Λ_c^+ physics at BESIII

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Abstract. Based on the data sets collected by BESIII detector near the $\Lambda_c^+\bar{\Lambda}_c^-$ production threshold, *i.e.* at $\sqrt{s}$ = 4574.5, 4580.0, 4590.0 and 4599.5 MeV, we report the preliminary study of the production behaviour of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ process, including its Born cross section and electromagnetic form factor ratios. Using the large-statistic data at $\sqrt{s}$ = 4599.5 MeV, we measured the absolute branching fractions of Cabibbo-favored hadronic decays of Λ_c^+ baryon with a double tag technique. The branching fractions for twelve hadronic decay modes are significantly improved. We also report the model-independent measurement of the branching fraction of the semi-leptonic decays $\Lambda_c^+ \to \Lambda e^+\nu_e$ and $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$.

1. Introduction

The electromagnetic structure of hadrons, parameterized in terms of electromagnetic form factors (EMFFs), provides a key to understand the strong interaction. Assuming that one-photon exchange dominates the production of spin-1/2 baryons B, the Born 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 [1]:

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

Here, α is the fine-structure constant, β=$\sqrt{1 - 4m_B^2c^4/s}$ the velocity of the baryon, s the square of center-of-mass (CM) energy and m_B is the mass of the baryon. The Coulomb factor C parameterizes the electromagnetic interaction between the outgoing baryon-antibaryon. For neutral baryons the Coulomb factor is unit, while for point-like charged fermions it reads $C = \varepsilon R$ [2, 3], where $\varepsilon = \pi\alpha/\beta$ is an enhancement factor resulting in a nonzero cross section at threshold and $R = \sqrt{1 - \beta^2}/(1 - e^{-\pi\alpha/\beta})$ is the Sommerfeld resummation factor. In the $e^+e^- \to p\bar{p}$ process, the BaBar collaboration observed a rapid rise of the cross section near threshold, followed by a plateau around 200 MeV above threshold [4]. The BESIII collaboration also observed the cross section enhancement [5]. The non-vanishing cross section near threshold as well as the wide-range plateau have led to various theoretical interpretations [6, 7, 8]. Recently, the BESIII collaboration has observed the non-zero cross section near threshold in the $e^+e^- \to \Lambda\bar{\Lambda}$ process. Naturally, it is also interesting to explore the production behaviour of Λ_c^+, the lightest baryon containing the charm quark. Previously, the Belle collaboration measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ using initial-state radiation (ISR) technique [9], 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 Born cross section and EMFF ratios are highly needed.

The decays of charm baryon provide crucial information for the study of both strong and weak interactions. The hadronic decays of Λ_c^+ provide important input to Λ_b physics, while the semi-leptonic (SL) decays of Λ_c^+ provide a stringent test on non-perturbative theoretical models. The $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay is dominated by the Cabibbo-favored transition $c \to s l^+ \nu_l$, which occurs, to a good approximation, independently of the spin-zero spectator ud di-quark. In addition, theoretical calculations are proved to be quite challenging for lattice quantum chromodynamics (LQCD) due to the complexity of form factors in $\Lambda_c^+ \to \Lambda l^+ \nu_l$ [10]. Consequently, the model-independent measurement of hadronic and SL decays with better precision is a key ingredient in theoretical predictions and LQCD calculation, which in turn, will play an important role in understanding different Λ_c^+ decays.

2. The production of Λ_c^+

Born cross section of $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ reaction is measured at four CM energies: $\sqrt{s} = 4574.5$, 4580.0, 4590.0 and 4599.5 MeV. At each CM energy, ten Cabibbo-favored hadronic decay modes: $\Lambda_c^+ \to pK^-\pi^+$, pK_S^0, $\Lambda\pi^+$, $pK^-\pi^+\pi^0$, $pK_S^0\pi^0$, $\Lambda\pi^+\pi^0$, $pK_S^0\pi^+\pi^-$, $\Lambda\pi^+\pi^+\pi^-$, $\Sigma^0\pi^+$, and $\Sigma^+\pi^+\pi^-$, as well as the ten corresponding charge-conjugate modes are independently reconstructed. Each mode will produce one measurement of the Born cross section and the total cross section is obtained from weighted average over the 20 individual measurements [11]. The resulting cross sections at four CM energies are listed in Table 1 and shown in Figure 1 together with the Belle data [9] for comparison.

Table 1. The average Born cross section of $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ measured at each CM energy, where the uncertainties are statistical and systematic, respectively. (BESIII preliminary results)

$\sqrt{s}$ (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	8.545	0.66	$207 \pm 17 \pm 13$
4590.0	8.162	0.71	$245 \pm 19 \pm 16$
4599.5	566.9	0.74	$237 \pm 3 \pm 15$

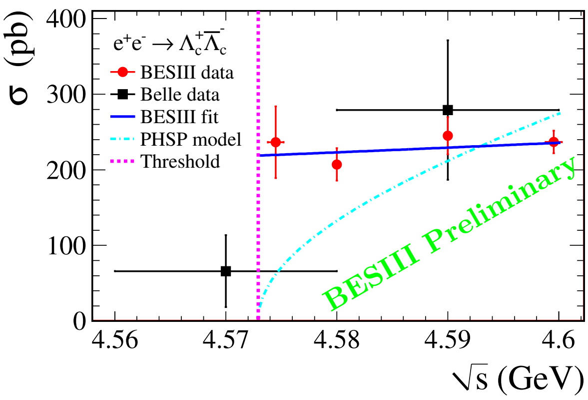

Figure 1. The Born cross section of $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ obtained by BESIII (this work) and Belle. The blue solid curve represents the input line-shape for KKMC when determining the $f_{\rm ISR}$. The dash-dot cyan curve denotes the prediction of the phase space (PHSP) model.

The data 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 $\cos\theta_{\Lambda_c^+}$. In each $\cos\theta_{\Lambda_c^+}$ bin, the total yield is obtained by summing yields of all the ten tagged modes. The one-dimensional bin-by-bin efficiency corrections are applied on these total yields. The same procedure is performed by tagging $\bar{\Lambda}_c^-$ decay channels. 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, as shown in Figure 2.

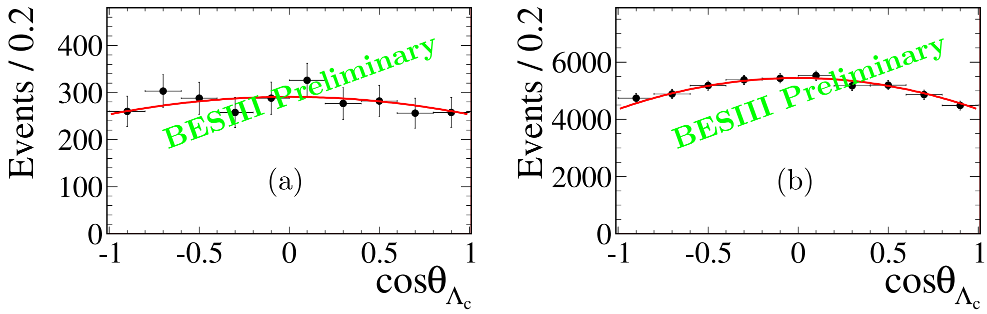

Figure 2. The angular distribution and corresponding fit results in data at $\sqrt{s} = 4574.5$ MeV (a) and 4599.5 MeV (b).

Table 2 listed the resulting α_{Λ_c} parameters obtained from the fits, as well as the $|G_E/G_M|$ ratios extracted using the equation:

$$|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c}). \tag{2}$$

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. (BESIII preliminary results)

$\sqrt{s}$ (MeV)	α_{Λ_c}	$|G_E/G_M|$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

3. Λ_c^+ hadronic decay

Based on the data sample with an integrated luminosity of 566.9 pb^{-1} collected with the BESIII detector [12] at $\sqrt{s} = 4599.5$ MeV, we apply a tagged technique pioneered by the MARK-III Collaboration [13] to study the hadronic decay of Λ_c^+. To identify the $\Lambda_c^+\bar{\Lambda}_c^-$ signal candidates, we firstly reconstruct one $\bar{\Lambda}_c^-$ baryon [called single tag (ST)] through the final states of any of the singly tagged modes. For a given decay mode j, the ST yields is determined to be

$$N_j^{\rm ST} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_j \cdot \varepsilon_j, \tag{3}$$

where $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ is the total number of produced $\Lambda_c^+\bar{\Lambda}_c^-$ pairs and ε_j is the corresponding efficiency. Then we define double-tag (DT) events as those where the partner Λ_c^+ recoiling against the $\bar{\Lambda}_c^-$ is reconstructed in one of the signal modes. That is, in DT events, the $\Lambda_c^+\bar{\Lambda}_c^-$ event is fully reconstructed. The DT yield with $\Lambda_c^+ \to i$ (signal mode) and $\bar{\Lambda}_c^- \to j$ (tagging mode) is

$$N_{ij}^{\rm DT} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_i \cdot \mathcal{B}_j \cdot \varepsilon_{ij}, \tag{4}$$

Table 3. Comparison of the measured BFs in this work with previous results from PDG. For our results, the first uncertainties are statistical and the second are systematic.

Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

where ε_{ij} is the efficiency for simultaneously reconstructing modes i and j. Hence, the ratio of the DT yield ($N_{ij}^{\rm DT}$) and ST yield ($N_j^{\rm ST}$) provides an absolute measurement of the BF:

$$\mathcal{B}_i = \frac{N_{ij}^{\rm DT}}{N_j^{\rm ST}}\frac{\varepsilon_j}{\varepsilon_{ij}}. \tag{5}$$

Because of the large acceptance of the BESIII detector and the low multiplicities of Λ_c hadronic decays, $\varepsilon_{ij} \approx \varepsilon_i\varepsilon_j$. Hence, the ratio $\varepsilon_j/\varepsilon_{ij}$ is insensitive to most systematic effects associated with the decay mode j, and a signal BF $\mathcal{B}_i$ obtained using this procedure is nearly independent of the efficiency of the tagging mode. Therefore, $\mathcal{B}_i$ is sensitive to the signal mode efficiency (ε_i), whose uncertainties dominate the contribution to the systematic error from the efficiencies. We use a least-squares fitter, which considers statistical and systematic correlations among the different hadronic modes, to obtain the BFs of the twelve Λ_c^+ decay modes globally. In total, there are thirteen free parameters (twelve $\mathcal{B}_i$ and $N_{\Lambda_c^+\bar{\Lambda}_c^-}$) to be estimated. The extracted BFs of Λ_c^+ are listed in Table 3. The total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced is obtained to be $N_{\Lambda_c^+\bar{\Lambda}_c^-} = (105.9 \pm 4.8 \pm 0.5) \times 10^3$. The goodness-of-fit is evaluated as $\chi^2/ndf = 9.9/(24-13) = 0.9$.

4. Λ_c^+ semi-leptonic decay

Using the similar strategy in hadronic decay measurements, we select the data sample of $\bar{\Lambda}_c^-$ baryons by reconstructing exclusive hadronic decays. The ST $\bar{\Lambda}_c^-$ are reconstructed using eleven hadronic decay modes: $\bar{\Lambda}_c^- \to \bar{p}K_S^0$, $\bar{p}K^+\pi^-$, $\bar{p}K_S^0\pi^0$, $\bar{p}K^+\pi^-\pi^0$, $\bar{p}K_S^0\pi^+\pi^-$, $\bar{\Lambda}\pi^-$, $\bar{\Lambda}\pi^-\pi^0$, $\bar{\Lambda}\pi^-\pi^+\pi^-$, $\bar{\Sigma}^0\pi^-$, $\bar{\Sigma}^-\pi^0$ and $\bar{\Sigma}^-\pi^+\pi^-$, where the intermediate particles K_S^0, $\bar{\Lambda}$, $\bar{\Sigma}^0$, $\bar{\Sigma}^-$ and π^0 are reconstructed by their decays into $K_S^0 \to \pi^+\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Sigma}^0 \to \gamma\bar{\Lambda}$ and $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Sigma}^- \to \bar{p}\pi^0$ and $\pi^0 \to \gamma\gamma$, respectively. The total observed events of the eleven ST modes is $N_{\Lambda_c^{tag}} = 14415 \pm 159$. The signal candidates for $\Lambda_c^+ \to \Lambda l^+\nu_l$ are selected from the remaining tracks recoiling against the ST $\bar{\Lambda}_c^-$ candidates. As the neutrino is missing, we employ a kinematic variable

$$U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$$

to obtain information of the neutrino, where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and momentum carried by the neutrino, respectively. They are calculated by $E_{\rm miss} = E_{\rm beam} -$

$E_\Lambda - E_{e^+}$ and $\vec{p}_{\rm miss} = \vec{p}_{\Lambda_c^+} - \vec{p}_\Lambda - \vec{p}_{e^+}$, where $\vec{p}_{\Lambda_c^+}$ is the momentum of Λ_c^+ baryon, $E_\Lambda(\vec{p}_\Lambda)$ and E_{e^+} $(\vec{p}_{e^+})$ are the energies (momenta) of the Λ and the positron, respectively. Here, the $\vec{p}_{\Lambda_c^+}$ is given by $\vec{p}_{\Lambda_c^+} = -\hat{p}_{\rm tag}\sqrt{E_{\rm beam}^2 - m_{\bar{\Lambda}_c^-}^2}$, where $\hat{p}_{\rm tag}$ is the momentum direction of ST $\bar{\Lambda}_c^-$ and $m_{\bar{\Lambda}_c^-}$ is the nominal $\bar{\Lambda}_c^-$ mass. For signal events, $U_{\rm miss}$ is expected to peak around zero.

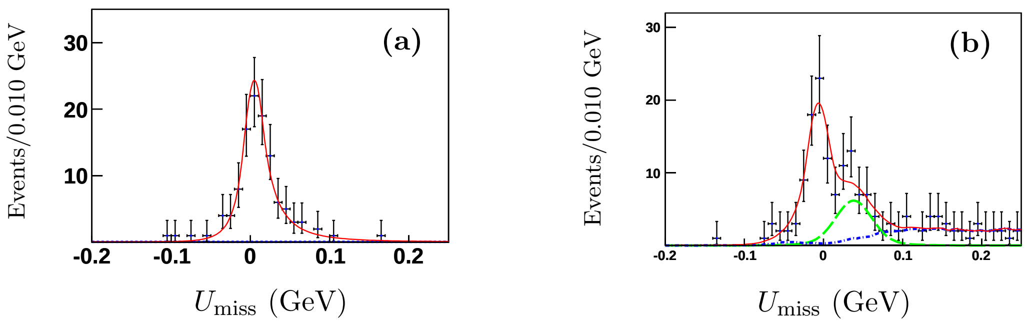

Figure 3. (a) Fit to the $U_{\rm miss}$ distribution of process $\Lambda_c^+ \to \Lambda e^+\nu_e$. (b) Fit to the $U_{\rm miss}$ distribution of process $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$. The points with error bars are data, the (red) solid curve shows the total fit and the (blue) dashed curve is the background shape. The green-dashed line in the right subfigure denotes the MC-driven background shapes which is supposed to simulate the remaining background.

Figure 3(a) shows the fit result of the $U_{\rm miss}$ distribution for $\Lambda_c^+ \to \Lambda e^+\nu_e$. From the fit, we obtain the number of SL signals to be 109.4 ± 10.9. After subtracting all the background events, we determine the net number of $\Lambda_c^+ \to \Lambda e^+\nu_e$ to be $N_{\rm semi} = 103.5 \pm 10.9$, where the uncertainty is statistical. The absolute BF for $\Lambda_c^+ \to \Lambda e^+\nu_e$ is determined by

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = \frac{N_{\rm semi}}{N_{\bar{\Lambda}_c^-}^{\rm tot} \times \varepsilon_{\rm semi} \times \mathcal{B}(\Lambda \to p\pi^-)}, \tag{6}$$

where $\varepsilon_{\rm semi} = (30.92 \pm 0.26)\%$ is the overall efficiency for detecting the $\Lambda_c^+ \to \Lambda e^+\nu_e$ decay in ST events, weighted by the ST yields of data for each tag. Inserting the values of $N_{\rm semi}$, $N_{\bar{\Lambda}_c^-}^{\rm tot}$, $\epsilon_{\rm semi}$ and $\mathcal{B}(\Lambda \to p\pi^-)$ in Eq. (6), we get $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$, where the first error is statistical and the second systematic.

Using a technique analogous to that of $\Lambda_c^+ \to \Lambda e^+\nu_e$, in which the $U_{\rm miss}$ is used as the final signal variable, the process $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$ is also studied. The fitting model includes MC-driven background shapes to simulate the remaining background, shown in Fig. 3(b). Accordingly, the $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$ is determined to be $(3.49 \pm 0.46 \pm 0.27)\%$. With the result of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$ in hand, the ratio $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)/\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$ is obtained to be $(0.96 \pm 0.16(\text{stat.}) \pm 0.04(\text{sys.}))\%$, which verified the lepton universality in baryon decays.

5. Summary

In summary, based on the data sets collected by BESIII detector near the $\Lambda_c^+\bar{\Lambda}_c^-$ production threshold, we report the preliminary study of the production behaviour of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ process, including its Born cross section and electromagnetic form factor ratios. Using the data at $\sqrt{s} = 4599.5$ MeV, BESIII firstly measured the absolute hadronic branching fractions of twelve Cabibbo-favored decays of Λ_c^+ baryon. BESIII also presented the first model-independent measurement of the branching fraction of the semi-leptonic decay $\Lambda_c^+ \to \Lambda e^+\nu_e$ and $\Lambda\mu^+\nu_\mu$.

6. Reference

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