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Study of exclusive *B* decays to charmed baryons

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Using 29.1 fb^{-1} of data accumulated at the $\Upsilon(4S)$ with the Belle detector at KEKB, we have studied the decay modes $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$, $B^- \to \Lambda_c^+ \overline{p} \pi^-$, and $\overline{B}^0 \to \Lambda_c^+ \overline{p}$. We report branching fractions of exclusive B decays to charmed baryons with four-, three- and two-body final states, including intermediate Σ_c^{++} and Σ_c^0 states. We observed $\overline{B}^0 \to \Sigma_c(2455)^{++} \overline{p} \pi^-$ for the first time with a branching fraction of $(2.38^{+0.63}_{-0.55} \pm 0.41 \pm 0.62) \times 10^{-4}$ and observed evidence for the two-body decay $B^- \to \Sigma_c(2455)^0 \overline{p}$ with a branching fraction of $(0.45^{+0.26}_{-0.19} \pm 0.07 \pm 0.12) \times 10^{-4}$. We also set improved upper limits for the two-body decays $\overline{B}^0 \to \Lambda_c^+ \overline{p}$ and $B^- \to \Sigma_c(2520)^0 \overline{p}$.

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Baryon production in flavored meson decays is unique to the B meson system due to the heavy mass of the constituent b quark. Several studies of inclusive charmed baryon production in B meson decays [1] have been made and a large branching fraction for $\overline{B} \to \Lambda_c^+ X$ of $(6.4 \pm 1.1)\%$ has been reported. However, the mechanism is not well understood. The measured inclusive Λ_c^+ momentum spectra indicate that multibody final states are dominant in baryonic B decays. With a data sample of 2.39 fb^{-1}, CLEO [2] has studied exclusive charmed baryonic decay modes and measured the branching fractions for $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ and $B^- \to \Lambda_c^+ \overline{p} \pi^-$. They found no evidence for $\overline{B}^0 \to \Lambda_c^+ \overline{p}$ and provided an upper limit. So far, no observations of two-body decays have been reported. On the other hand, there are theoretical predictions for branching fractions of two-body baryonic modes based on a pole model [3], a QCD sum rule [4], a diquark model [5], and a bag model [6]. The predictions of the different models vary by an order of magnitude, and experimental measurement can be used to discriminate among them. We have made a systematic study of exclusive charmed baryonic decays of $\overline{B}^0$ and B^- mesons into four-, three- and two-body final states including $\Sigma_c^{++/0}$ intermediate resonances, by analyzing the $\Lambda_c^+ \overline{p} \pi^+ \pi^-$, $\Lambda_c^+ \overline{p} \pi^-$ and $\Lambda_c^+ \overline{p}$ final states. Charge conjugate modes are included unless otherwise mentioned. This analysis is based on a data sample of 29.1 fb^{-1} corresponding to 3.17×10^7 $B\overline{B}$ pairs. The data were accumulated at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric collider of 3.5 GeV e^+ and 8.0 GeV e^- [7].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer cylindrical drift chamber (CDC), a mosaic of aerogel threshold Čerenkov counters (ACC), a barrel-like array of time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect muons and K_L mesons (KLM). The detector is described in detail elsewhere [8]. We use a GEANT based Monte Carlo (MC) simulation to model the response of the detector and determine the acceptance [9].

In searches for the decay modes $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$, $B^- \to \Lambda_c^+ \overline{p} \pi^-$, and $\overline{B}^0 \to \Lambda_c^+ \overline{p}$, the $\Lambda_c^+ \to p K^- \pi^+$ decay mode is used. Particle identification information from the CDC dE/dx, ACC and TOF is used to provide a mass assignment for each track. A likelihood ratio $LR(A,B) = L_A/(L_A + L_B) > 0.6$ is required to identify a particle as type A, where B is

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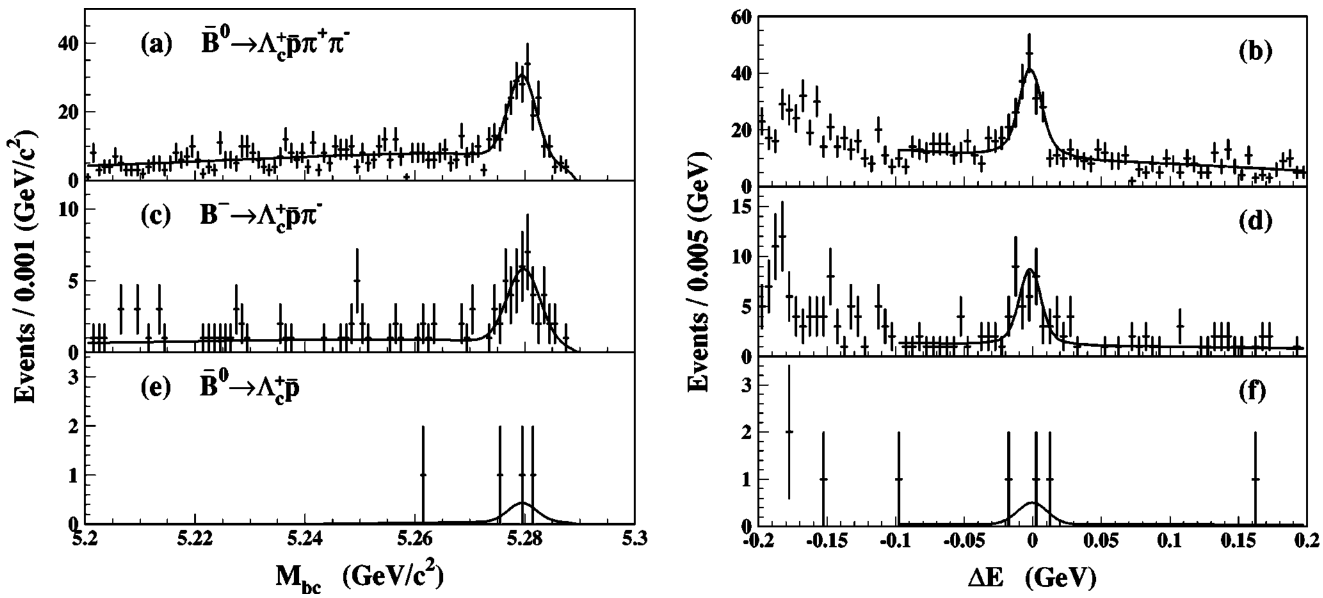

FIG. 1. $M_{\rm bc}$ distributions for $|\Delta E|<0.030$ GeV and ΔE distributions for $M_{\rm bc}>5.270$ GeV/c^2: (a) and (b) for $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$, (c) and (d) for $B^- \to \Lambda_c^+ \overline{p} \pi^-$, and (e) and (f) for $\overline{B}^0 \to \Lambda_c^+ \overline{p}$. Points with errors indicate the data and the curves indicate fits (see text for details).

the other possible assignment among $\pi^\pm$, $K^\pm$ and $p(\overline{p})$. Electron and muon candidate tracks are removed if their probabilities from the ECL, CDC dE/dx and KLM are greater than 95%. Candidate Λ_c^+'s are tagged if the invariant mass of the p, K^- and π^+ track combination is within 0.010 GeV/c^2 of the Λ_c^+ mass; tagged events are then examined for the three search modes by adding $\overline{p}$, π^-, and π^+ tracks. The width $\sigma_{\Lambda_c^+}$ is found to be 4.9 MeV/c^2, consistent with the MC simulation.

In order to select $\overline{B}$ meson candidates, we use the beam energy-constrained mass and energy difference, which are defined as $M_{\rm bc}=\sqrt{E_{\rm beam}^2-(\Sigma \vec{p}_i)^2}$ and $\Delta E=\Sigma E_i - E_{\rm beam}$ in the center-of-mass (c.m.) frame of the e^+e^- collision. $E_{\rm beam}$ is the beam energy, and E_i and $\vec{p}_i$ are the energy and momentum vector for the i-th daughter particle of a B candidate. B candidates are selected with a loose cut to retain sideband events by requiring $M_{\rm bc}>5.2\,{\rm GeV}/c^2$ and $|\Delta E|<0.2$ GeV. A vertex-constrained fit for the three daughter tracks is carried out at the Λ_c^+ vertex. For each decay mode, the virtual Λ_c^+ track and additional tracks are required to form a good vertex. If there are multiple candidates for both Λ_c^+ and B, the candidate with the minimum $\chi^2=\chi^2_{\Lambda_c^+}+\chi^2_B+(M_{\rm bc}-5.279)^2/\sigma^2_{M_{\rm bc}}$ is selected. Here, $\chi^2_{\Lambda_c^+}$ and χ^2_B are the χ^2's from the fits for the Λ_c^+ and B vertices, respectively, and $\sigma_{M_{\rm bc}}$ is the MC value of the $M_{\rm bc}$ width (2.8 MeV/c^2). Loose cuts on $\chi^2_{\Lambda_c^+}$ and χ^2_B are applied to remove background from tracks arising from K_S^0 and Λ decays.

Event selection requirements are optimized using signal MC events and continuum background MC events consisting of $u\overline{u}$, $d\overline{d}$, $s\overline{s}$, and $c\overline{c}$ quark-antiquark pairs generated with the expected fractions. To suppress the continuum background, we use a Fisher discriminant constructed from 10 variables: 8 modified Fox Wolfram moments [10], $\cos\Theta_B$, and $\cos\Theta_{\Lambda_c^+}$. Here, $\cos\Theta_B$ is the cosine of the direction of the B meson with respect to the electron beam direction, and $\cos\Theta_{\Lambda_c^+}$ is the cosine of the direction of the daughter Λ_c^+ with respect to the thrust axis of the tracks not associated with the B candidates. Both quantities are defined in the c.m. system. A set of 10 coefficients for each mode is optimized to maximize separation of the signal from the continuum background. The probability density functions for the signals and for the continuum, $P_{\rm sig}$ and $P_{\rm con}$, respectively, are parametrized with Gaussian functions for the three search

TABLE I. Branching fractions for $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$, $B^- \to \Lambda_c^+ \overline{p} \pi^-$, and $\overline{B}^0 \to \Lambda_c^+ \overline{p}$. The errors are statistical, systematic, and a common error due to the uncertainty in the value of $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$. The CLEO results are renormalized to $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)=(5.0\pm1.3)\%$ [12] for comparison.

Mode	Efficiency (%)	Yield	Significance	$\mathcal{B}$ ($\times 10^{-4}$)	CLEO ($\times 10^{-4}$)
$\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$	8.07	141^{+16}_{-15}	12.2	$11.0^{+1.2}_{-1.2}\pm1.9\pm2.9$	$11.7^{+4.0}_{-3.7}\pm2.7\pm3.0$
$B^- \to \Lambda_c^+ \overline{p} \pi^-$	10.2	$30.2^{+7.0}_{-6.4}$	6.0	$1.87^{+0.43}_{-0.40}\pm0.28\pm0.49$	$5.5^{+2.0}_{-1.8}\pm1.0\pm1.4$
$\overline{B}^0 \to \Lambda_c^+ \overline{p}$	12.9	$2.4^{+2.1}_{-1.5}$	1.9	$0.12^{+0.10}_{-0.07}\pm0.02\pm0.03$	
		<6.1 (90% C.L.)		<0.31 (90% C.L.)	<1.85 (90% C.L.)

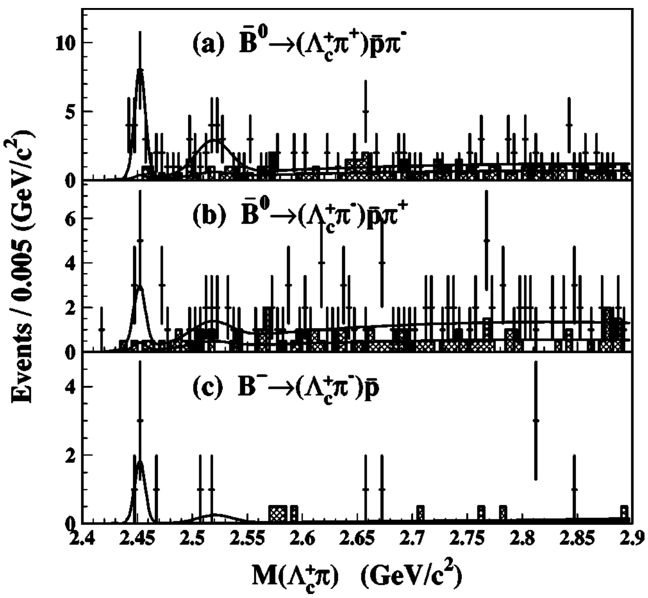

FIG. 2. Invariant mass distributions (a) $M(\Lambda_c^+\pi^+)$ and (b) $M(\Lambda_c^+\pi^-)$ for $\overline{B}^0\to\Lambda_c^+\overline{p}\pi^+\pi^-$, and (c) $M(\Lambda_c^+\pi^-)$ for $B^-\to\Lambda_c^+\overline{p}\pi^-$. Points with errors and shaded histograms indicate the distributions for the B signal and the sideband regions, respectively. The curves indicate fits (see text for details).

modes and for the continuum events. A cut on the likelihood ratio $R_{\rm sfw}=P_{\rm sig}/(P_{\rm sig}+P_{\rm con})>0.6$ is applied to all decay modes. In the MC simulation this cut removed 76% of the continuum background while retaining 86% of the signal for $\Lambda_c^+\overline{p}\pi^+\pi^-$.

Figure 1 shows the $M_{\rm bc}$ and ΔE distributions for the three decay modes, after a tight cut is made in the (ΔE, $M_{\rm bc}$) variable not plotted. The $M_{\rm bc}$ background distributions are parametrized by the ARGUS function [11], while a Gaussian is used for the signal. The ΔE distributions are fitted with a second-order polynomial for the background and a double Gaussian for the signal. Here, the width parameters are fixed to the values fitted to the signal MC events. The mean and width of $M_{\rm bc}$ in the data are found to be consistent with the MC values of 5.279 GeV/c^2 and 2.8 MeV/c^2, respectively. The width of ΔE is also consistent with the MC value (9.9 MeV) when fit to a single Gaussian. We obtain signal yields of 154^{+17}_{-16} and $38.8^{+7.6}_{-7.0}$ from the fits to the $M_{\rm bc}$ distributions (a) and (c), and 141^{+16}_{-15} and $30.2^{+7.0}_{-6.4}$ from the fits to the ΔE distributions (b) and (d), respectively. Here, we choose the asymmetric range of $-0.100<\Delta E<0.200$ GeV to exclude feed-down from higher multiplicity modes with extra pions; these produce the structure observed in the region $\Delta E<-0.150$ GeV. Since $M_{\rm bc}$ is used in the χ^2 calculation for the best candidate selection as described previously, we use the yields resulting from the fits to the ΔE distributions to calculate branching fractions.

We observe $\overline{B}^0\to\Lambda_c^+\overline{p}\pi^+\pi^-$ and $B^-\to\Lambda_c^+\overline{p}\pi^-$ signals. For $\overline{B}^0\to\Lambda_c^+\overline{p}$ we find a statistical significance of only 1.9σ from a fit to a Gaussian function for the signal with mean and width fixed to those from the signal MC simulation, and a linear background function. We thus set an upper limit of 6.1 events at the 90% confidence level based on the likelihood function, using the Bayesian method with a prior uniform in the branching fraction.

Table I summarizes the observed yields and branching fractions. Here, the detection efficiencies are calculated assuming nonresonant decays and do not include the branching fraction $\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)=(5.0\pm1.3)\%$ [12]. We assume the fractions of charged and neutral B mesons to be equal in the branching fraction calculations. We include a correlated systematic error of 2% per track for tracking and particle identification. Systematics due to the $\chi^2_{\Lambda_c^+}$, χ^2_B and $R_{\rm sfw}$ cuts are estimated by varying cut values. The signal shape systematic error is evaluated from the variation in fit results obtained with different-order polynomials used for the background and single and double Gaussians used for the signal. The resulting total systematic errors for $\Lambda_c^+\overline{p}\pi^+\pi^-$, $\Lambda_c^+\overline{p}\pi^-$ and $\Lambda_c^+\overline{p}$ are 17.2%, 14.8% and 13.3%, respectively. Table I shows the CLEO measurements renormalized to the same $\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)$ for comparison. Our branching fraction for $\overline{B}^0\to\Lambda_c^+\overline{p}\pi^+\pi^-$ is consistent with their measurement; however, our result for $B^-\to\Lambda_c^+\overline{p}\pi^-$ is somewhat lower (1.5σ). We also set a more restrictive upper limit on $\overline{B}^0\to\Lambda_c^+\overline{p}$.

TABLE II. Efficiencies, yields, significances and branching fractions for decay modes with $\Sigma_c^{++/0}$ resonances. The errors are statistical, systematic, and a common error due to the uncertainty in the value of $\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)$.

Mode	Efficiency (%)	Yield	Significance	$\mathcal{B}$ ($\times10^{-4}$)
$\overline{B}^0\to\Sigma_c(2455)^{++}\overline{p}\pi^-$	4.93	$18.6^{+4.9}_{-4.3}$	5.3	$2.38^{+0.63}_{-0.55}\pm0.41\pm0.62$
$\overline{B}^0\to\Sigma_c(2520)^{++}\overline{p}\pi^-$	6.38	$16.5^{+5.8}_{-5.2}$	3.5	$1.63^{+0.57}_{-0.51}\pm0.28\pm0.42$
$\overline{B}^0\to\Sigma_c(2455)^{0}\overline{p}\pi^+$	4.80	$6.4^{+3.2}_{-2.7}$	2.6	$0.84^{+0.42}_{-0.35}\pm0.14\pm0.22$
		<11.6 (90% C.L.)		<1.59 (90% C.L.)
$\overline{B}^0\to\Sigma_c(2520)^{0}\overline{p}\pi^+$	6.35	$4.8^{+4.5}_{-4.0}$	1.2	$0.48^{+0.45}_{-0.40}\pm0.08\pm0.12$
		<11.7 (90% C.L.)		<1.21 (90% C.L.)
$B^-\to\Sigma_c(2455)^{0}\overline{p}$	6.00	$4.3^{+2.5}_{-1.8}$	3.0	$0.45^{+0.26}_{-0.19}\pm0.07\pm0.12$
		<8.5 (90% C.L.)		<0.93 (90% C.L.)
$B^-\to\Sigma_c(2520)^{0}\overline{p}$	7.47	$1.7^{+1.8}_{-1.1}$	1.8	$0.14^{+0.15}_{-0.09}\pm0.02\pm0.04$
		<5.2 (90% C.L.)		<0.46 (90% C.L.)

Figure 2 shows the $\Lambda_c^+\pi^\pm$ invariant mass distributions in the B signal region, $|\Delta E|<0.030$ GeV and $M_{\rm bc}>5.270$ GeV/c^2. Significant signals are observed for the $\Sigma_c(2455)$ and $\Sigma_c(2520)$. The shaded histograms are the distributions for events in the sideband region $0.040<|\Delta E|<0.100$ GeV, normalized to the signal region $|\Delta E|<0.030$ GeV; these account for continuum Σ_c background. The two curves indicate the results of separate fits to the distributions for the B signal and the sideband regions, with Σ_c masses and widths fixed to fit values for the signal MC events generated with Particle Data Group (PDG) values for masses and widths [12]. The background shapes are taken from a nonresonant signal MC. To extract the Σ_c yields, we performed a simultaneous likelihood fit to the distributions for the B signal and sideband regions. We express the expected number N_{Σ_c} of B events as $N_{\Sigma_c}=N_{Bb}-r\cdot N_{sb}$, where N_{Bb} is the yield in the B signal region, N_{sb} is the yield in the sideband region, and $r=0.5$ is the normalization factor due to the ratio of their ΔE ranges, assuming a linear background shape.

Table II summarizes the observed signal yields and branching fractions. We observe the $\overline{B}^0\to\Sigma_c(2455)^{++}\overline{p}\pi^-$ decay for the first time with a statistical significance of 5.3σ. We also see 3.5σ evidence for $\overline{B}^0\to\Sigma_c(2520)^{++}\overline{p}\pi^-$, $2.6\,\sigma$ evidence for $\overline{B}^0\to\Sigma_c(2455)^0\overline{p}\pi^+$, and less evidence for $\overline{B}^0\to\Sigma_c(2520)^0\overline{p}\pi^+$. We see $3.0\,\sigma$ evidence for the two-body decay $B^-\to\Sigma_c(2455)^0\overline{p}$, and less evidence for $B^-\to\Sigma_c(2520)^0\overline{p}$. For those modes with a significance of three sigmas or less, we set upper limits on their branching fractions.

Our results provide stringent constraints upon theoretical predictions [3–6]. The predictions for $\overline{B}^0\to\Lambda_c^+\overline{p}$ in [3–5] were already much larger than the CLEO experimental upper limit [2]; here we set an even more restrictive upper limit. A recent study based on a bag model [6] gives predictions of branching fractions of $\leqslant(0.1\sim0.3)\times10^{-4}$ for $\overline{B}^0\to\Lambda_c^+\overline{p}$ and $(4.3\sim15.1)\times10^{-4}$ for $B^-\to\Lambda_c^+\overline{p}\pi^-$. Our upper limit for $\overline{B}^0\to\Lambda_c^+\overline{p}$ does not contradict this model, while our measured result for $B^-\to\Lambda_c^+\overline{p}\pi^-$ is much smaller than its predicted value.

In summary, we have observed the exclusive three-body decay $\overline{B}^0\to\Sigma_c(2455)^{++}\overline{p}\pi^-$ for the first time and observed evidence for the exclusive two-body decay $B^-\to\Sigma_c(2455)^0\overline{p}$. We make improved measurements of the branching fractions for $\overline{B}^0\to\Lambda_c^+\overline{p}\pi^+\pi^-$ and $B^-\to\Lambda_c^+\overline{p}\pi^-$, and also set a more restrictive upper limit on $\overline{B}^0\to\Lambda_c^+\overline{p}$.

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