}/V_{cb}| \). Assuming similar ratios \( R_{\pi^+}/D^+ \) for \( D_s \) and \( D_{sJ} \) mesons, only a few \( \bar{B}^0 \rightarrow D_{sJ}^+\pi^+ \) events would be observed in the current Belle data sample. The decays \( \bar{B}^0 \rightarrow D_{sJ}^+K^- \) are of special interest because the quark content of the initial \( \bar{B}^0 \) meson \((bd)\) is completely different from that of the \( D_{sJ}^+K^- \) final state \((css\bar{u})\), indicating an unusual configuration with both initial quarks involved in the weak decay. Branching fractions for the pseudoscalar \( D_s^+ \) meson \( \mathcal{B}(\bar{B}^0 \rightarrow D_s^+K^-) = (4.6^{+1.2}_{-1.3}) \cdot 10^{-5} \) and \( (3.2 \pm 1.0 \pm 1.0) \cdot 10^{-5} \) 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 PQCD factorization \( W \) exchange process (Fig. 1a) \[16, 17\] or, alternatively, from final state interactions (Fig. 1b) \[18, 19\], 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 \( ss \) pair creation (shown in Fig. 1c) may also contribute.

\[\text{FIG. 1: Diagrams describing } \bar{B}^0 \rightarrow D_{sJ}^+K^- \text{ decay.}\]

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 (SVD), 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 \( p > 100 \text{MeV}/c \) 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 \( \pm 12 \text{MeV}/c^2 \) \((\sim 3\sigma \text{ in the } \pi^0\) mass resolution) of the \( \pi^0\) mass are considered \( \pi^0\) candidates; the \( \pi^0\) momentum is required to be larger than 100 MeV/c.

\( K_S^0 \) candidates are formed from \( \pi^+\pi^- \) pairs with an invariant mass within \( \pm 10 \text{MeV}/c^2 \) \((\sim 3\sigma)\) 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 \( \alpha \) between the \( K_S^0 \) flight and momentum directions is required to satisfy \( \cos \alpha > 0.8 \).

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

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

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

Combinatorial background for channels involving the \( D_{sJ}^*(2460)^+ \) was further suppressed by requiring \( \cos \theta_{D_{sJ}\gamma} < 0.7 \). The helicity angle \( \theta_{D_{sJ}\gamma} \) is defined as the angle between the direction opposite the \( B \) momentum and the \( D_s^+ \) momentum in the \( D_{sJ}\gamma \) 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 \( \pi^0 \) candidates with invariant masses closest to their nominal values and the \( B \) daughter \( K^+ \) or \( \pi^- \) 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 $e^+e^- \rightarrow q\bar{q}$ continuum events ($q = u, d, s, \text{or} c$). 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 $L_S$ ($L_{BG}$) is obtained using signal MC (sideband) data from the product of probability density functions for the Fisher discriminant and $\cos\theta_B$, where $\theta_B$ is the $B$ flight direction in the CM system with respect to the $z$ axis. We require $R = L_S/(L_S + L_{BG}) > 0.4$ for $D_s^+ \rightarrow \bar{K}^{*0}K^+$ and $R > 0.25$ for the other $D_s^+$ decay modes, which have lower backgrounds. For the $B^0 \rightarrow D_{sJ}^+(2317)^+K^-$ mode these requirements retain 92%, 85%, and 95% of signal events while removing 47%, 67%, and 64% of continuum events, for $D_{sJ}^+ \rightarrow \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K_0^S K^+$, respectively. The fractions retained (or removed) for the other $B$ decay modes are similar, varying by a few percent.

The $\Delta E$ and $\Delta M(D_{sJ})$ distributions for the various $D_{sJ}^+K^-$ and $D_{sJ}^-\pi^+$ combinations are shown in Fig. 2 for the range $5.272 \text{GeV}/c^2 < M_{bc} < 5.288 \text{GeV}/c^2$. To obtain the $\Delta M(D_{sJ})$ distributions we relax the $\Delta M(D_{sJ})$ requirements and apply a tight selection on $\Delta E$. Each $\Delta E$ 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 widths 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 $B^0 \rightarrow D_{sJ}^+(2317)^+K^-$ signal is observed; no significant signals are observed in the remaining modes (Fig. 2). The $B^0$ yields, based on fits to histograms combining all three $D_s^+$ decay modes, are listed in the

![FIG. 2: $\Delta E$ (left) and $\Delta M(D_{sJ})$ (right) distributions for $B^0$ 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 $M_{bc}$, and $\Delta M(D_{sJ})$ (left) or $\Delta E$ (right) are applied; see the text.](image-url)
TABLE I: Signal yields, efficiencies, product branching fractions (or limits), and significances for the $B^0 \to D_{sJ}^+ K^-$ 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 $\Delta E$ | Efficiency $(10^{-4})$ | Product $\mathcal{B}(B^0 \to D_{sJ}h) \times 10^{-5}$ | Signif. |
|--------------------|--------------------------|-----------------|------------------------|----------------------------------------------------------|---------|
| $B^0 \to D_{sJ}^*(2317)^+ K^-$ |                         |                 |                        |                                                          |         |
| $D_s \to \phi \pi$ | $7.5^{+3.1}_{-2.5}$   | $8.8 \pm 0.6$  | $8.6^{+2.4}_{-1.9}$  | $5.6 \pm 2.4$                                            | $4.6$   |
| $D_s \to \bar{K}^{*0} K$ | $3.3^{+2.6}_{-1.8}$   | $7.1 \pm 0.5$  | $3.1^{+2.3}_{-1.7}$  | $2.3$                                                    |         |
| $D_s \to K_s^0 \pi^+$ | $5.7^{+2.8}_{-2.1}$   | $5.8 \pm 0.5$  | $6.6^{+3.2}_{-2.4}$  | $4.1$                                                    |         |
| Simultaneous fit |                         |                 |                        |                                                          | $5.3^{+1.5}_{-1.3}$ | $6.7$   |
| Sum of three modes | $16.6^{+4.6}_{-4.1}$ | $17.6 \pm 4.5$ |                        |                                                          |         |

Various studies are performed to confirm the $B^0 \to D_{sJ}^*(2317)^+ K^-$ signal. The parameters of the signal peak are allowed to float in the $\Delta M(D_{sJ})$ fit: a mean (351.2 $\pm$ 1.6) MeV/$c^2$ and a width (6.0 $\pm$ 1.2) MeV/$c^2$ are obtained, in good agreement with the MC expectations, (348.5 $\pm$ 0.3) MeV/$c^2$ and (6.1 $\pm$ 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 $\Delta E$ and $M_{bc}$.

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 $\Delta E$ sideband 0.05 GeV $< |\Delta E| < 0.2$ GeV, and the $M_{bc}$ sideband 5.2 GeV/$c^2 < M_{bc} < 5.26$ GeV/$c^2$. After rescaling the fit results to the $B$ signal region, the background contribution is estimated to be $-0.8 \pm 0.7$ (1.1 $\pm$ 0.9) events using the $\Delta E$ ($M_{bc}$) sideband. As both $\Delta E$ and $M_{bc}$ 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 $B^0 \to D_{sJ}^*(2317)^+ K^-$ decay is compared with those predicted for possible $D_s^{*+}(2317)^+$ quantum number hypotheses. (The helicity angle $\theta_{D_s \pi}$ is defined as $\theta_{D_s \pi}$, with $\pi^0$ substituted for $\gamma$.) The distribution is expected to be flat if the $D_s^{*+}(2317)^+$ 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 four 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 $B^0 \to D_{sJ}^*(2317)^+ K^-$ 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) and peak position (allowed to float). The branching fraction thus obtained is in good agreement with the values from the $\Delta E$ and $M_{bc}$ fits. Efficiencies include all interme-
of the MC sample used to determine efficiency (4%); and the uncertainty on the number of D meson measurements imply that the racetrack reconstruction (1% error terms are the statistical uncertainty, the total systematic error, and the uncertainty of charged track reconstruction (1%)

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 $\mathcal{B}(\overline{B}^0 \rightarrow D_{sJ}^+(2317)^+ K^-) \times \mathcal{B}(D_{sJ}^+(2317)^+ \rightarrow D_s^+ \pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \cdot 10^{-5}$. 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 $\sim 25\%$ uncertainty in $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+)$. [26]

The major sources contributing to the systematic error are uncertainties in efficiencies of charged track reconstruction (1% $\times N_{\text{tracks}}$), particle identification for charged pions (2% $\times N_{\pi^-}$) and kaons (2-3% $\times N_K$); the photon and $\pi^0$ reconstruction efficiencies and energy scale (5%); the $K_S^0$ vertex reconstruction (3%); the efficiency of the $\Delta E$ (2%) and topological likelihood ratio ($\mathcal{R}$) selections (3%); the background and signal shape definition for the $B$ signal (3%); 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 $\overline{B}^0 \rightarrow D_{sJ}^+ K^-$ and $D_{sJ}^- \pi^+$ decay modes were studied for the first time. The $\overline{B}^0 \rightarrow D_{sJ}^+(2317)^+ K^-$ mode was observed, with a product branching fraction $\mathcal{B}(\overline{B}^0 \rightarrow D_{sJ}^+(2317)^+ K^-) \times \mathcal{B}(D_{sJ}^+(2317)^+ \rightarrow D_s^+ \pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \cdot 10^{-5}$. Recent measurements imply that the $D_{sJ}^+(2317)^+ \rightarrow D_s^+ \pi^0$ channel is dominant and the $D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma$ fraction is around 30%. Taking into account these approximate values, we can conclude that $\mathcal{B}(\overline{B}^0 \rightarrow D_{sJ}^+(2317)^+ K^-)$ is of the same order of magnitude as $\mathcal{B}(\overline{B}^0 \rightarrow D_s^+ K^-)$ and at least a factor of two larger than the $\overline{B}^0 \rightarrow D_{sJ}(2460)^+ K^-$ branching fraction, in contrast to the naive expectation that decays with the same spin-doublet $D_{sJ}^+(2317)^+$ and $D_{sJ}(2460)^+$ mesons would have similar rates. No significant signals for $\overline{B}^0 \rightarrow D_{sJ}^- \pi^+$ decays were seen.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (contract No. 10175071, China); DST (India); the BK21 program of MOEHRD and the CHEP SRC program of KOSEF (Korea); KBN (contract No. 2P03B 01324, Poland); MIST (Russia); MESS (Slovenia); Swiss NSF; NSC and MOE (Taiwan); and DOE (USA).
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