PROCEEDINGS OF SCIENCE

First observation of doubly-Cabibbo-suppressed decay in the baryon sector at Belle: $\Lambda_c \to pK^+\pi^-$

Kiyoshi Tanida[*] **for the Belle collaboration**
Advanced Science Research Center, Japan Atomic Energy Agency
E-mail: `tanida@post.j-parc.jp`

We report the first observation of a doubly Cabibbo-suppressed decay of a charmed baryon, $\Lambda_c \to pK^+\pi^-$, using the 980 fb^{-1} data sample collected by the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We measure the branching ratio of this decay with respect to its Cabibbo-favored counterpart to be $\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+) = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, where the uncertainties are statistical and systematic, respectively.

VIII International Workshop On Charm Physics
5-9 September, 2016
Bologna, Italy

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[*] Speaker.

PoS(CHARM2016)048

1. Introduction

Several doubly Cabibbo-suppressed (DCS) decays of charmed mesons have been observed [1, 2, 3, 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 [1, 3, 4, 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; only an upper limit, $\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+) < 0.46\%$ with 90% confidence level, has been reported by the FOCUS Collaboration [7]. Theoretical calculations of DCS decays of charmed baryons have been very few and limited to two-body decay modes [8, 9].

In this article, we report the first observation of the DCS decay $\Lambda_c^+ \to pK^+\pi^-$ and the measurement of its branching ratio with respect to its counterpart CF decay $\Lambda_c^+ \to pK^-\pi^+$[1][10]. Typical decay diagrams of DCS and CF decays are shown in Fig. 1. In brief, the diagrams are categorized as external W-emission, internal W-emission, and W-exchange processes. Since W exchange is allowed in $\Lambda_c^+ \to pK^-\pi^+$ as shown in Fig. 1(e) but absent in $\Lambda_c^+ \to pK^+\pi^-$, the ratio $\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)$ may be smaller than the naïve expectation [7] of $\tan^4\theta_c$ (0.285%), where θ_c is the Cabibbo mixing angle [11] and $\sin\theta_c = 0.225 \pm 0.001$ [12]. We can also compare the ratio $\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)$ with similar ratios in charmed meson decays, such as $\sqrt{\frac{\mathscr{B}(D^+\to K^+\pi^+\pi^-)}{\mathscr{B}(D^+\to K^-\pi^+\pi^-)}\frac{\mathscr{B}(D_s^+\to K^+K^+\pi^-)}{\mathscr{B}(D_s^+\to K^+K^-\pi^+)}} = (1.25\pm0.08)\tan^4\theta_c$ [1] or $\mathscr{B}(D^0 \to K^+\pi^-)/\mathscr{B}(D^0 \to K^-\pi^+) = (1.24\pm0.05)\tan^4\theta_c$ [2]. By doing so, similarities and differences between charmed meson and baryon decays can provide additional insight into flavor-$SU(3)$ symmetry and QCD. For example, flavor-$SU(3)$ symmetry breaking in Λ_c^+ decay may affect the ratio as is the case in D meson decay.

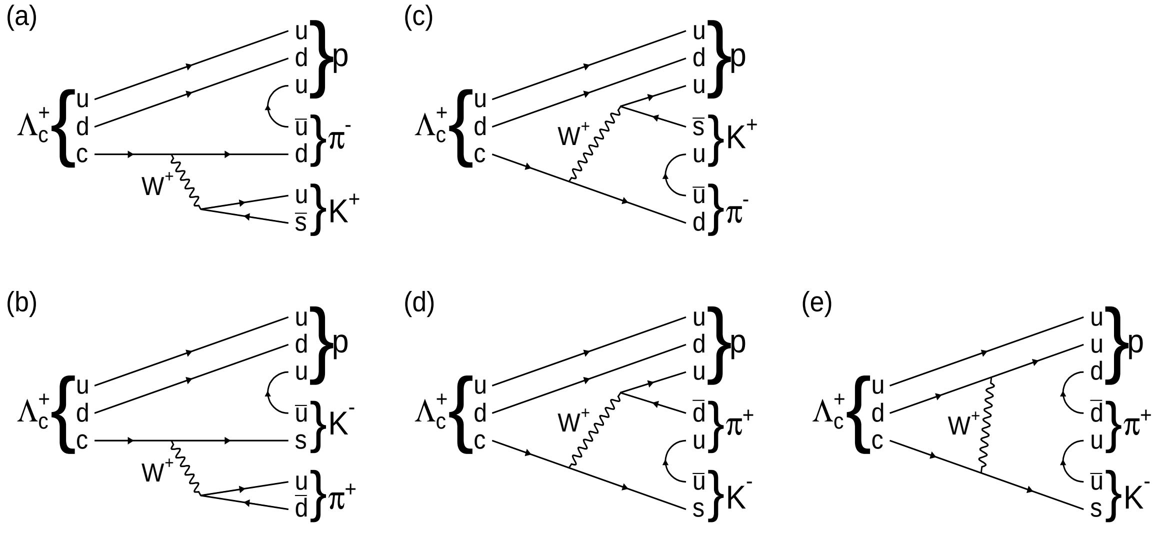

Figure 1: Typical external [internal] W-emission diagrams for (a) [(c)] $\Lambda_c^+ \to pK^+\pi^-$ and (b) [(d)] $\Lambda_c^+ \to pK^-\pi^+$, and (e) a typical W-exchange diagram of $\Lambda_c^+ \to pK^-\pi^+$ [10].

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[1] Unless stated otherwise, charge-conjugate modes are implied throughout this paper.

2. The Belle detector and analysis procedure

We analyze data taken at or near the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, and $\Upsilon(5S)$ resonances collected by the Belle detector at the KEKB asymmetric-energy e^+e^- collider [13]. The integrated luminosity of the data sample is 980 fb^{-1}. The Belle detector is a large-solid-angle magnetic spectrometer comprising a silicon vertex detector (SVD) [14], a 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 superconducting solenoid coil that provides a 1.5 T magnetic field. The detector is described in detail elsewhere [15]. We use samples of $e^+e^- \to c\bar{c}$ Monte Carlo (MC) events, which are generated with PYTHIA [16] and EvtGen [17] and propagated by GEANT3 [18] to simulate the detector performance, to estimate reconstruction efficiencies and to study backgrounds.

In the present analysis, our strategy is quite simple, as the ratio of branching fraction, $\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)$ can be estimated, in a good approximation, just by the ratio of event number $N(\Lambda_c^+ \to pK^+\pi^- + \text{C.C.})/N(\Lambda_c^+ \to pK^-\pi^+ + \text{C.C.})$ (C.C. means charge conjugate) under the same selection criteria. This is because each single particle (p, $\bar{p}$, K^+, K^-, π^+ and π^-) appears once (and only once) in both denominator and numerator, and thus acceptances and efficiencies for single particles cancel almost exactly. Corrections to the ratio are quite small, as explained in Section 3.

The selection criteria follow mostly those typically used in other charmed hadron studies at Belle (for example, Ref. [1, 19, 20]). However, our final criteria are determined by a figure-of-merit (FoM) study performed without touching the DCS signal, using a control sample of the CF decay ($\Lambda_c^+ \to pK^-\pi^+$) in real data, together with sidebands to the DCS signal region [10]. We use this blinded study to optimize the FoM, defined as $n_{\text{sig}}/\sqrt{n_{\text{sig}} + n_{\text{bkg}}}$, where n_{sig} is the fitted yield of the control sample multiplied by the presumed ratio of the DCS and CF decays (0.0025), and n_{bkg} is the number of background events from the sideband region in the DCS decay.

3. Results and discussions

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Figure 2 shows invariant mass distributions, $M(pK^-\pi^+)$ (CF) and $M(pK^+\pi^-)$ (DCS), with the final selection criteria. DCS decay events are clearly observed in $M(pK^+\pi^-)$. We perform a binned least-χ^2 fit to the two distributions from 2.15 GeV/c^2 to 2.42 GeV/c^2 with 0.01 MeV/c^2 bin width, and the figures are drawn with merged bins. The probability density functions (PDFs) for the fits are the sum of two Gaussian distributions, with a common central value, to represent the signals, and polynomials of fifth and third order for the combinatorial backgrounds in the $M(pK^-\pi^+)$ and $M(pK^+\pi^-)$ distributions, respectively. In the fit to $M(pK^+\pi^-)$, the resolution and central value of the signal function are fixed to be the same as those found from the fit to $M(pK^-\pi^+)$. The equality of these quantities is expected from first principles and is confirmed using the MC simulation. The reduced χ^2 values ($\chi^2/d.o.f$) of the fits are 1.03 (27749/26989) and 1.01 (27131/26995) for the CF and DCS decays, respectively. From the fit results, the signal yields of $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to pK^+\pi^-$ decays are determined to be $(1.452 \pm 0.015) \times 10^6$ events and 3587 ± 380 events, respectively, where the uncertainties are statistical. There is a small excess above background on

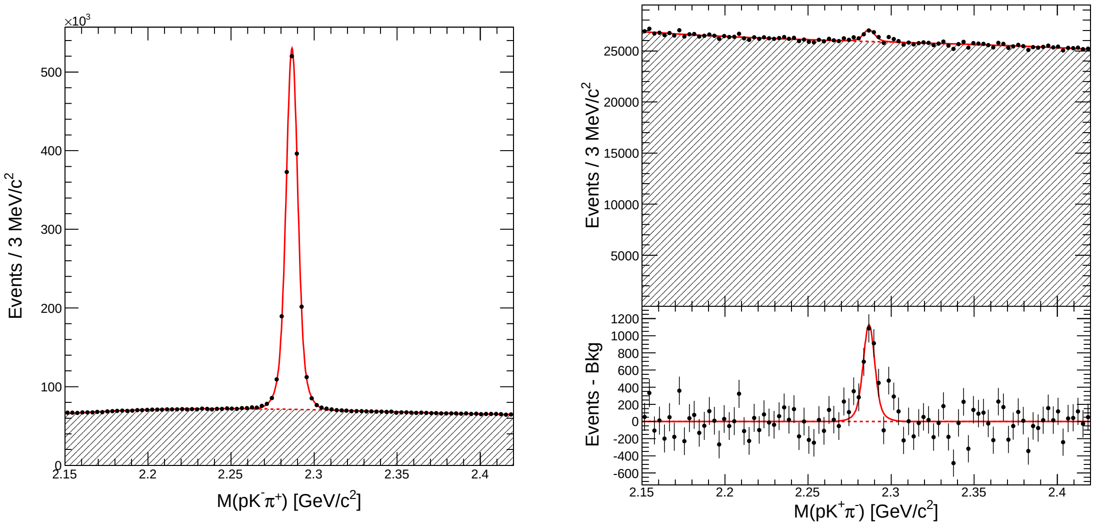

Figure 2: Distribution of $M(pK^-\pi^+)$ (left) and $M(pK^+\pi^-)$ (right-top) [10]. The right-bottom plot is for residuals of data with respect to the fitted combinatorial background to the $M(pK^+\pi^-)$ spectrum. The curves indicate the fit results: the full fit model (solid) and the combinatoric background only (dashed).

the right side of the Λ_c^+ peak (around 2.297 GeV/c^2) in the DCS spectrum of Fig. 2. We attribute this to a statistical fluctuation as no known process would make such a narrow feature at this position even when possible particle misidentification, such as the misidentification of both the K and the π, is taken into account.

The DCS decay has a peaking background from the SCS decay $\Lambda_c^+ \to \Lambda K^+$ with $\Lambda \to p\pi^-$, which has the same final state topology. However, because of the long Λ lifetime, many of the Λ vertexes are displaced by several centimeters from the main vertex so the DOCA and χ^2 requirements suppress most of this background. The remaining SCS-decay yield is included in the signal yield of $\Lambda_c^+ \to pK^+\pi^-$ decay and is estimated via the relation

$$\mathscr{N}(SCS;\Lambda \to p\pi^-) = \frac{\varepsilon(SCS;\Lambda \to p\pi^-)}{\varepsilon(CF)} \frac{\mathscr{B}(SCS;\Lambda \to p\pi^-)}{\mathscr{B}(CF)} \mathscr{N}(CF),$$

where $\mathscr{N}(CF)$ is the signal yield of the CF decay, $\mathscr{B}(SCS;\Lambda \to p\pi^-)/\mathscr{B}(CF) = (0.61 \pm 0.13)\%$ is the branching ratio [12], and $\varepsilon(SCS;\Lambda \to p\pi^-)/\varepsilon(CF) = 0.023$ is the relative efficiency found using MC samples. This calculation gives a yield of 208 ± 78 events from this source, where the uncertainty is estimated by comparing the signal yields from this calculation and a fit to $M(pK^+\pi^-)$ with loosened selection criteria for the vertex point and Λ selection in $M(p\pi^-)$. After subtraction of this SCS component, the signal yield of the DCS decay is $3379 \pm 380 \pm 78$, where the first uncertainty is statistical and the second is systematic due to this subtraction.

To estimate the statistical significance of the DCS signal, we exclude the SCS signal by vetoing events with 1.1127 GeV/c^2 $< M(p\pi^-) <$ 1.1187 GeV/c^2. The significance is estimated as $\sqrt{-2\ln(\mathscr{L}_0/\mathscr{L})}$, where $\mathscr{L}_0$ and $\mathscr{L}$ are the maximum likelihood values from binned maximum likelihood fits with the signal yield fixed to zero and allowed to float, respectively. The calculated significance corresponds to 9.4σ.

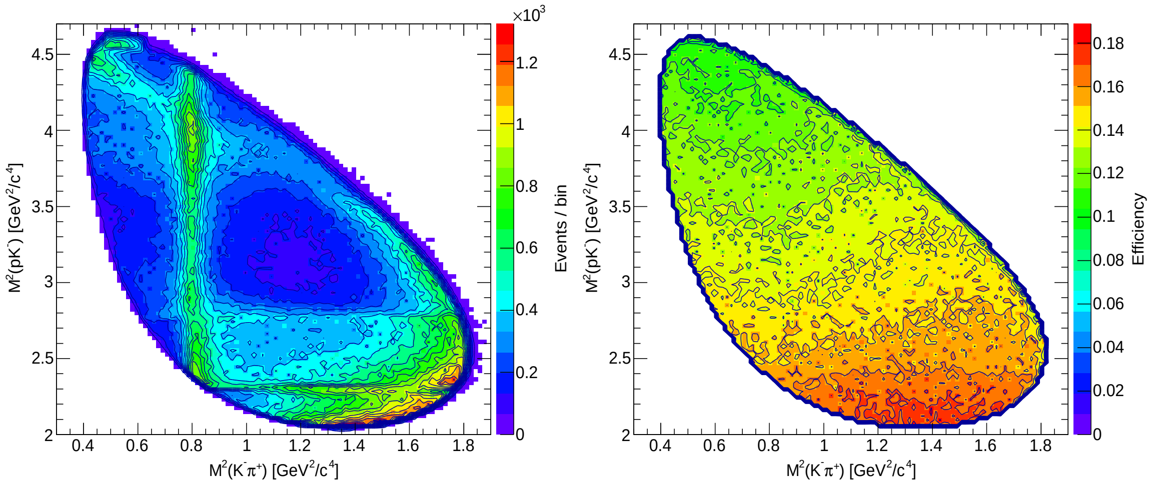

Figure 3: Invariant mass squared of $K^-\pi^+$ versus pK^- within 2.2746 GeV$/c^2$ $< M(pK^-\pi^+) <$ 2.2986 GeV$/c^2$ in real data (left) and estimated efficiency using the MC (right) [10]. The bin widths of x and y axes are 0.016 GeV$^2/c^4$ and 0.027 GeV$^2/c^4$, respectively.

We calculate the reconstruction efficiency using a mixture of subchannels weighted with their corresponding branching fractions. For the CF decay, the subchannels and their branching fractions are taken from the Ref. [12] and the estimated efficiency of the CF decay is $(13.83 \pm 0.05)\%$, where the uncertainty is from MC statistics. To estimate the uncertainty arising from the mix of intermediate states in the CF decay, the reconstruction efficiency is calculated using the efficiency of each bin of the $M^2(K^-\pi^+)$ *vs.* $M^2(pK^-)$ Dalitz distribution [21], shown in Fig. 3, and weighting them by the number of events in the bin of the real data. The relative difference between the reconstruction efficiencies, before and after this weighting, is 3.0%. For the DCS decay, we use the $pK^*(892)^0$, $\Delta(1232)^0K^+$, and non-resonant subchannels with branching fractions of 0.23, 0.18, and 0.59, respectively. These values represent the branching fractions for the corresponding subchannels of the CF decay, adjusted for the fact that $\Lambda(1520)$ cannot be produced in the DCS decay. With the assumed subchannels and their branching fractions, the reconstruction efficiency of the DCS decay is estimated to be $(13.71 \pm 0.05)\%$, where the uncertainty is from MC statistics. Due to the low signal-to-background ratio in the DCS signal peak, the uncertainty from the assumed mixture of intermediate states cannot be estimated using the method used for the CF decay. Therefore, the largest difference between the efficiency of a subchannel and the overall reconstruction efficiency is taken as the efficiency uncertainty; the largest relative difference is 4.5% from $\Delta(1232)^0K^+$ subchannel. The relative efficiency of the CF and DCS decays is 1.01 ± 0.05, where the uncertainty is due to the uncertainty in the composition of the intermediate states as described above.

The branching ratio, $\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)$, is $(2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, where the uncertainties are statistical and systematic, respectively. Sources of the systematic uncertainty and their values are listed in Table 1. The uncertainty from the binning and range of the fits is estimated by changing the bin width to 3 MeV$/c^2$ and adjusting the fitted range of the invariant mass distributions. The uncertainty due to the PDF shapes is estimated by changing the order of the polynomial background function, by changing the signal function to the sum of three Gaussian

Table 1: Systematic uncertainties and sources.

Source	Uncertainty (%)
Background from SCS signal	±2.3
Intermediate states	±5.4
Binning and fit range (DCS)	±5.5
Binning and fit range (CF)	±0.6
PDF shape (DCS)	±2.6
PDF shape (CF)	±1.4
MC statistics	±0.4
PID	±2.2
Charge-conjugate mode	±1.8
Total	±9.0

distributions, and by fixing the resolution of the signal function to the MC-derived resolution value. The PID uncertainty is determined by data-MC comparison of several control samples. We treat the relative efficiency difference between charge-conjugate modes as a systematic uncertainty.

The branching fraction of the CF decay, $(6.84 \pm 0.24^{+0.21}_{-0.27}) \times 10^{-2}$, was already well-measured in a previous Belle analysis [22]. Combining that with our measurement, we determine the absolute branching fraction of the DCS decay to $(1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$, where the first uncertainty is the total uncertainty of the branching ratio and the second is uncertainty of the branching fraction of CF decay. This measured branching ratio corresponds to $(0.82 \pm 0.12)\tan^4\theta_c$, where the uncertainty is the total.

The branching ratio suggests a slightly smaller decay width than the naïve expectation, although the significance is only 1.5σ. This is consistent with the expectation that the Δ isobar, in addition to $\Lambda^*(1520)$, does not contribute to the DCS decay [9]. Omitting those two contributions, which are $(25 \pm 4)\%$ [12], from the CF decay rate, the ratio becomes $(1.10 \pm 0.17)\tan^4\theta_c$ which is consistent with $\tan^4\theta_c$ within 1σ. This result suggests that W-exchange effects are modest in the decay $\Lambda_c^+ \to pK^-\pi^+$, except possibly for the sub-mode with an intermediate Δ. In addition, we note that the observed DCS/CF ratio for charmed baryons is not significantly different from the measured ratio for charmed meson decay.

4. Summary

In summary, the first DCS decay of a charmed baryon, $\Lambda_c^+ \to pK^+\pi^-$, is observed with a statistical significance of 9.4σ. The branching ratio relative to its counterpart CF decay is $(2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, which corresponds to $(0.82 \pm 0.12)\tan^4\theta_c$. This result sheds new light on charmed hadron decays, and such DCS measurements are important ingredients in modeling the non-leptonic decays of hadrons. However, the current experimental precision on the strengths of DCS modes and the level of detail of the available theoretical results are not sufficient to constrain the relative importance of the different subprocesses shown in Fig. 1. Future progress in this field will require more precise experimental measurements as well as more refined theoretical calculations.

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