Measurement of the absolute branching fraction of the inclusive semileptonic Λ_c^+ decay

(BESIII Collaboration)

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Using a data sample corresponding to an integrated luminosity of 567 pb⁻¹ collected at a center-of-mass energy of $\sqrt{s}=4.6$ GeV with the BESIII detector, we measure the absolute branching fraction of the inclusive semileptonic Λ_c^+ decay with a double-tag method. We obtain $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$, where the first uncertainty is statistical and the second systematic. Using the known Λ_c^+ lifetime and the charge-averaged semileptonic decay width of nonstrange charmed measons $(D^0$ and $D^+)$, we obtain the ratio of the inclusive semileptonic decay widths $\Gamma(\Lambda_c^+ \to X e^+ \nu_e)/\bar{\Gamma}(D \to X e^+ \nu_e) = 1.26 \pm 0.12$.

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Since the first observation of the Λ_c^+ baryon, the lightest baryon containing a charm quark, in 1979 [1], its hadronic decays have been studied extensively. However, information about semileptonic decays of the Λ_c^+ baryon is sparse [2–6]. The branching fraction of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ was first measured by the ARGUS collaboration [3] and then measured by the CLEO collaboration [4] more than 20 years ago. Recently, the BESIII collaboration measured the absolute branching fraction of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ to be $(3.63 \pm 0.43)\%$ [5]. 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 branching fraction of the inclusive semileptonic decay has been measured previously by the MARK II collaboration 35 years ago, with a result of $(4.5 \pm 1.7)\%$ [7]. The uncertainty is much larger than that of the exclusive decay. Thus, a more precise measurement for the inclusive semileptonic decay is required. In addition, using the known Λ_c^+ lifetime, the semileptonic decay width $\Gamma(\Lambda_c^+ \to X e^+ \nu_e)$, where X refers to any particle system with baryon number one, can be determined. Comparing $\Gamma(\Lambda_c^+ \to X e^+ \nu_e)$ with the charge-averaged nonstrange D semileptonic decay width $\Gamma(D \to Xe^+\nu_e)$, the ratio $\Gamma(\Lambda_c^+ \to X e^+ \nu_e)/\bar{\Gamma}(D \to X e^+ \nu_e)$ can be obtained. Using current data results in $\Gamma(\Lambda_c^+ \to X e^+ \nu_e)/\bar{\Gamma}(D \to X e^+ \nu_e)$ $Xe^+\nu_e$ = 1.44 ± 0.54 [8, 9]. This ratio is predicted to be 1.67 [9, 10] using an effective-quark theory calculation and about 1.2 based on a calculation using the heavyquark expansion [11]. Therefore, a more precise measurement of $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)$ is desirable to test these theoretical predictions.

In this Letter, we present the first absolute measurement of the branching fraction of the inclusive semileptonic Λ_c^+ decay using a double-tag method. This analysis is based on a data sample corresponding to an integrated luminosity of 567 pb⁻¹, which is the largest Λ_c^+ sample taken just above the $\Lambda_c^+\bar{\Lambda}_c^-$ production threshold collected up to now. The data sample was accumulated at a center-of-mass energy $\sqrt{s}=4.6$ GeV and recorded with the BESIII detector [12] at the Beijing Electron-Positron Collider II (BEPCII). A detailed description of the BESIII detector can be found in Ref. [12].

A GEANT4-based [13] Monte Carlo (MC) simulation is used to estimate the signal efficiency, optimize the selection criteria and understand the backgrounds. In the

simulation, the effects of beam-energy spread and initial state radiation (ISR) are incorporated using KKMC [14], and the final-state radiation (FSR) is modeled by Photos [15]. The 'inclusive' MC samples consist of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs, $D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$ pairs, ISR to lower-mass charmonium (ψ) states, and continuum QED and QCD processes $e^+e^- \to q\bar{q}$ (q=u,d,s). All known decay modes of Λ_c^+ , $D_{(s)}^{(*)}$ and ψ are generated with the branching fractions taken from the Particle Data Group (PDG) [8] by EVTGEN [16, 17], and the remaining unknown decay modes of ψ are generated by LUNDCHARM [18]. The equivalent luminosities of the simulated data samples are several times that of real data.

Since the data are taken just above the production threshold of $\Lambda_c^+ \bar{\Lambda}_c^-$, no additional hadrons are produced. The double-tag technique, first developed by the MARK III collaboration [19], is used to determine the absolute branching fraction of the inclusive semileptonic decay. First, we fully reconstruct one $\bar{\Lambda}_c^-$ [referred to as the single-tag (ST), and then search for candidates of the signal decay in the rest of the event that is recoiling against the tagged Λ_c^- . Hence, the absolute branching fraction of the inclusive semileptonic decay can be measured without knowing the number of $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs produced, thus eliminating the related systematic uncertainty from the measurement. The ST candidates are reconstructed through the decays $\bar{\Lambda}_c^- \to \bar{p} K_S^0$ and $\bar{\Lambda}_c^- \to \bar{p} K^+ \pi^-$, which have large branching fractions and low backgrounds. The charge conjugated modes are implied throughout this Letter unless otherwise stated.

The charged tracks, except those from K_S^0 , are required to have a polar angle θ with respect to the beam direction within the multilayer drift chamber (MDC) acceptance $|\cos\theta| < 0.93$, and a distance of closest approach to the interaction point (IP) within 10 cm along the beam direction and 1 cm in the plane transverse to the beam direction. Particle identification (PID) for charged pions, kaons and protons is performed by exploiting time-offlight (TOF) information and specific ionization energy loss dE/dx measured by the MDC. The confidence level (C.L.) under each particle hypothesis $(p, K, \text{ or } \pi)$ is calculated; each charged track is assigned the particle type with the largest PID C.L. The K_S^0 meson candidates are reconstructed from two oppositely charged tracks to which no PID criteria are applied and which are assigned the pion mass hypothesis. The charged tracks from the

TABLE I. Summary of ΔE requirements, detection efficiencies and ST yields for the different tag modes.

Tag mode	$\Delta E \text{ (MeV)}$	Efficiency (%)	Yield
$\bar{\Lambda}_c^- \to \bar{p} K_S^0$	(-21, 19)	56.5 ± 0.3	1214 ± 36
$\bar{\Lambda}_c^- \to \bar{p} K^+ \pi^-$	(-20, 16)	50.1 ± 0.1	6092 ± 82

 K_S^0 candidate must satisfy $|\cos\theta| < 0.93$. Furthermore, due to the long lifetime of the K_S^0 meson, there is a less stringent criterion on the distance of the closest approach to the IP in the beam direction of less than 20 cm and there is no requirement on the distance of closest approach in the plane transverse to the beam direction. The invariant mass of the track pair is required to be in the range $(0.487, 0.511)~{\rm GeV}/c^2$. Furthermore, the $\pi^+\pi^-$ pair is constrained to be consistent with originating from a common decay vertex by means of a vertex fit. In addition, the decay length, which is the distance between the IP and the decay vertex, is required to be larger than twice its resolution.

To suppress combinatorial backgrounds, two kinematic variables are used to select the ST candidates. These are the energy difference $\Delta E \equiv E_{\bar{\Lambda}_c^-} - E_{\rm beam}$ and the beam-constrained mass $M_{\rm BC}=\sqrt{E_{\rm beam}^2/c^4-|\vec{p}_{\bar{\Lambda}_c}^-|^2/c^2},$ where $E_{\rm beam}$ is the beam energy, $E_{\bar{\Lambda}_c^-}$ and $\vec{p}_{\bar{\Lambda}_c^-}$ are the reconstructed energy and three momentum of the ST candidate in the rest frame of the e^+e^- system, respectively. We require ΔE to be within $(-3\sigma, 3\sigma)$ of the peak of the ΔE distribution, where σ is the resolution of the ΔE distribution. Table I gives the ΔE requirements for each ST mode. If there are multiple candidates for the same tag mode in a given event, only the combination with the smallest $|\Delta E|$ is retained for further analysis. To determine the ST yields, we apply a fit to the $M_{\rm BC}$ distributions, as shown in Fig. 1. In the fits, the signal shape is modeled by the shape obtained from the MC convolved with a Gaussian function that describes the resolution difference between data and MC simulation; the combinatorial background is described by an ARGUS function [20]. We obtain the ST yields by subtracting the integral of the background function in the signal region $2.282 < M_{\rm BC} < 2.300 \ {\rm GeV}/c^2$ from the total number of events in the same region. The tails of the M_{BC} distribution above the nominal Λ_c^+ mass are due to the effects of ISR and FSR. The ST yields and the corresponding detection efficiencies are summarized in Table I.

In the selected ST sample of Λ_c^- candidates, we search for charged tracks consistent with being an electron or positron. To ensure that the charged tracks originate from the IP, the same distance of closest approach selection criteria are used as for the non- K_S^0 daughters of the ST candidates. The track is required to satisfy $|\cos \theta| < 0.8$ to ensure that it lies within the acceptance

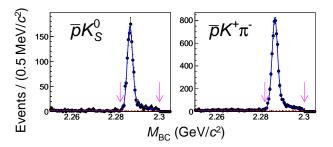


FIG. 1. (Color online) $M_{\rm BC}$ distributions for the different ST modes in data. The solid blue line is the total fit, the dashed red line is the background component, and the pink arrows denote the $M_{\rm BC}$ signal region.

of the barrel of the electromagnetic calorimeter (EMC), which has better energy resolution than the EMC endcaps. The momentum of the charged track is required to be greater than $200~{\rm MeV}/c$, as it is difficult to separate positrons from other hadrons with low momenta. The selected tracks are divided into right-sign (RS) and wrong-sign (WS) samples, where the charge of the RS (WS) track is required to be opposite (equal) to that of the ST candidate.

The PID of the selected tracks is implemented with the information of the dE/dx, TOF and EMC, and the C.L. under each particle hypothesis $(e, \pi, K \text{ or } p)$ is calculated. Positron candidates must satisfy CL(e) > 0.001 and $CL(e)/(CL(e) + CL(\pi) + CL(K) + CL(p)) > 0.8$. To further suppress the backgrounds from charged pions, $E_e/p_e > 0.8$ is required, where E_e and p_e are the deposited energy in the EMC and momentum measured by the MDC, respectively. The remaining selected charged tracks are assigned the hadron type corresponding to the highest C.L. that is greater than 0.001. The track is rejected if it does not have a C.L. greater than 0.001 for any hypothesis.

The identified positron sample contains sizable backgrounds from misidentified hadrons. To evaluate these backgrounds, knowledge of their yields and corresponding misidentification probabilities is required. The real RS and WS positron yields are determined individually by unfolding the matrix [21–23]

$$\begin{pmatrix} N_e^{\text{obs}} \\ N_\pi^{\text{obs}} \\ N_K^{\text{obs}} \\ N_p^{\text{obs}} \end{pmatrix} = \begin{pmatrix} P_{e \to e} & P_{\pi \to e} & P_{K \to e} & P_{p \to e} \\ P_{e \to \pi} & P_{\pi \to \pi} & P_{K \to \pi} & P_{p \to \pi} \\ P_{e \to K} & P_{\pi \to K} & P_{K \to K} & P_{p \to K} \\ P_{e \to p} & P_{\pi \to p} & P_{K \to p} & P_{p \to p} \end{pmatrix} \begin{pmatrix} N_e^{\text{true}} \\ N_\pi^{\text{true}} \\ N_T^{\text{true}} \\ N_p^{\text{true}} \end{pmatrix},$$

where N_a^{obs} is the observed yield of particle species a (a denotes e, π , K or p), $P_{a\to b}$ is the probability to identify particle a as particle b, and N_a^{true} is the true yield of particle a in the studied sample. The elements of the PID efficiency matrix $P_{a\to b}$ are obtained by studying corresponding control samples selected from data. The charged pion and proton samples are selected from

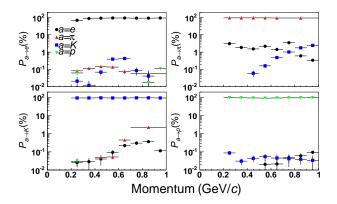


FIG. 2. (Color online) PID efficiencies obtained from data.

 $J/\psi \to p\bar{p}\pi^+\pi^-$ events. The charged kaon and positron samples are selected from $J/\psi \to K^+K^-K^+K^-$ and radiative Bhabha events, respectively. Due to the different event topologies, the PID efficiency of positrons from $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs (one positron and several hadrons) differs from that from radiative Bhabha events (one electron, one positron and one shower). The relative difference (\sim 4.2%) is corrected by comparing the positron efficiency obtained from radiative Bhabha MC samples and $\Lambda_c^+ \bar{\Lambda}_c^$ pair MC samples. No correction to the other elements is implemented. The momentum dependence of the PID efficiency matrix is mostly determined in intervals of 100 MeV/c, though some intervals are wider due to limited statistics, as presented in Fig. 2. The muon component is omitted in the unfolding procedure due to its small yields (almost the same as the positron yields), the small mis-PID probability from muon to positron (similar to that from pion to positron, shown in Fig. 2) and the negligible effect on the branching fraction measurement. In addition, because the selected pion sample contains the muon component due to their similar PID behaviour in the BESIII detector, the muon component is implicitly taken into account.

To estimate the contribution from non- Λ_c^+ decays in the signal region, the unfolded positron yield in the $M_{\rm BC}$ sideband region is scaled by a factor of 0.78 that accounts for the relative amount of background in the sideband and signal regions determined by the fit to the $M_{\rm BC}$ distribution. Since low-background ST modes are used, the contribution from non- Λ_c^+ decays is small (3.8%).

The RS sample contains primary positrons, which directly originate from Λ_c^+ decays, and secondary positrons, not directly arising from Λ_c^+ decays and originating predominantly from γ conversions and π^0 Dalitz decays. Detailed MC studies indicate that the secondary positrons are charge symmetric, hence their yield can be evaluated from the WS positron sample and subtracted from the total RS positron yields. The reliability of the WS subtraction has been validated by MC studies.

The tracking efficiency in a given momentum interval,

TABLE II. Positron yields in data after each procedure. The uncertainties are statistical.

$\Lambda_c^+ \to X e^+ \nu_e$	RS	WS
Observed yields		_
tag signal region	228.0 ± 15.1	26.0 ± 5.1
tag sideband region	11.0 ± 3.3	2.0 ± 1.4
PID unfolding		
tag signal region	250.1 ± 17.1	28.3 ± 6.2
tag sideband region	12.1 ± 3.8	1.7 ± 1.5
Sideband subtraction	240.7 ± 17.4	27.0 ± 6.3
WS subtraction	213.7 ± 18.5	
Correction of tracking efficiency	272.1 ± 23.5	

including the track reconstruction efficiency, selection efficiency and resolution effects, is corrected by unfolding the following matrix equation

$$N_i^{\text{true}} = \sum_j T(i|j) N_j^{\text{pro}}, \tag{1}$$

where the tracking efficiency matrix T(i|j) describes the probability of positrons produced in the j-th momentum interval to be reconstructed in the i-th momentum interval, $N_j^{\rm pro}$ is the number of primary positrons produced in the j-th momentum interval and $N_i^{\rm true}$ is the true yield of positron reconstructed in the i-th momentum interval. The tracking efficiency matrix is obtained by studying the positron MC sample selected from Λ_c^+ semileptonic events. After this procedure, we obtain the efficiency-corrected positron momentum spectrum above $200~{\rm MeV}/c$ in the laboratory frame. Table II summarizes the positron yields obtained after each correction step.

The fraction of positrons below 200 MeV/c is obtained by fitting the efficiency-corrected positron momentum spectrum with the sum of the spectra of the exclusive decay channels (Table III), as shown in Fig. 3. In the fit, the branching fraction of each component is allowed to vary within the given uncertainty. From the fit, we obtain the fraction of positrons below 200 MeV/c to be $(5.6\pm1.5)\%$, where the uncertainty is systematic derived from variations of the fit assumptions. The branching fraction of the inclusive semileptonic decay of the Λ_c^+ baryon is then calculated with

$$\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = \frac{N^{\text{pro}}(p_e > 200 \text{ MeV}/c)}{N_{\text{tag}}[1 - f(p_e < 200 \text{ MeV}/c)]},$$
 (2)

where $N^{\rm pro}(p_e>200~{\rm MeV}/c)$ is the yield of positrons with momentum p_e above 200 MeV/c after the correction of the tracking efficiency, $N_{\rm tag}$ is the ST yield and $f(p_e<200~{\rm MeV}/c)$ is the fraction of positron below 200 MeV/c. Finally, we obtain $\mathcal{B}(\Lambda_c^+\to Xe^+\nu_e)=(3.95\pm0.34)\%$, where the uncertainty includes only the statistical component of that on the signal and ST yields.

TABLE III. Λ_c^+ semileptonic decays used to extrapolate the positron momentum spectrum. The branching fraction of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decay is from BESIII measurement [5] and the uncertainty of the unobserved decay channels are 100% of the predicted branching fractions. The form factor of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decay is from QCD sum rules [24] and the other two, unobserved, semileptonic decay modes are generated by PYTHIA [27] according to the simple V-A matrix element.

Decay channel	B (%)	Model
$\Lambda_c^+ \to \Lambda e^+ \nu_e$	3.63 ± 0.43 [5]	$F_1^V(q^2) = \frac{2.52}{5.09 - q^2} [24]$
$\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$	0.38 ± 0.38 [25]	РҮТНІА [<mark>27</mark>]
$\Lambda_c^+ \to n e^+ \nu_e$	0.27 ± 0.27 [26]	РҮТНІА [<mark>27</mark>]

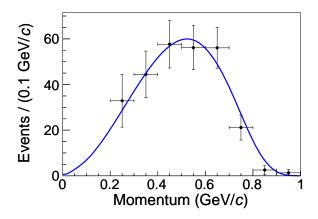


FIG. 3. (Color online) Extrapolation of the positron momentum spectrum in the laboratory frame obtained from data, shown as points with error bars. The blue curve shows the extrapolated spectrum.

The systematic uncertainties in this analysis are listed in Table IV. The tag yield systematic uncertainty is estimated to be 1.0% by using alternative fits to the $M_{\rm BC}$ distribution with different signal shapes, background parameters and fitting ranges. The systematic uncertainty related to the tracking efficiency is estimated to be 1.0% by studying radiative Bhabha events [5]. The systematic uncertainty in the positron identification efficiency is estimated by comparing the positron PID efficiencies in different MC simulated semileptonic Λ_c^+ decays. The largest relative difference of the positron PID efficiency is assigned as the systematic uncertainty. The uncertainties in the other elements of the PID efficiency matrix are estimated by comparing the matrix elements obtained from $\Lambda_c^+ \bar{\Lambda}_c^-$ pair MC samples with those obtained from radiative Bhabha, $J/\psi \to p\bar{p}\pi^+\pi^-$ and $J/\psi \to K^+K^-K^+K^-$ MC samples. Adding them in quadrature, we assign 0.9% as the systematic uncertainty related to PID. The uncertainty associated with the $M_{\rm BC}$ sideband subtraction is estimated to be 0.5% by using an alternative $M_{\rm BC}$ sideband region. To estimate the uncertainty in the extrapolation of the positron momentum spectrum, we

TABLE IV. Sources of systematic uncertainties.

Source	Relative uncertainty (%)
Tag yield	1.0
Tracking	1.0
PID	0.9
Sideband subtraction	0.5
Extrapolation	1.5
Data and MC statistics	0.4
Sum	2.3

perform an alternative fit in which the branching fraction of each fit component is unconstrained. In addition, we use an alternative form-factor model and repeat the fit. Adding these effects in quadrature, we attribute 1.5% as the systematic uncertainty related to the extrapolation procedure. The uncertainty due to limited statistics of data and MC simulation used to determine the PID efficiency matrix and tracking efficiency matrix is estimated by repeating the PID unfolding procedure and correction of tracking efficiency. In each repetition, we vary each element of the PID efficiency matrix and tracking efficiency matrix within the corresponding error. The corresponding systematic uncertainty is derived from 10,000 independent repetitions and is estimated to be 0.4%. Adding all uncertainties in quadrature, the total systematic uncertainty is determined to be 2.3%.

The absolute branching fraction of the inclusive semileptonic decays of the Λ_c^+ baryon is determined to be $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$, where the first and second uncertainties are statistical and systematic, respectively. Compared with the branching fraction of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ measured by the BESIII collabration [5], the ratio $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)}$ is determined to be $(91.9 \pm 12.5 \pm$ 5.4)%, where the systematic uncertainty related to the tracking efficiency of the positron cancels. Using the known Λ_c^+ lifetime [8], we obtain the semileptonic decay width $\Gamma(\Lambda_c^+ \to Xe^+\nu_e) = (1.98 \pm 0.18) \times 10^{11} \text{ s}^{-1}$. Comparing this with the charge-averaged semileptonic decay width of nonstrange charmed measons $\bar{\Gamma}(D \rightarrow$ $Xe^+\nu_e$) [8], the ratio $\frac{\Gamma(\Lambda_c^+\to Xe^+\nu_e)}{\Gamma(D\to Xe^+\nu_e)}$ is determined to be 1.26 ± 0.12 . A comparison of the branching fraction and ratio of the semileptonic decay width between experimental measurements and theoretical predictions can be found in Table V.

In summary, by analysing a data sample corresponding to an integrated luminosity of 567 pb⁻¹ taken at a center-of-mass energy $\sqrt{s}=4.6$ GeV, we report the absolute measurement of the inclusive semileptonic Λ_c^+ decay branching fraction $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$. The uncertainty is reduced by a factor of four compared to the MARK II result [7]. Based on the BE-SIII measurements [5], we obtain the ratio of the branch-

TABLE V. Comparison of the branching fraction (in 10^{-2}) and ratio of the semileptonic decay width between experimental measurements and theoretical predictions.

Result	$\Lambda_c^+ \to X e^+ \nu_e$	$\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)}$
BESIII	3.95 ± 0.35	1.26 ± 0.12
MARK II [7]	4.5 ± 1.7	1.44 ± 0.54
Effective-quark Method [9, 10]		1.67
Heavy-quark Expansion [11]		1.2

ing fraction to be $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)} = (91.9 \pm 12.5 \pm 5.4)\%$. We also determine the ratio $\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\Gamma(D \to X e^+ \nu_e)} = 1.26 \pm 0.12$,

which restricts different models as given in Table V.

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