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Λ_c^+ decays at BESIII

Yixiong Zhou

University of Chinese Academy of Sciences, Beijing 100049, Peoples Republic of China

E-mail: zhouyixiong@mails.ucas.ac.cn

Abstract.
Based on 567 pb^{-1} data taken at the center-of-mass energies $\sqrt{s}$ =4.599 GeV with BESIII detector, we report the following results: (a) improved measurements of the relative branching fractions (BFs) for the singly Cabbibo-suppressed decays of $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$, (b) the first evidence for the $\Lambda_c^+ \to p\eta$ is found with 4.2σ, (c) the most precise upper limit for $\Lambda_c^+ \to p\pi^0$, the absolute BFs of the two neutron decay modes $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ are measured with better precision, (d) the measurement of the absolute BFs for the two W-exchange only decays $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Xi(1530)^0 K^+$, (e) the significant improved measurement of the absolute BF of the inclusive decay $\Lambda_c^+ \to \Lambda + X$, (f) the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ process is measured with unprecedented precision using the data at $\sqrt{s}$ = 4.575, 4.580, 4.590 and 4.599 GeV.

1. Introduction

Weak decays of charmed baryons offer excellent opportunities for testing different theoretical approaches [1]. Since the first observation of the charmed baryon ground state Λ_c^+ in 1979 [2], the progress in both theoretical and experimental studies of heavy baryon decays has been relatively sparse due to the lack of experimental data. Recently, using the 567 pb^{-1} data taken at the center-of-mass energies $\sqrt{s}$ =4.599 GeV BESIII has studied twelve Cabibbo-favoured (CF) Λ_c^+ decay modes with a significantly improved precision [3], and first observed the neutron decay mode $\Lambda_c^+ \to nK_S^0\pi^+$ [4]. However, other Cabibbo-suppressed and neutron modes are only known with poor precision, or even have not been explored yet.

In this proceeding, we report six measurements from the BESIII collaboration. The first two results are studies about the BFs of singly Cabibbo-suppressed (SCS) decays of $\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-, p\eta$ and $p\pi^0$ [5, 6]. Then the first observation of the $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ [7], and the first absolute measurement of two W-exchange dominant decay modes $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Xi(1530)^0 K^+$ [8]. The $\Lambda_c^+ \to \Lambda + X$ is measured with significantly improved precision [9], and end this report with the measurement of cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ at $\sqrt{s}$ = 4.575, 4.580, 4.590 and 4.599 GeV [10]. Throughout the proceeding, charge conjugate is implied.

2. Measurement of Singly SCS Decays $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$

The SCS decay $\Lambda_c^+ \to p\pi^+\pi^-$ proceeds via the external W-emission and W-exchange processes, while the SCS decay $\Lambda_c^+ \to pK^+K^-$ proceeds via the internal W-emission and W-exchange diagrams only. Precisely measuring and comparing their BFs may help to reveal the Λ_c^+ internal dynamics. A measurement of the SCS mode $\Lambda_c^+ \to p\phi$ is of particular interest because it receives contributions only from the internal W-emission diagrams, which can reliably be obtained by a factorization approach. Thus an improved measurement of $\Lambda_c^+ \to p\phi$ BF is essential to validate the theoretical models and test the application of large-N_c factorization in the charmed baryon sector [1], where N_c is the number of colors.

In this analysis single-tag (ST) method is performed, two variables are used to identify the Λ_c^+ candidates, which are the energy difference $\Delta E \equiv |E_{\rm beam} - E_{\Lambda_c^+}|$ and the beam-constrained mass, $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam} - |\vec{p}_{\Lambda_c^+}|^2}$. Here $E_{\rm beam}$ is the beam energy and $\vec{p}_{\Lambda_c^+}$ is the momentum of the Λ_c^+ candidate in the rest frame of the initial e^+e^- system. To obtain the signal yields of the decays $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$, a maximum likelihood fit is performed to the corresponding $M_{\rm BC}$ distributions. For the decay $\Lambda_c^+ \to pK^+K^-$, to determine the signal yields via $\phi(N^{\phi}_{sig})$ and non-ϕ ($N^{non-\phi}_{sig}$) processes, we perform a two-dimensional unbinned extended maximum likelihood fit to the $M_{\rm BC}$ versus $M_{K^+K^-}$ distributions for events in the ΔE region and sideband region simultaneously.

Finally we obtain the ratios of branching fractions: $\frac{\mathcal{B}(\Lambda_c^+\to p\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)} = (6.70 \pm 0.48 \pm 0.25)\%$, $\frac{\mathcal{B}(\Lambda_c^+\to p\phi)}{\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)} = (1.81 \pm 0.33 \pm 0.13)\%$, and $\frac{\mathcal{B}(\Lambda_c^+\to pK^+K^-{}_{\text{non}-\phi})}{\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)} = (9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$, where the first uncertainties are statistical, and the second are systematic.

3. Evidence for the SCS decay $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$

The SCS decays $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ have not yet been studied experimentally. These two decays proceed predominantly through internal W-mission and W-exchange diagrams, which are non-factorizable and not subject to color and helicity suppression in charmed baryon decay. Some theoretical models [11, 12] predict the BFs of these two processes under different assumptions (the flavor SU(3) symmetry, final state interactions) obtaining different results. Therefore, measurements of these BFs will help us to understand the underlying dynamics of charmed baryon decays and distinguish between the different models.

Using similar approach as described above, ST method is employed. In the studies of $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ decays, the η mesons are reconstructed in their two most prominent decay modes, $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$, while π^0 meson is reconstructed in its dominant decay mode $\pi^0 \to \gamma\gamma$. To extract the signal yield for the decay $\Lambda_c^+ \to p\eta$, we perform unbinned maximum likelihood fits to the $M_{\rm BC}$ distributions for the two η decay modes simultaneously, constrained to the same $\mathcal{B}(\Lambda_c^+ \to p\eta)$ and taking into account the different detection efficiencies and decay BFs of η. The resultant BF is determined to be $\mathcal{B}(\Lambda_c^+ \to p\eta)$ =(1.24±0.28(stat.)±0.10(syst.))×10^{-3} with a statistical significance of 4.2σ, where the significance is estimated by the difference of maximum likelihood values for simultaneous fits with and without signal. Since no significant $\Lambda_c^+ \to p\pi^0$ signal is observed, we set the upper limit at 90% C.L. on the signal yield N^{up} =27.9, corresponding to the BF $\mathcal{B}(\Lambda_c^+ \to p\pi^0)$ <0.27×10^{-3}.

4. Observation of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$

So far, measured decay modes account for only about 60% [13] of all Λ_c^+ decays, primarily consisting of modes with a $\Lambda(\Sigma)$ hyperon or a proton in the final state. Decays to the Σ^- hyperon are Cabibbo-allowed and are expected to have large rates. However, no experimental measurements exist except for $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ [13]. Therefore, searching for additional decay modes with Σ^- in the final state is important to build up knowledge on Λ_c^+ decays.

In this work a double-tag (DT) method is used. First we reconstruct the $\bar{\Lambda}_c^-$ with eleven exclusive hadronic decay mode: $\bar{\Lambda}_c^- \to \bar{p}K^0_S$, $\bar{p}K^+\pi^-$, $\bar{p}K^0_S\pi^0$, $\bar{p}K^+\pi^+\pi^0$, $\bar{p}K^0_S\pi^+\pi^-$, $\bar{\Lambda}\pi^-$, $\bar{\Lambda}\pi^-\pi^0$, $\bar{\Lambda}\pi^-\pi^+\pi^-$, $\bar{\Sigma}^0\pi^0$, $\bar{\Sigma}^-\pi^0$ and $\bar{\Sigma}^-\pi^+\pi^-$, and the intermediate particles are reconstructed through their decays $K^0_S \to \pi^+\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Sigma}^0 \to \gamma\bar{\Lambda}$ with $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Sigma}^- \to \bar{p}\pi^0$, and $\pi^0 \to \gamma\gamma$. The total ST yield is $N^{tot}_{\bar{\Lambda}_c^-}$=14415±159, where the uncertainty is statistical only.

Candidates for $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+(\pi^0)$ are reconstructed in the system recoiling against the ST $\bar{\Lambda}_c^-$, the Σ^- candidates are reconstructed with decays of $\Sigma^- \to n\pi^-$. The kinematic variable $M_{miss} = \sqrt{(E_{\rm beam} - E_{miss})^2 - |\overrightarrow{p}_{\Lambda_c^+} - \overrightarrow{p}_{miss}|^2}$ is used to obtain information on the missing neutron, where E_{miss} and $\overrightarrow{p}_{miss}$ are the missing energy and momentum carried by the neutron, which are calculated by $E_{miss} = E_{beam} - E_{\pi^+\pi^+\pi^-(\pi^0)}$ and $\overrightarrow{p}_{miss} = \overrightarrow{p}_{\Lambda_c^+} - \overrightarrow{p}_{\pi^+\pi^+\pi^-(\pi^0)}$, where $\overrightarrow{p}_{miss}$ is the momentum of the Λ_c^+ baryon. The momentum $\overrightarrow{p}_{\Lambda_c^+}$ is given by $\vec{p}_{\Lambda_c^+} = -\hat{p}_{\rm tag}\sqrt{E_{\rm beam}^2 - m_{\Lambda_c^+}^2}$, where $\hat{p}_{\rm tag}$ is the direction of the momentum of the ST $\bar{\Lambda}_c^-$ candidate and $m_{\Lambda_c^+}$ is the mass of the Λ_c^+ taken from the PDG [13]. Similarly we can calculate the missing mass of the neutron and π^- ($M_{n\pi^-}$) to represent the reconstructed mass of the Σ^-.

To improve the resolution of the signal mass, as well as to better handle the backgrounds around the Σ^- and neutron mass regions, the signal yields is extracted by performing an unbinned maximum likelihood fit to the mass difference $M_{n\pi^-} - M_n$ spectra.

Finally we obtain the absolute BFs for $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ are $\mathcal{B}(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+) = (1.81 \pm 0.17 \pm 0.09)\%$ and $\mathcal{B}(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0) = (2.11 \pm 0.33 \pm 0.14)\%$.

5. Measurements of Absolute Branching Fractions for $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Xi(1530)^0 K^+$

The Cabibbo-favored decays $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Xi(1530)^0 K^+$ proceed only through the W-exchange process. There are large cancellation between different matrix elements occur in both S-and P-wave decays, making theoretical prediction very difficult [1], which result in very large variations of the predicted BFs [11, 12]. Hence, an absolute and more precise determination of these BF's is an important input for the modelisation of the hadronic decays of charmed baryons.

A similar DT method is performed, an additional ST $\Lambda_c^+ \to p\pi^+\pi^-$ mode is used, we only detect one K^+ in the DT side and deduce the presence of $\Xi^{(*)0}$ in the final state from four-momentum conservation. To extract the DT signal yields, we perform an unbinned maximum likelihood fit to the M_{miss} spectra. The $\Lambda_c^+ \to \Xi^{(*)0}K^+$ signal shape is obtained from the MC-derived signal shape convoluted with a Gaussian function common to both signal channels whose parameters are left free in the fit. The background shape is described by a quadratic function, which is validated by the candidate events in the ST $M_{\rm BC}$ sideband region of data and the MC-simulated background samples.

The absolute BFs are determined to be $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+) = (5.90 \pm 0.86 \pm 0.39) \times 10^{-3}$ and $\mathcal{B}(\Lambda_c^+ \to \Xi(1530)^0 K^+) = (5.02 \pm 0.99 \pm 0.31) \times 10^{-3}$.

6. Measurement of absolute branching fraction of the inclusive decay $\Lambda_c^+ \to \Lambda + X$

The inclusive decay $\Lambda_c^+ \to \Lambda + X$, where X means any possible final state particles, is mediated by the $c \to s$ Cabibbo-favored (CF) transition that dominates the decays of the Λ_c^+ [11, 12]. The decay rate of the $\Lambda_c^+ \to \Lambda + X$ is important to calibrate the amplitude of the CF transition in the charmed baryon sector in theory. Previous measurement has a relative low accuracy, with an uncertainty larger than 30%. The precise measurement of BF $\Lambda_c^+ \to \Lambda + X$ benefits the understanding of the Λ_c^+ baryon.

To study the signal $\Lambda_c^+ \to \Lambda + X$ with the DT method, we first select the anti-particle $\bar{\Lambda}_c^-$ by the two decay modes, $\bar{\Lambda}_c^- \to \bar{p}K_S^0$ and $\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$. Then we search for a Λ candidate among the remaining tracks on the recoiling side of the tagged $\bar{\Lambda}_c^-$. The sideband region of $M_{p\pi^-}$ are defined as [1.096,1.106] GeV/c^2 and [1.126,1.136] GeV/c^2, and for $M_{\rm BC}$ are [2.25,2.27] GeV/c^2. The signal yield is determined from the distribution of $M_{\rm BC}$ versus the invariant mass of $p\pi^-$ system $M_{p\pi^-}$ by

$$N^{\text{sig}} = N^{\text{S}} - \frac{N^{\text{A}} + N^{\text{B}}}{2} - f \cdot (N^{\text{D}} - \frac{N^{\text{C}} + N^{\text{E}}}{2}), \tag{1}$$

where N^{S}, N^{A}, N^{B}, N^{C}, N^{D} and N^{E} represent the numbers of events observed in the regions of S, A, B, C, D and E. Here the regions A and B are the $M_{p\pi^-}$ sideband M_{BC} signal regions, regions C and D are the $M_{p\pi^-}$ sideband M_{BC} sideband regions, and regions E are the $M_{p\pi^-}$ signal M_{BC} sideband regions. Backgrounds due to mis-reconstruction of Λ are assumed to be flat in the $M_{p\pi^-}$ distribution, which can be estimated from the events in regions A and B. While the peaking backgrounds in the $M_{p\pi^-}$ distribution, which are from non-Λ_c^+ decays with Λ correctly reconstructed, can be estimated using the sideband region of M_{BC}, namely the regions C, D and E. f is the ratio of background area of the signal region over that of the sideband region in the M_{BC} distribution, which is obtained from the fit to the combined M_{BC} distribution of data for the two tagging modes.

In summary, we measure the BF of $\Lambda_c^+ \to \Lambda + X$ to be $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$. The precision of the BF is improved by a factor of 4 compared to previous measurements [13]. Furthermore, we search for direct CP violation in this decay for the first time. The CP asymmetry is measured to be $\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%$. The precision is limited by statistical uncertainty and no evidence for CP violation is found.

7. Precision measurement of the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ cross section near threshold

The electromagnetic structure of hadrons, parameterized in terms of electromagnetic form factors (EMFFs), provides a key to understand quantum chromodynamics effects in bound states. Assuming that one-photon exchange dominates the production of spin-1/2 baryons B, the cross section of the process $e^+e^- \to B\bar{B}$ can be parameterized in terms of EMFFs, *i.e.* G_E and G_M, in the following way [14]:

$$\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2 C\beta}{3s}|G_M(s)|^2[1 + \frac{2m_B^2c^4}{s}|\frac{G_E(s)}{G_M(s)}|^2]. \tag{2}$$

Here, α is the fine-structure constant, β=$\sqrt{1 - 4m_B^2c^4/s}$ the velocity of the baryon, s the square of the center-of-mass (CM) energy, and m_B is the mass of the baryon. Previously, the Belle collaboration measured the cross section of e^+e^- using the initial-state radiation (ISR) technique [15], but the results suffer from significant uncertainties in CM energy and cross section. Therefore, near $\Lambda_c^+\bar{\Lambda}_c^-$ threshold, precise measurements of the production cross section and EMFF ratios are highly desirable.

Yields are extracted from an unbinned maximum likelihood fit to each M_{BC} distribution, the cross section of the i-th mode is determined using $\sigma_i = \frac{N_i}{\varepsilon_i \cdot \mathcal{L}_{\text{int}} \cdot f_{\text{VP}} \cdot BR_i \cdot f_{\text{ISR}}}$, where N_i and ε_i represent the yield and corresponding detection efficiency. The integrated luminosity $\mathcal{L}_{\text{int}}$ is taken from Ref. [16, 17]. The vacuum polarization (VP) correction factor f_{VP} is calculated to be 1.055 at all four CM energies [18]. The BR_i represents the product of branching fractions of the i-th Λ_c^+ decay mode and its subsequent decay(s). The f_{ISR} is the ISR correction factor derived in Ref. [19] and implemented in KKMC. Since the calculation of f_{ISR} requires the cross section line-shape as input, an iterative procedure has been performed. The resulting cross sections at the four CM energies are listed in Table. 1.

The data sets collected at $\sqrt{s}$ = 4574.5 and 4599.5 MeV are large enough to perform a detailed study in the CM frame of the Λ_c polar angle θ_{Λ_c}, which is defined as the angle between the Λ_c momentum and the beam direction. The data fulfilling all selection criteria are divided into ten bins in $\cos\theta_{\Lambda_c^+}$. The total yields of Λ_c^+ and $\bar{\Lambda}_c^-$ are combined bin-by-bin, and the shape function $f(\theta) \propto (1 + \alpha_{\Lambda_c^+} \cos^2\theta)$ is fitted to the combined data. Table 2 lists the resulting $\alpha_{\Lambda_c^+}$

Table 1. The average cross section of e^+e^- measured at each CM energy, where the uncertainties are statistical and systematic, respectively. The observed cross section can be obtained by multiplying the $f_{\rm ISR}$ and the σ.

$\sqrt{s}$ (MeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$f_{\rm ISR}$	σ (pb)
4574.5	47.67	0.45	$236 \pm 11 \pm 46$
4580.0	8.54	0.66	$207 \pm 17 \pm 13$
4590.0	8.16	0.71	$245 \pm 19 \pm 16$
4599.5	566.93	0.74	$237 \pm 3 \pm 15$

parameters obtained from the fits, as well as the $|G_E/G_M|$ ratios extracted using the equation $|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c^+})/(1+\alpha_{\Lambda_c^+})$.

Table 2. Shape parameters of the angular distribution and $|G_E/G_M|$ ratios at $\sqrt{s} = 4574.5$ and 4599.5 MeV. The uncertainties are statistical and systematic, respectively.

$\sqrt{s}$ (MeV)	$\alpha_{\Lambda_c^+}$	$\lvert G_E/G_M\rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

8. Summary

Six published results on the hadronic decays of Λ_c^+ at BESIII are reported. The decays of $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ are measured with improved precision. The first evidence of $\Lambda_c^+ \to p\eta$ is found with 4.2σ. The $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ is first observed. The first absolute measurement of the BFs of $\Lambda_c^+ \to \Xi^0K^+$ and $\Lambda_c^+ \to \Xi(1530)^0K^+$ are performed. The BF of the inclusive decay $\Lambda_c^+ \to \Lambda + X$ is measured with significant improved precision. The cross sections of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ have been measured with high precision, the Λ_c^+ form factor ratio $|G_E/G_M|$ is measured for the first time. Many other analysis of Λ_c^+ will be available at BESIII.

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