Recent results of charmed baryon decays at Belle

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Abstract

We report the recent results of charmed baryon decays, based on the data collected by the Belle experiment at the KEKB collider. This includes the observation of the doubly Cabibbo-suppressed decay $\Lambda_c^+ \rightarrow \pi^- K^+ p$, search for the decay $\Lambda_c^+ \rightarrow \phi p \pi^0$, and the branching fraction measurement of $\Lambda_c^+ \rightarrow \pi^+ K^- p \pi^0$.

1 Introduction

In this report, we present the recent results of charmed baryon decays based on the data collected by the Belle experiment at the KEKB $e^+ e^-$ asymmetric-energy collider\textsuperscript{1}. (Throughout this paper charge-conjugate modes are implied.) The experiment took data at center-of-mass energies corresponding to several $\Upsilon(nS)$ resonances; the total data sample recorded exceeds 1 ab$^{-1}$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere\textsuperscript{2, 3}.

2 Observation of the doubly Cabibbo-suppressed $\Lambda_c^+$ decay

Several doubly Cabibbo-suppressed (DCS) decays of charmed mesons have been observed\textsuperscript{4}. Their measured branching ratios with respect to the corresponding Cabibbo-favored (CF) decays play an important role in constraining models of the decay of charmed hadrons and in the study of flavor- $SU(3)$ symmetry\textsuperscript{5, 6}. On the other hand, because of the smaller production cross-sections for charmed baryons, DCS decays of charmed baryons have not yet been observed, and only an upper limit, $\frac{\mathcal{B}(\Lambda_c^+ \rightarrow p K^+ \pi^-)}{\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)} < 0.46\%$ at 90\% confidence level (CL), has been reported by the

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FOCUS Collaboration [7]. Here we present the first observation of the DCS decay $\Lambda_c^+ \to pK^+\pi^-$ and the measurement of its branching ratio with respect to the CF decay $\Lambda_c^+ \to pK^-\pi^+$, using 980 fb$^{-1}$ of data [8].

Figure 1 shows invariant mass distributions of (a) $pK^-\pi^+$ (CF) and (b) $pK^+\pi^-$ (DCS) combinations. DCS decay events are clearly observed in $M(pK^+\pi^-)$. In order to obtain the signal yield, a binned least-$\chi^2$ fit is performed. From the mass fit, we extract $(1.452 \pm 0.015) \times 10^6 \Lambda_c^+ \to pK^-\pi^+$ events and $3587 \pm 380 \Lambda_c^+ \to pK^+\pi^-$ events. The latter has a peaking background from the single Cabibbo-suppressed (SCS) decay $\Lambda_c^+ \to \Lambda(\to p\pi^-)K^+$, which has the same final-state topology. After subtracting the SCS contribution, we have $3379 \pm 380 \pm 78$ DCS events, where the first uncertainty is statistical and the second is the systematic due to SCS subtraction. The corresponding statistical significance is 9.4 standard deviations. We measure the branching ratio,

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3},$$

where the uncertainties are statistical and systematic, respectively. This measured branching ratio corresponds to $(0.82 \pm 0.21)\tan^4\theta_c$, where the uncertainty is the total, which is consistent within 1.5 standard deviations with the naive expectation ($\sim \tan^4\theta_c$ [7]). Multiplying this ratio with the previously measured $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$ by the Belle Collaboration [9], we obtain the absolute branching fraction of the DCS decay,

$$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4},$$

where the first uncertainty is the total uncertainty of the branching ratio and the second is uncertainty of the branching fraction of the CF decay. After subtracting the contributions of $\Lambda^*(1520)$ and $\Delta$ isobar intermediates, which contribute only to the CF decay, the revised ratio, $\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.10 \pm 0.17)\tan^4\theta_c$ is consistent with the naive expectation within 1.0 standard deviation.

3 Search for $\Lambda_c^+ \to \phi p\pi^0$ and branching fraction measurement of $\Lambda_c^+ \to K^-\pi^+ p\pi^0$

The story of exotic hadron spectroscopy begins with the discovery of the $X(3872)$ by the Belle collaboration in 2003 [10]. Since then, many exotic XYZ states have been reported by Belle and other experiments [4]. Recent observations of two hidden-charm pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$ by the LHCb collaboration in the $J/\psi p$ invariant mass spectrum of the $\Lambda_0^b \to J/\psi pK^-$ process [11] raises the question of whether a hidden-strangeness pentaquark $P_s^+$, where the $c\bar{s}$ pair in $P_c^+$ is replaced by an $s\bar{s}$ pair, exists [13, 12, 14]. The strange-flavor analogue of the $P_c^+$ discovery
channel is the decay $\Lambda_c^+ \rightarrow \phi p \pi^0$ [13, 14], shown in Fig. 2 (a). The detection of a hidden-strangeness pentaquark could be possible through the $\phi p$ invariant mass spectrum within this channel [see Fig. 2 (b)] if the underlying mechanism creating the $P_s^+$ states also holds for $P_s^+$, independent of the flavor [14], and only if the mass of $P_s^+$ is less than $M_{\Lambda_c^+} - M_{\pi^0}$. In an analogous $s\bar{s}$ process of $\phi$ photoproduction ($\gamma p \rightarrow \phi p$), a forward-angle bump structure at $\sqrt{s} \approx 2.0$ GeV has been observed by the LEPS [15] and CLAS collaborations [16]. However, this structure appears only at the most forward angles, which is not expected for the decay of a resonance [17].

Previously, the decay $\Lambda_c^+ \rightarrow \phi p \pi^0$ has not been studied by any experiment. Here, we report a search for this decay, using 915 fb$^{-1}$ of data [18]. In addition, we search for the nonresonant decay $\Lambda_c^+ \rightarrow K^+K^-p\pi^0$ and measure the branching fraction of the Cabibbo-favored decay $\Lambda_c^+ \rightarrow K^-\pi^+p\pi^0$.

In order to extract the signal yield, we perform a two-dimensional (2D) unbinned extended maximum likelihood fit to the variables $m(K^+K^-p\pi^0)$ and $m(K^+K^-)$. Projections of the fit result are shown in Fig. 3. From the fit, we extract $148.4 \pm 61.8$. 

Figure 1: Distributions of (a) $M(pK^-\pi^+)$ and (b) $M(pK^+\pi^-)$ and residuals of data with respect to the fitted combinatorial background. The solid curves indicate the full fit model and the dashed curves the combinatorial background.

Figure 2: Feynman diagram for the decay (a) $\Lambda_c^+ \rightarrow \phi p \pi^0$ and (b) $\Lambda_c^+ \rightarrow P_s^+\pi^0$. 

Figure 3: Projections of the fit result for the variables $m(K^+K^-p\pi^0)$ and $m(K^+K^-)$. From the fit, we extract $148.4 \pm 61.8$. 

signal events, $75.9 \pm 84.8$ nonresonant events, and $7158.4 \pm 36.4$ combinatorial background events. The statistical significances are found to be 2.4 and 1.0 standard deviations for $\Lambda_c^+ \rightarrow \phi p \pi^0$ and nonresonant $\Lambda_c^+ \rightarrow K^+ K^- p \pi^0$ decays, respectively.

We use the well-established decay $\Lambda_c^+ \rightarrow p K^- \pi^+$ [4] as the normalization channel for the branching fraction measurements. The branching fraction is calculated as

$$B(\Lambda_c^+ \rightarrow \text{final state}) = \frac{Y_{\text{Sig}}/\varepsilon_{\text{Sig}}}{Y_{\text{Norm}}/\varepsilon_{\text{Norm}}} \times B(\Lambda_c^+ \rightarrow p K^- \pi^+),$$

where $Y$ represents the observed yield in the signal region of the decay of interest and $\varepsilon$ corresponds to the reconstruction efficiency as obtained from the MC simulation, and $B(\Lambda_c^+ \rightarrow p K^- \pi^+) = (6.46 \pm 0.24)\%$ [13]. For the $\phi p \pi^0$ final state, we include $B(\phi \rightarrow K^+ K^-) = (48.9 \pm 0.5)\%$ [4] in the denominator of Eq. (1).

Since the significances are below 3.0 standard deviations both for $\phi p \pi^0$ signal and $K^+ K^- p \pi^0$ nonresonant decays, we set upper limits on their branching fractions at 90\% CL using a Bayesian approach. The limit is obtained by integrating the likelihood function from zero to infinity; the value that corresponds to 90\% of this total area is taken as the 90\% CL upper limit. We include the systematic uncertainty in the calculation by convolving the likelihood distribution with a Gaussian function whose width is set equal to the total systematic uncertainty. The results are

$$B(\Lambda_c^+ \rightarrow \phi p \pi^0) < 15.3 \times 10^{-5},$$
$$B(\Lambda_c^+ \rightarrow K^+ K^- p \pi^0)_{\text{NR}} < 6.3 \times 10^{-5},$$

which are the first limits on these branching fractions.
To search for a putative $P_{s}^{+} \rightarrow \phi p$ decay, we select $\Lambda_{c}^{+} \rightarrow K^{+}K^{-}p\pi^{0}$ candidates in which $m(K^{+}K^{-})$ is within 0.020 GeV/$c^2$ of the $\phi$ meson mass \[4\] and plot the background-subtracted $m(\phi p)$ distribution (Fig. 4). This distribution is obtained by performing 2D fits as discussed above in bins of $m(\phi p)$. The data shows no clear evidence for a $P_{s}^{+}$ state. We set an upper limit on the product branching fraction $\mathcal{B}(\Lambda_{c}^{+} \rightarrow P_{s}^{+}\pi^{0}) \times \mathcal{B}(P_{s}^{+} \rightarrow \phi p)$ by fitting the distribution of Fig. 4 to the sum of a RBW function and a phase space distribution determined from a sample of simulated $\Lambda_{c}^{+} \rightarrow \phi p\pi^{0}$ decays. We obtain $77.6 \pm 28.1$ $P_{s}^{+}$ events from the fit, which gives an upper limit of

$$\mathcal{B}(\Lambda_{c}^{+} \rightarrow P_{s}^{+}\pi^{0}) \times \mathcal{B}(P_{s}^{+} \rightarrow \phi p) < 8.3 \times 10^{-5}$$

at 90% CL. This limit is calculated using the same procedure as that used for our limit on $\mathcal{B}(\Lambda_{c}^{+} \rightarrow \phi p\pi^{0})$. From the fit, we also obtain,

$$M_{P_{s}^{+}} = (2.025 \pm 0.005) \text{ GeV}/c^2 \text{ and } \Gamma_{P_{s}^{+}} = (0.022 \pm 0.012) \text{ GeV},$$

where the uncertainties are statistical only.

Figure 4: The background-subtracted distribution of $m(\phi p)$ in the $\phi p\pi^{0}$ final state. The points with error bars are data, and the (blue) solid line shows the total PDF. The (red) dotted curve shows the fitted phase space component (which has fluctuated negative).

The high statistics decay $\Lambda_{c}^{+} \rightarrow K^{-}\pi^{+}p\pi^{0}$ is used to adjust the data-MC differences in the $\phi p\pi^{0}$ signal and $K^{+}K^{-}p\pi^{0}$ nonresonant decays. For the $\Lambda_{c}^{+} \rightarrow K^{-}\pi^{+}p\pi^{0}$ sample, the mass distribution is plotted in Fig. 5. We fit this distribution to obtain the signal yield. We find $242,039 \pm 2,342$ signal candidates and $472,729 \pm 467$ background candidates. We measure the ratio of branching fractions,

$$\frac{\mathcal{B}(\Lambda_{c}^{+} \rightarrow K^{-}\pi^{+}p\pi^{0})}{\mathcal{B}(\Lambda_{c}^{+} \rightarrow K^{-}\pi^{+}p)} = (0.685 \pm 0.007 \pm 0.018),$$

where the first uncertainty is statistical and the second is systematic. Multiplying this ratio by the world average value of $\mathcal{B}(\Lambda_{c}^{+} \rightarrow K^{-}\pi^{+}p) = (6.46 \pm 0.24)\%$ \[19\], we obtain
\[ B(\Lambda_c^+ \rightarrow K^-\pi^+p\pi^0) = (4.42 \pm 0.05 \pm 0.12 \pm 0.16)\%, \]

where the first uncertainty is statistical, the second is systematic, and the third reflects the uncertainty due to the branching fraction of the normalization decay mode \( (B_{\text{Norm}}) \). This is the most precise measurement of \( B(\Lambda_c^+ \rightarrow K^-\pi^+p\pi^0) \) to date and is consistent with the recently measured value \( B(\Lambda_c^+ \rightarrow K^-\pi^+p\pi^0) = (4.53 \pm 0.23 \pm 0.30)\% \) by the BESIII collaboration [20].

Figure 5: Fit to the invariant mass distribution of \( m(K^-\pi^+p\pi^0) \). The points with the error bars are the data, the (red) dotted and (green) dashed curves represent the combinatorial and signal candidates, respectively, and (blue) curve represents the total PDF. The \( \chi^2/\text{number of bins} \) of the fit is 1.43, which indicate that the fit gives a good description of the data.

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