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Charmed baryon decays at BESIII

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Studies on the weak decays of charmed baryons provide useful information for understanding the interplay of weak and strong interactions in the charm sector. In 2014, the BESIII experiment accumulated a data set of 567 pb^{-1} at the center-of-mass energy of $\sqrt{s}$=4.6 GeV, an energy point slightly above the $\Lambda_c^+\bar{\Lambda}_c^-$ mass. This is the world first threshold data of the Λ_c^+ baryon and provides systematical measurements on the production and decay properties of the Λ_c^+. So far BESIII has published 17 papers of about 30 reaction channels based on the data set taken at 4.6 GeV. In this proceeding, I summarize the BESIII results on the Λ_c^+ decays in the recent three years. In addition, some prospects on the future programme of charmed baryons are discussed.

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1. Introduction

Measurements of weak decays of charmed baryons provide useful information for understanding the interplay of weak and strong interactions in the charm sector [1]. The lightest charmed baryon Λ_c^+, with quark configuration udc, serves as the cornerstone of charmed baryon spectroscopy. However, the progress of the theoretical and experimental studies of Λ_c^+ decays has been slow [2, 3]. In 2014, the BESIII experiment accumulated a data set of 567 pb^{-1} at the center-of-mass energy of $\sqrt{s}$=4.6 GeV, an energy point slightly above the $\Lambda_c^+\bar{\Lambda}_c^-$ mass.

BESIII utilizes the exclusive two-body channel $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ at the mass threshold and presents unique advantages of clean background, high efficiency and employing a double-tag technique [1]. The excellent performance of photon detection at BESIII facilitates reconstruction of particles decaying into the neutral photon or π^0 and study the Λ_c^+ decays with controlled level of backgrounds from continuum processes. For the double-tag technique, a full reconstruction of a $\bar{\Lambda}_c^-$ baryon on one side of tagged events together with the known momentum and energy of colliding beams provides a source of tagged Λ_c^+ particles of known four-momentum on the other side. The tag yield, which provides the normalization for the branching fraction measurement, is extracted by analyzing the high-resolution variable of beam-constrained mass $M_{\rm BC} = \sqrt{E^2_{\rm beam} - |\vec{p}_{\rm tag}|^2}$, where $\vec{p}_{\rm tag}$ is the three-momentum of the tag $\bar{\Lambda}_c^-$ candidate and $E_{\rm beam}$ is the beam energy in the e^+e^- center-of-mass system. When a tagged Λ_c^+ decays to a neutrino, neutron or K_L^0, the mass of the (missing) particle can be inferred from energy-momentum conservation. This tagging technique, which obviates the need for knowledge of the luminosity or the production cross section, is a unique and powerful tool for charmed baryon decay measurements at threshold. Relying on this Λ_c^+ data set, BESIII made many absolute branching fraction measurements of hadronic and semi-leptonic decays [3, 4], such as $\Lambda_c^+ \to pK^-\pi^+$ [5], $nK_S^0\pi^+$ [6] and $\Lambda e^+\nu_e$ [7]. These progresses from BESIII have promoted many theoretical studies on the charmed baryons. In this proceeding, I will elaborate the recent studies on the Λ_c^+ decays at BESIII, based on the existing data set of 567 pb^{-1} at 4.6 GeV.

2. Recent studies on the Λ_c^+

2.1 Spin-correlated analyses of the Λ_c^+ two-body decays

Currently, the spin of the Λ_c^+ is inferred to be $\frac{1}{2}$ from the naive quark model [8], and no solid experimental confirmation on this assumption. A large number of theoretical predictions and experimental studies on the Λ_c^+ properties and decays are made based on the spin-1/2 assumption [3, 9–12]. Based on the BESIII data at $\sqrt{s}$ = 4.6 GeV, we test the spin-1/2 and 3/2 hypotheses of the Λ_c^+ based on the angular distributions of the Λ_c^+ decays into pK_S^0, $\Lambda\pi^+$, $\Sigma^0\pi^+$ and $\Sigma^+\pi^0$ [13]. The decays are studied by the single-tag method, *i.e.* either the Λ_c^+ or $\bar{\Lambda}_c^-$ from $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ is reconstructed. The helicity formalism [14, 15] is applied in order to examine the implications of the Λ_c^+ spin hypotheses for the joint angular distribution of the charmed baryon and its daughter particles. According to the study, it is found that the spin of $\frac{1}{2}$ hypothesis is preferred over the $\frac{3}{2}$ with a significance of about 6σ. Hence, we conclude that the spin of the Λ_c^+ baryon to be $\frac{1}{2}$, consistent with the expectation of the naive quark model.

The hadronic weak decays of charmed baryons are expected to violate parity conservation. For instance, in a two-body decay $\Lambda_c^+ \to BP$ (B denotes a $J^P = \frac{1}{2}^+$ baryon and P denotes a

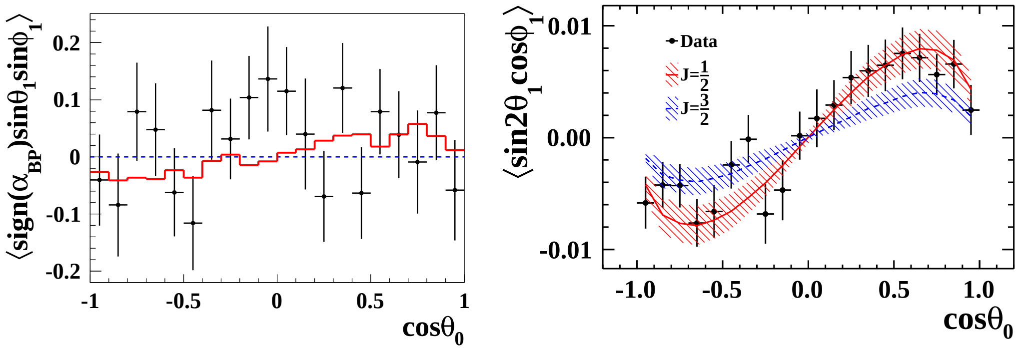

Figure 1: (left) Fitted results of the spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ hypotheses [13]. The bands represent the fit uncertainty due to statistical uncertainties. Here θ_0 is the Λ_c^+ production angle relative to the e^--beam direction; (right) Effect of the Λ_c^+ transverse polarization vs cosθ_0 in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ [17]. The solid curve represents total fit to data and the dotted line show expectation of zero polarization.

$J^P = 0^-$ pseudoscalar meson) the decay asymmetry parameter is defined as $\alpha_{BP}^+ \equiv \frac{2\mathrm{Re}(s^*p)}{|s|^2+|p|^2}$, where s and p stand for the parity-violating s-wave and parity-conserving p-wave amplitudes in the decay, respectively [9, 10, 16]. At BESIII, the decay asymmetry parameters are determined by analyzing the multi-dimensional angular distributions, where the full cascade decay chains are considered. The detailed method can be found in Ref. [17], in which a joint extraction of the four decay parameters of $\alpha_{\Lambda\pi}$, $\alpha_{\Sigma^+\pi^0}$, $\alpha_{\Sigma^0\pi^+}$ and $\alpha_{p\bar{K}^0}$ at the same time was carried out based on the Λ_c^+ sample at 4.6 GeV. The non-zero transverse polarization of the Λ_c^+ will aid the determinations of the decay asymmetries. The asymmetry parameters for the $p\bar{K}^0$, $\Lambda\pi^+$, $\Sigma^+\pi^0$ and $\Sigma^0\pi^+$ modes are measured to be $0.18\pm0.43\pm0.14$, $-0.80\pm0.11\pm0.02$, $-0.57\pm0.10\pm0.07$, and $-0.73\pm0.17\pm0.07$, respectively. In comparison with previous results, the measurements for the $\Lambda\pi^+$ and $\Sigma^+\pi^0$ modes are consistent but have an improved precision, while the parameters for the $p\bar{K}^0$ and $\Sigma^0\pi^+$ modes are measured for the first time taking advantage of the non-zero transverse polarization with a significance of 2.1σ as shown in Fig 1. At present, no theoretical model provides predictions that are fully consistent with all these measurements and BESIII measurements have become benchmarks to calibrate the QCD-derived theoretical models [9, 10]. Till now, about 10 times larger Λ_c^+ samples are ready and the significance of Λ_c^+ polarization could be enhanced to be more than 5σ. So the precisions of the decay asymmetries will be improved as a consequence.

2.2 Two-body decays $\Lambda_c^+ \to \Sigma^+\eta$ and $\Sigma^+\eta'$

The two-body Cabibbo-favored (CF) decay of the Λ_c^+ to an octet baryon and a pseudoscalar meson, $\Lambda_c^+ \to B(\frac{1}{2}^+)P$, is one of the simplest hadronic channels to be treated theoretically [3], and measurements of the branching fractions (BFs) can be used to calibrate different theoretical approaches. BESIII measured the BFs for $\Lambda_c^+ \to \Sigma^+\eta$ and $\Sigma^+\eta'$ with respect to the CF modes $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Sigma^+\omega$, respectively [18], by analyzing the Λ_c^+ data at $\sqrt{s} = 4.6$ GeV. Only evidences for the two decays are found and the relative BFs are measured as $\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta)}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\pi^0)} = 0.35\pm0.16\pm0.03$ and $\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\omega)} = 0.86\pm0.34\pm0.07$. Incorporating the BESIII results of $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)$ and $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\omega)$ from Ref. [5], we obtain $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta) = (0.41\pm0.19\pm0.05)\%$, and

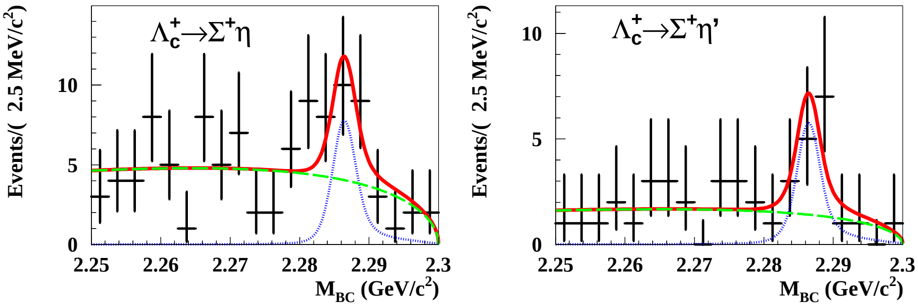

Figure 2: Fits to the $M_{\rm BC}$ distributions for the decays of $\Lambda_c^+ \to \Sigma^+\eta$(left) and $\Lambda_c^+ \to \Sigma^+\eta'$ (right).

$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta') = (1.34 \pm 0.53 \pm 0.21)\%$. The result of $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)$ is compatible with previous measurement at CLEO [19], and $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')$ is measured for the first time.

2.3 The three-body decays $\Lambda_c^+ \to \Lambda\eta\pi^+$ and $\Lambda_c^+ \to pK_S^0\eta$

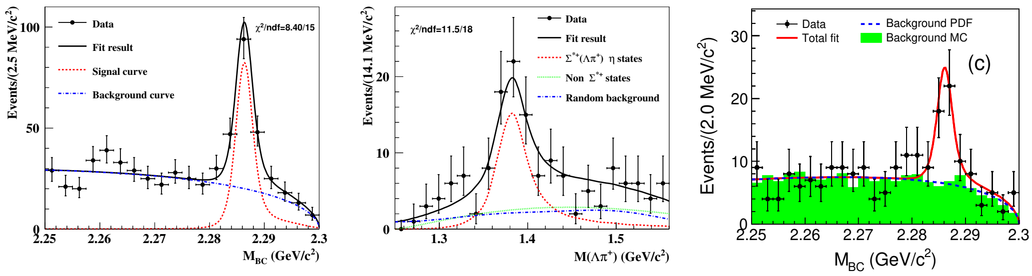

Figure 3: (left) Fit to the $M_{\rm BC}$ distribution for the $\Lambda_c^+ \to \Lambda\eta\pi^+$ decay; (middle) Fit to the $\Lambda\pi^+$ invariant mass spectrum of $\Lambda_c^+ \to \Lambda\eta\pi^+$ candidates; (right) Fit to the $M_{\rm BC}$ distribution for the $\Lambda_c^+ \to pK_S^0\eta$ decay.

Comprehensive studies of different BFs for Λ_c^+ decays to multi-body final states are important to understand the strong interactions in the charmed-baryon decays [20, 21]. Especially, it contains a rich of intermediate states, which can be used for studying light-hadron spectroscopy. In addition, several spin-correlated variables for testing P, CP or T violations can be constructed due to the rich spin structures in the final states. Recently, BESIII analyzed the three-body decays of $\Lambda_c^+ \to \Lambda\eta\pi^+$ [22] and $\Lambda_c^+ \to pK_S^0\eta$ [23] based on the single-tag method using the data sample at $\sqrt{s} = 4.6$ GeV, with input of the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced [5]. Theoretically, the decay $\Lambda_c^+ \to \Lambda\eta\pi^+$ is taken as an ideal process to study the $a_0(980)$ and $\Lambda(1670)$, because the final states $\eta\pi^+$ and $\Lambda\eta$ are in pure isospin $I = 1$ and $I = 0$ combinations [24–26]. $\Lambda_c^+ \to pK_S^0\eta$ is regarded as an important channel to understand the properties of the intermediate $N(1535)$ resonance [27, 28], which is still puzzling for its decays to final states containing strange hadrons, like ηN and $K\Lambda$.

According to the fits in Fig. 3, the measurement gives $\mathcal{B}(\Lambda_c^+ \to \Lambda\eta\pi^+) = (1.84\pm0.21\pm0.15)\%$, $\mathcal{B}(\Lambda_c^+ \to \Sigma^{*+}\eta) = (0.91\pm0.18\pm0.09)\%$ and $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (0.414\pm0.084\pm0.028)\%$, where the first uncertainties are statistical and the second systematic. These are the first absolute measurements of the BFs for these two modes, and are consistent with the previous relative measurements [29, 30], but with improved precisions. BESIII provides improved measurements of the absolute BFs of these modes, compared to the previous measurements at CLEO [29, 30]. Studies on the Λ_c^+ data samples with larger statistics [4] are desired for detailed studies of the intermediate states.

2.4 The inclusive decays of Λ_c^+

Taking advantage of the unique pair production of the $\Lambda_c^+\bar{\Lambda}_c^-$ at 4.6 GeV, BESIII is able to probe the decay rate of the Λ_c^+ inclusive decays, where part of the Λ_c^+ decay final states are undetected. The first absolute measurement of the branching fraction of the inclusive semileptonic decay $\Lambda_c^+ \to e^+X$ has been conducted at BESIII using a double-tag method [31]. Semileptonic decays provide relatively cleaner probes to explore the decay dynamics of the charmed baryon than the corresponding hadronic decays [1, 4]. BESIII measured the absolute branching fraction of $\Lambda_c^+ \to \Lambda e^+\nu_e$ to be $(3.63 \pm 0.43)\%$ [32], which trigger the first Lattice QCD calculation on the semileptonic decay of the Λ_c^+ [33]. A comparison of this exclusive branching fraction and the inclusive semileptonic decay branching fraction of the Λ_c^+ baryon will guide searches for new semileptonic decay modes. The absolute branching fraction is determined to be $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$. Compared with $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$, the ratio $\frac{\mathcal{B}(\Lambda_c^+\to\Lambda e^+\nu_e)}{\mathcal{B}(\Lambda_c^+\to Xe^+\nu_e)}$ is determined to be $(91.9 \pm 12.5 \pm 5.4)\%$, which shows that other semileptonic modes are at maximum at the level of permil. Comparing this with the charge-averaged semileptonic decay width of nonstrange charmed measons $\bar{\Gamma}(D \to Xe^+\nu_e)$ [2], the ratio $\frac{\Gamma(\Lambda_c^+\to Xe^+\nu_e)}{\bar{\Gamma}(D\to Xe^+\nu_e)}$ is determined to be 1.26 ± 0.12, which are compatible with theoretical predictions within uncertainties [34–36].

The total branching fraction of exclusive $\bar{K}^0/K^0$ decays of Λ_c^+ is evaluated to be $(22.4 \pm 0.9)\%$ based on a statistical isospin model [37], while the sum of the observed decay rates only accounts for $(16.1 \pm 0.8)\%$. Therefore determining the inclusive rate of Λ_c^+ decaying to $\bar{K}^0/K^0$ will help to quantify the missing decay modes and test the predictions in the statistical isospin model. Employing 11 single Λ_c^+ tag modes, the inclusive branching fraction $\mathcal{B}(\Lambda_c^+ \to K_S^0X)$ is directly measured to be $(9.9 \pm 0.6 \pm 0.4)\%$ [38]. Then, we extrapolate $\mathcal{B}(\Lambda_c^+ \to \bar{K}^0/K^0X) = (19.8 \pm 1.2 \pm 0.8 \pm 1.0)\%$, where the third uncertainty accounts for possible differences between $\mathcal{B}(\Lambda_c^+ \to K_S^0X)$ and $\mathcal{B}(\Lambda_c^+ \to K_L^0X)$ [39] This result is consistent with calculations with the statistical isospin model within 1.3σ.

3. Summary and future prospects on studying charmed baryon

Charm baryon weak decays remain an exciting field for both theoretical and experimental investigations. So far BESIII has published 17 papers of about 30 channels based on the existing data set of 567 pb^{-1} at 4.6 GeV taken in 2014. In this proceeding, we summarize BESIII results on the Λ_c^+ decays in the recent three years. However, the information on the charmed baryon decays are still poorly known, especially for the heavier states of the Ξ_c and Ω_c [2, 9].

During 2020-2021 data-taking at BESIII, about 10 times larger Λ_c^+ samples were accumulated at the center-of-mass energies between 4.61 GeV and 4.95 GeV. The sensitivities of the Λ_c^+ decay rates will be improved at least by a factor of 3. Many Cabibbo suppressed decay modes will be investigated and more semi-leptonic decays will be explored extensively. With larger statistics, we could explore the Λ_c^+ spin-correlated observables with double tag method, where the pairs of $\Lambda_c^+\bar{\Lambda}_c^-$ are in a C-odd quantum entangled state. Hence, we have chance to observe the effect of Λ_c^+ polarization and test CP violations for the two-body decays by comparing decay asymmetry parameters measured separately for Λ_c^+ and $\bar{\Lambda}_c^-$ [4, 40]. In addition, more sophisticated amplitude analyses of Λ_c^+ multi-body decays become feasible with improved statistics.

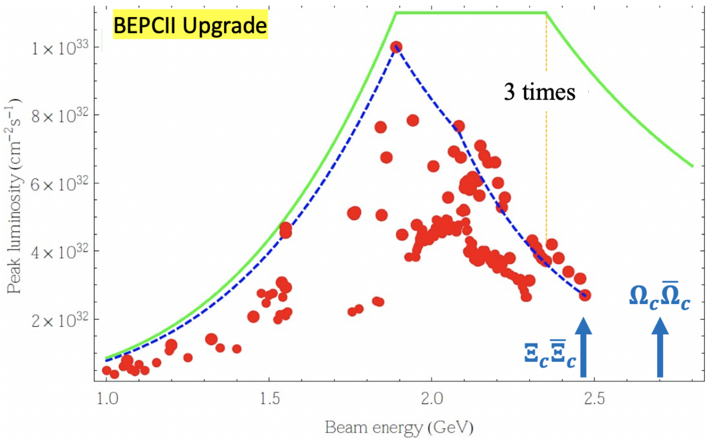

Figure 4: Plan of the upgraded luminosity as function of beam energy of the BEPCII, along with the current performance of the luminosity.

Now the BEPCII team is working on the upgrade on the luminosity and beam energy of the collider. In the upgrade plan, a peak luminosity of $1.1 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ will be achieved in the beam energy region from 1.89 GeV to 2.35 GeV, which corresponds to an increased luminosity of 3 times higher than the current luminosity at the energy of 2.35 GeV. This will greatly improve the efficiency of collecting more Λ_c^+ data between 4.6 GeV and 4.7 GeV. For team energy, the plan is to extend the collision energy up to 5.6 GeV from the current limit of 4.95 GeV. This will fully cover the production energy region of the ground-state singly charmed baryons Σ_c, Ξ_c and Ω_c. We expect BESIII will provide systematical studies on the properties of all these charmed baryons after the successful fulfilling of the upgrade plan.

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