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Recent charmed baryon results from BESIII

Jiaxiu. Teng (1)(2)(*)

(1) *University of Science and Technology of China*
(2) *State Key Laboratory of Particle Detection and Electronics*

Summary. — BESIII has collected 4.5 fb^{-1} of e^+e^- collision data between 4.6 and 4.7 GeV. This unique data offers ideal opportunities to study Λ_c^+ decays. In this article, we report the partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ and the first observation of the singly-Cabibbo-suppressed decay $\Lambda_c^+ \to n\pi^+$. In addition, we report the measurement in $\Lambda_c^+ \to \Lambda e^+\nu_e$, the observation of $\Lambda_c^+ \to pK^-e^+\nu_e$, and improved measurement of $\Lambda_c^+ \to Xe^+\nu_e$.

1. – Introduction

Λ_c^+ is the lowest-lying charmed baryon, and its properties need more explorations in both theory and experiments. Most of the charmed baryons and many b-baryons decay to Λ_c^+. Thus, the measurement of Λ_c^+ is essential for our understanding of heavy charmed baryons and bottomed baryons. Λ_c^+ is an excellent ground to study the dynamics of light quarks in the environment of a heavy quark, and an excellent platform for understanding QCD with transitions involving the charm quark. Studies of Λ_c^+ are also helpful to reveal information of strong- and weak-interactions in charm region, complementary to charmed mesons. Experimental results provide precise test for low-energy non-perturbative QCD phenomenological model and lattice quantum chromodynamics (LQCD) calculations, and promote the understanding of the mechanism of strong interaction in charm region.

BESIII has collected 4.5 fb^{-1} of e^+e^- collision data between 4.6 and 4.7 GeV. In this energy region, $\Lambda_c^+\bar{\Lambda}_c^-$ are produced in pairs with no additional accompanying hadrons. These large data samples collected just above the Λ_c^+ production threshold provide a clean environment and an excellent opportunity to search for Λ_c^+ decays.

In most of the analyses reported in this article, a double tag (DT) method [1] and a missing technique are used. First, a data sample of the process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ is selected, called the single-tag (ST) sample, by tagging a $\bar{\Lambda}_c^-$ baryon with one of the exclusive hadronic decay modes listed as follows: $\bar{p}K^+\pi^-$, $\bar{p}K_S^0$, $\bar{p}K^+\pi^-\pi^0$, $\bar{p}K_S^0\pi^0$, $\bar{p}K_S^0\pi^+\pi^-$, $\bar{\Lambda}\pi^-$, $\bar{\Lambda}\pi^-\pi^0$, $\bar{\Lambda}\pi^-\pi^+\pi^-$, $\bar{\Sigma}^0\pi^-$, $\bar{\Sigma}^-\pi^+\pi^-$, $\bar{\Sigma}^-\pi^0$, $\bar{\Sigma}^-\pi^-\pi^0$, $\bar{p}\pi^+\pi^-$, and $\bar{\Sigma}^0\pi^-\pi^+\pi^-$.

(*) On behalf of the BESIII Collaboration.

Then the signal processes are searched and selected in the recoiling side. Most systematic uncertainties in ST side can be cancelled in this way. Also lower backgrounds can be obtained. For the decays including neutral particles such as neutron or neutrino that cannot be detected in the final state, a missing technique using kinematic relation constraints is used to obtain information on the missing neutral particle.

2. – Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ [2]

In the partial wave analysis (PWA) analysis, the PWA fit is performed based on the new-developed TensorFlow based package TF-PWA [3] which use the helicity formula to calculate the amplitude. This analysis uses single tag method, and the signal purity within the signal region is larger than 80%. Fit fractions (FFs) and the partial wave amplitudes of intermediate resonances are derived by the PWA fit results on invariant mass spectra of $\pi^+\pi^0$, $\Lambda\pi^+$, and $\Lambda\pi^0$. The decays $\Lambda_c^+ \to \Lambda\rho(770)^+$ and $\Lambda_c^+ \to \Sigma(1385)\pi$ are studied for the first time using the partial wave amplitudes. Branching fractions (BFs) are determined to be $\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+) = (4.06 \pm 0.30 \pm 0.35 \pm 0.23) \times 10^{-2}$, $\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0) = (5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3}$, and $\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+) = (6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3}$, where the first uncertainties are statistical, the second are systematic, and the third are from the uncertainties of the intermediate process BFs $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)$ and $\mathcal{B}(\Sigma(1385) \to \Lambda\pi)$. The decay asymmetry parameters are determined to be $\alpha_{\Lambda\rho(770)^+} = -0.763 \pm 0.053 \pm 0.045$, $\alpha_{\Sigma(1385)^+\pi^0} = -0.917 \pm 0.069 \pm 0.056$, and $\alpha_{\Sigma(1385)^0\pi^+} = -0.789 \pm 0.098 \pm 0.056$, which are helpful to test theoretical calculations of the partial waves interference effects.

3. – First observation of the singly-Cabbibo-suppressed decay $\Lambda_c^+ \to n\pi^+$ [4]

Singly-Cabbibo-suppressed (SCS) decay contains non-negligible non-factorizable contributions. The study of SCS decay can provide information about factorizable and non-factorizable interference, and constrain non-factorizable contributions in theoretical calculations.

The DT method and neutron missing technique are used in this analysis. The spectrum of recoiling mass is fitted to extract the signals and a statistical significance of 7.3σ is observed for $\Lambda_c^+ \to n\pi^+$ process. The BF is measured to be $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-4}$. The Cabibbo-favored decays of $\Lambda_c^+ \to \Lambda\pi^+$ and $\Lambda_c^+ \to \Sigma^0\pi^+$ are measured to be $(1.31 \pm 0.08_{\text{stat}} \pm 0.05_{\text{syst}}) \times 10^{-2}$ and $(1.22 \pm 0.08_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-2}$, respectively, which are consistent with previous results.

By taking the upper limit of BF of $\Lambda_c^+ \to p\pi^0$ from the Belle experiment [10], the ratio of BFs between $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to n\pi^+$ is calculated to be larger than 7.2 at the 90% confidence level, which disagrees with most of the available phenomenological models predictions [5, 6, 7, 8, 9]. These results provide precise experimental inputs for theoretical calculations and can test different phenomenological models.

4. – Study of Λ_c^+ semi-leptonic decays

4·1. $\Lambda_c^+ \to \Lambda e^+\nu_e$. – [11]

The study of Λ_c^+ semi-leptonic (SL) decays provides valuable information about weak and strong interactions in baryons containing a heavy quark. The decay $\Lambda_c^+ \to \Lambda e^+\nu_e$, as the dominant component in Λ_c^+ SL decays, is interesting to measure. Its decay rate depends on the weak quark mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix element

$|V_{cs}|$ and strong interaction effects parameterized by form factors describing initial and final baryons hadronic transition.

The LQCD predicted both the differential decay rates and the form factors of the decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$. However, there are no direct experimental comparisons. This work in BESIII reports the first direct comparisons, which is important to test on Lattice calculations, and provides information on strong interactions in charm baryon sector.

The DT method and missing technique are used in this analysis. The neutrino is not detected, and the kinematic variable $U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|$ is used to obtain the information of neutrino, where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and missing momentum carried by the neutrino. The branching fraction $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ is measured to be $(3.56 \pm 0.11_{\rm stat} \pm 0.07_{\rm syst})\%$, which improves precision of the world average value by more than threefold.

Combining $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ measured in this work, life time of Λ_c^+, and the q^2-integrated rate predicted by LQCD, $|V_{cs}| = 0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda_c}}$ is determined, which is consistent with $|V_{cs}| = 0.939 \pm 0.038$ measured in $D \to K l \nu_l$ decays within 1σ. Measurement of $|V_{cs}|$ via $\Lambda_c^+ \to \Lambda l \nu_l$ is an important consistency test for the Standard Model and a probe for new physics.

This analysis also provides the first direct comparisons to LQCD for $\Lambda_c^+ \to \Lambda$ decay form factor and differential decay rate, as is shown in Fig. 1. The dependences of measured form factors show different kinematic behaviors compared to those predicted from LQCD calculations [12]. In particular, discrepancies can be seen at high q^2-region for $f_\perp(q^2)$ and $g_\perp(q^2)$, and at low q^2-region for $f_+(q^2)$. For $f_+(q^2)$ and $f_\perp(q^2)$, experimental measurement tends to have steeper slope than those from LQCD calculations, while on the contrary for $g_+(q^2)$ and $g_\perp(q^2)$. The corresponding comparison on differential decay rates, shown fair agreement throughout the q^2 region. This experimental measurement provides important inputs in understanding the Λ_c^+ SL decays and can help calibrate the calculation of SL decays of other charmed baryons and Λ_b.

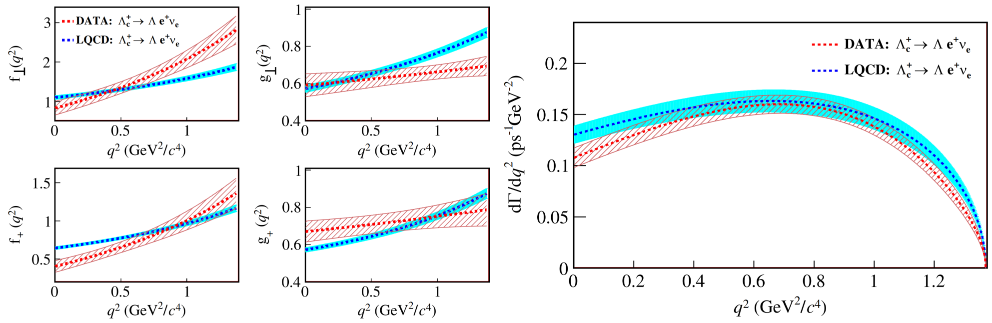

Fig. 1. – The left four figures show comparison of form factors with LQCD calculations. The bands show the total uncertainties. The right figure shows comparison of the differential decay rates with LQCD predictions. The band shows the total uncertainty.

4·2. $\Lambda_c^+ \to p K^- e^+ \nu_e$. – [13]

The decay rate of $\Lambda_c^+ \to p K^- e^+ \nu_e$ process depends on $|V_{cs}|$ and strong interaction effects parametrized by form factors describing initial and final baryons hadronic transition. The BF ratio $\mathcal{B}(\Lambda_c^+ \to \Lambda l^+ \nu_l)/\mathcal{B}(\Lambda_c^+ \to X l^+ \nu_l)$ is close to one, which is different with charm mesons. Searching for unknown exclusive SL Λ_c^+ decay is important to validate and understand this pattern. The comparison of measured $\mathcal{B}(\Lambda_c^+ \to \Lambda^* e^+\nu_e)$ and theoretical predictions can help check nonrelativistic quark model and constituent quark model.

The DT method and missing neutrino technique are used and the 2-dimensional fit to M_{pK^-} versus $U_{\rm miss}$ distributions are performed to extract the signal yields. The M_{pK^-} spectrum is studied to understand the nature of excited Λ^* states. The $\Lambda_c^+ \to pK^-e^+\nu_e$ decay is observed with 8.2σ significance considering systematic uncertainty, and the BF is measured to be $(0.88 \pm 0.17_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-3}$. Combining these with the inclusive SL Λ_c^+ BF measured by BESIII [19], the relative fraction is determined to be $[\mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e)/\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)] = (2.1 \pm 0.4_{\rm stat} \pm 0.2_{\rm syst})\%$, which indicates that SL Λ_c^+ decays are not saturated by the $\Lambda l^+\nu_l$ final state. In addition, the first evidence of $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ and $\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$ with significances of 3.3σ and 3.2σ are reported, respectively. The BF of decay $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ is measured to be $(1.02 \pm 0.52_{\rm stat} \pm 0.11_{\rm syst}) \times 10^{-3}$, which is consistent with the theoretical calculations [14, 15, 16, 17] within 2σ. The BF of decay $\Lambda_c^+ \to \Lambda(1405)[\to pK^-]e^+\nu_e$ is measured to be $(0.42 \pm 0.19_{\rm stat} \pm 0.04_{\rm syst}) \times 10^{-3}$. For several theoretical calculations [14, 15, 18], this BF measurement differs by a factor of roughly 100 times.

This is the first SL Λ_c^+ decay without Λ in the final state, and it extends the understanding of Λ_c^+ SL decays beyond $\Lambda_c^+ \to \Lambda l^+\nu_l$ processes. With larger samples, amplitude analysis of pK^- mass spectrum and form factors could be studied and will help us understand the internal structure of the contributing Λ^* states.

4·3. $\Lambda_c^+ \to Xe^+\nu_e$. – [19]

BESIII experiment also investigates the absolute BF for the inclusive SL decay $\Lambda_c^+ \to Xe^+\nu_e$, where X refers to any possible particle system. The BF is determined to be $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (4.06 \pm 0.10_{\rm stat} \pm 0.09_{\rm syst})\%$, which improves the precision of previous measurements by more than threefold. Considering the BFs of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.56 \pm 0.11_{\rm stat} \pm 0.07_{\rm syst})\%$ [11] and $\Lambda_c^+ \to pK^-e^+\nu_e = (0.88 \pm 0.17_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-3}$ [13], there are still about 0.4% unknown decay BF, indicating that some new Λ_c^+ SL decays may exist beyond the known $\Lambda_c^+ \to \Lambda l^+\nu_l$ and $\Lambda_c^+ \to pK^-l^+\nu_l$ $(l = e, \mu)$.

Combining $\tau_{\Lambda_c^+}$ and the charge-averaged SL decay width of non-strange charmed mesons, the inclusive SL decay width is obtained to be $\Gamma(\Lambda_c^+ \to Xe^+\nu_e) = (2.006 \pm 0.073) \times 10^{11}$ s^{-1}. Using the known Λ_c^+ lifetime and the charge-averaged SL decay width of nonstrange charmed mesons, the ratio of inclusive SL decay widths $\Gamma(\Lambda_c^+ \to Xe^+\nu_e)/\bar{\Gamma}(D \to Xe^+\nu_e) = 1.28 \pm 0.05$ is determined, where statistical and systematic uncertainties are combined. This experimental result is consistent with heavy quark expansion model prediction [20], but disfavors effective-quark method model prediction [21, 22].

5. – Summary and Prospects

Using 4.5 fb^{-1} data samples of $\Lambda_c^+\bar{\Lambda}_c^-$ collected by BESIII, many substantial progresses on the exploration of the charmed baryon Λ_c^+ decays have been made. In the future, more results from Λ_c^+ decays are expected as a benefit of the higher statistics and data samples at more higher energy region. After the upgrade of BEPCII, the luminosity will be improved by 3 times higher at 4.7 GeV, and the maximum energy will be extended to 5.6 GeV, which will cover all the ground-state charmed baryons. The upgrades will provide good platform to study the production and decay of these charmed baryons, CP violation search, and help develop more reliable QCD-derived models in charm sector.

In addition, studies on the production and decay of excited charmed baryons could also be carried out in the future.

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