Measurements of the Branching Fractions of the Semileptonic Decays $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$ and the Asymmetry Parameter of $\Xi_c^0 \to \Xi^- \pi^+$

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Using data samples of 89.5 and 711 fb^{-1} recorded at energies of $\sqrt{s} = 10.52$ and 10.58 GeV, respectively, with the Belle detector at the KEKB e^+e^- collider, we report measurements of branching fractions of semileptonic decays $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$ ($\ell = e$ or μ) and the CP-asymmetry parameter of $\Xi_c^0 \to \Xi^- \pi^+$ decay. The branching fractions are measured to be $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.31 \pm 0.04 \pm 0.07 \pm 0.38)\%$ and $\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = (1.27 \pm 0.06 \pm 0.10 \pm 0.37)\%$, and the decay parameter $\alpha_{\Xi\pi}$ is measured to be $0.63 \pm 0.03 \pm 0.01$ with much improved precision compared with the current world average. The corresponding ratio $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu)$ is $1.03 \pm 0.05 \pm 0.07$, which is consistent with the expectation of lepton flavor universality. The first measured asymmetry parameter $\mathcal{A}_{CP} = (\alpha_{\Xi^-\pi^+} + \alpha_{\bar{\Xi}^+\pi^-})/(\alpha_{\Xi^-\pi^+} - \alpha_{\bar{\Xi}^+\pi^-}) = 0.024 \pm 0.052 \pm 0.014$ is found to be consistent with zero. The first and the second uncertainties above are statistical and systematic, respectively, while the third ones arise due to the uncertainty of the $\Xi_c^0 \to \Xi^- \pi^+$ branching fraction.

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Charmed baryons play an important role in studies of strong and weak interactions, especially via investigations of their semileptonic decays [1–8] and charge-parity violation (CPV) [9,10]. Such decay amplitudes are the product of a well-understood leptonic current for the lepton system and a more complicated hadronic current for the quark transition. For semileptonic decays of SU(3) antitriplets, Λ_c^+ and $\Xi_c^{+,0}$, thanks to the spin-zero light diquark constituents, a simpler and more powerful theoretical calculation of form factors, hadronic structures, and nonperturbative aspects of strong interactions can be performed in a relatively simple version of quantum chromodynamics (QCD) [1].

Thus far semileptonic decays of Λ_c^+ only have been comprehensively studied and are statistically limited by low production rates and/or high background levels of current experiments. Within uncertainties CP symmetry and lepton flavor universality (LFU) are found to be conserved [11–14]. A violation of LFU would be a clear sign of new physics [15–19]. The tantalizing deviation from standard model predictions in $b \to c\ell\nu$ and $b \to s\ell\ell$ processes [20–26] inspires tests of LFU in more semileptonic decays of heavy quarks. For Ξ_c^0, the ARGUS Collaboration first observed 18.1 ± 5.9 $\Xi_c^0 \to \Xi\ell X$ events ($\ell = e$ or μ) [27]. Later, the CLEO Collaboration found 54 ± 10 $\Xi_c^0 \to \Xi^- e^+ \nu_e$ events [28]. The ratio of the branching fractions, $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$, was $0.96 \pm 0.43 \pm 0.18$ from ARGUS and $3.1 \pm 1.0^{+0.3}_{-0.5}$ from CLEO measurements, respectively. With the absolute branching fraction $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.52)\%$ measured by Belle recently [29], the averaged $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)$ is $(2.34 \pm 1.59)\%$ [30]. A variety of models have been developed to predict the decay branching fraction for $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)$ resulting in a range from 1.35% to $(7.26 \pm 2.54)\%$ [4–8]. A precise measurement is crucial to test these models as well as to constrain the model parameters.

Though the standard model accommodates CPV which is one of the conditions needed to explain our matter-dominated Universe [31], the magnitude of this effect as predicted by the Kobayashi–Maskawa mechanism is not sufficient [32]. CPV has been established in many meson decays [33–41], but CPV has never been observed in any baryon system. Studies of CP-violating processes in the charm baryon sector are very scarce [13,14,42–44]. Since there should be CPV sources other than those currently known, it is imperative to search for those also in the charm baryon sector, and several phenomenology studies about CPV in charmed baryon decays have been conducted [45–48].

CP violation in two body decays of charmed baryons can manifest itself as an asymmetry between the parity-violating decay parameter α for a process and its charge conjugate. For the $\Xi_c^0 \to \Xi^- \pi^+ \to \Lambda \pi^- \pi^+$ process, the decay parameter $\alpha_{\Xi^-\pi^+}$ (denoted as α^+) enters the angular distribution expression,

$$\frac{dN}{d\cos\theta_{\Xi^-}} \propto 1 + \alpha_{\Xi^-\pi^+} \alpha_{\Xi^-} \cos\theta_{\Xi^-}. \quad (1)$$

Here, θ_{Ξ^-} is the angle between the Λ momentum vector and the opposite of the Ξ_c^0 momentum in the Ξ^- rest frame [49],

dN is the number of signal events in each $\cos\theta_{\Xi^-}$ bin, and α_{Ξ^-} is the decay parameter of the Ξ^- [50]. The definition of $\alpha_{\bar{\Xi}^+\pi^-}$ (denoted as α^-) is analogous for the charge-conjugated decay mode. The only charge-averaged measurement of the decay parameters $\alpha_{\Xi\pi}$ is from CLEO with the result $-0.56 \pm 0.39^{+0.10}_{-0.09}$ [51], which falls in the range of $[-0.99, -0.38]$ expected from theoretical predictions [52–57]. The CP-asymmetry parameter $\mathcal{A}_{CP} = (\alpha^+ + \alpha^-)/(\alpha^+ - \alpha^-)$ can be calculated for $\Xi_c^0 \to \Xi^-\pi^+$ and $\bar{\Xi}_c^0 \to \bar{\Xi}^+\pi^-$.

In this Letter, we present measurements of the branching fractions of $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ [58] with significantly improved precision using data samples of 89.5 and 711 fb^{-1} collected at $\sqrt{s} = 10.52$ and $\sqrt{s} = 10.58$ GeV, respectively, by the Belle detector [59] at the KEKB asymmetric-energy collider [60]. LFU is tested using these measured results. Charm baryons are produced in processes such as $e^+e^- \to c\bar{c} \to \Xi_c^0 +$ anything. Ξ^- is reconstructed via the $\Lambda\pi^-$ mode, and Λ decays into $p\pi^-$. The decay parameters of α^+ and α^- and the CP-asymmetry parameter $\mathcal{A}_{CP}$ are first measured for $\Xi_c^0(\bar{\Xi}_c^0) \to \Xi\pi$.

To optimize the signal selection criteria and calculate the signal reconstruction efficiency, we use MC simulated events. The $e^+e^- \to c\bar{c}$ process is simulated with PYTHIA [61], while the signal events of Ξ_c^0 semileptonic decays are generated using form factors from lattice QCD calculation [62], and $\Xi_c^0 \to \Xi^-\pi^+$ decays are generated with EVTGEN [63]. The MC events are processed with a detector simulation based on GEANT3 [64]. Simulated $\Upsilon(4S) \to B\bar{B}$ events with $B = B^+$ or B^0, and $e^+e^- \to q\bar{q}$ events with $q = u, d, s$, and c at $\sqrt{s} = 10.52$ GeV and 10.58 GeV, are used as background samples in which the signals are removed, which are called generic simulated samples.

For leptons and pions which are direct daughters of Ξ_c^0, the impact parameters perpendicular to and along the e^+ beam direction with respect to the interaction point are required to be less than 0.5 cm and 4 cm, respectively, and transverse momentum is restricted to be higher than 0.1 GeV$/c$. For charged tracks, information from different detector subsystems is combined to form the likelihood $\mathcal{L}_i$ for species (i), where $i = e, \mu, \pi, K$, or p [65]. A track not from Λ with a likelihood ratio $\mathcal{L}_\pi/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6$ is identified as a pion. With this selection, the pion identification efficiency is about 94%, while 5% of the kaons are misidentified as pions. A track with a likelihood ratio $\mathcal{L}_e/(\mathcal{L}_e + \mathcal{L}_{\text{non}-e}) > 0.9$ is identified as an electron [66]. The γ conversions are removed by examining all combinations of an $e^\pm$ track with other oppositely charged tracks in the event that are identified as $e^\mp$, and requiring e^+e^- invariant mass larger than 0.2 GeV$/c^2$. Tracks with $\mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_K + \mathcal{L}_\pi) > 0.9$ are considered as muon candidates [67]. Furthermore, the muon tracks are required to hit at least five layers of the K_L^0 and muon subdetector, and not to be identified as kaons with $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) < 0.4$ to suppress backgrounds due to misidentification. With the above selections, the efficiencies of electron and muon identification are 96% and 75%, respectively, with pion fake rates less than 2%.

Candidate Λ baryons are reconstructed in the decay $\Lambda \to p\pi^-$ and selected if $|M_{p\pi^-} - m_\Lambda| < 3$ MeV$/c^2$ ($\sim 2.5\sigma$), where σ denotes the mass resolution. Here and throughout the text, M_i represents a measured invariant mass, and m_i denotes the nominal mass of the particle i [30]. The proton track from Λ decay is required to satisfy $\mathcal{L}_p/(\mathcal{L}_\pi + \mathcal{L}_p) > 0.2$ and $\mathcal{L}_p/(\mathcal{L}_K + \mathcal{L}_p) > 0.2$ with an efficiency of 95%. We define the Ξ^- signal region as $|M_{\Lambda\pi^-} - m_{\Xi^-}| < 6.5$ MeV$/c^2$ ($\sim 3\sigma$), and Ξ^- mass sidebands as 1.294 GeV$/c^2 < M_{\Lambda\pi^-} < 1.307$ GeV$/c^2$ and 1.337 GeV$/c^2 < M_{\Lambda\pi^-} < 1.350$ GeV$/c^2$. To suppress combinational background, we require the flight directions of Λ and Ξ^- candidates, which are reconstructed from their fitted production and decay vertices, to be within five degrees of their momentum directions. We also require the scaled momentum $p^*_{\Xi^- X}/p^*_{\max} > 0.45$ ($X = e^+, \mu^+$, or π^+), where $p^*_{\Xi^- X}$ is the momentum of the $\Xi^- X$ system in the center-of-mass frame, and $p^*_{\max} \equiv \sqrt{E^2_{\text{beam}} - m^2_{\Xi_c^0}}$ (E_{beam} is the beam energy). This requirement removes all $\Xi_c^0 \to \Xi^-\pi^+$ decays with Ξ_c^0 produced in B decays from the $\sqrt{s} = 10.58$ GeV sample. For $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$, the cosine of the opening angle between Ξ^- and ℓ^+ is further required to be larger than 0.25.

After the above selections, the obtained Ξ^-e^+, $\Xi^-\mu^+$, and $\Xi^-\pi^+$ mass spectra from data in $p^*_{\Xi^- X}/p^*_{\max}$ regions of (0.45, 0.55), (0.55, 0.65), (0.65, 0.75), and (0.75, 1) are shown in Fig. 1. The Ξ_c^0 signals are extracted from maximum-likelihood fits to these invariant mass spectra. For Ξ_c^0 semileptonic decays, the signal shapes are taken directly from MC simulation. The background shapes from wrongly constructed Ξ candidates can be described by the $M_{\Xi^-\ell^+}$ distributions of Ξ^- mass sidebands. The backgrounds from $\Xi_c \to \Xi\pi\ell^+\nu_\ell$ are taken from MC simulations of those processes. The backgrounds from $e^+e^- \to q\bar{q}$ due to mis-selected ℓ^+ can be represented by the $M_{\Xi^-\ell^+}$ distributions of $\Xi^-\ell^-$ events with their normalized Ξ^- mass sidebands subtracted. The other backgrounds are from $e^+e^- \to B\bar{B}$ with Ξ^- from one B and ℓ^+ from another $\bar{B}$, whose shapes are taken from generic simulated samples. Background from $\Omega_c^0 \to \Xi^-\ell^+\nu_\ell$ decays is assumed to be negligible since it is a $c \to d$ process and should be suppressed strongly. In fitting the $\Xi^-\mu^+$ mass spectrum, an additional background of simulated $\Xi_c^{0,+} \to \Xi^-\pi^+ +$ hadrons events from generic simulated samples is added. In the fit above, the shapes of all fit components are fixed while their yields are floated. In fitting the $\Xi^-\pi^+$ mass spectrum, the Ξ_c^0 signal shape is parameterized with a double-Gaussian function with the same mean value and all other parameters floated,

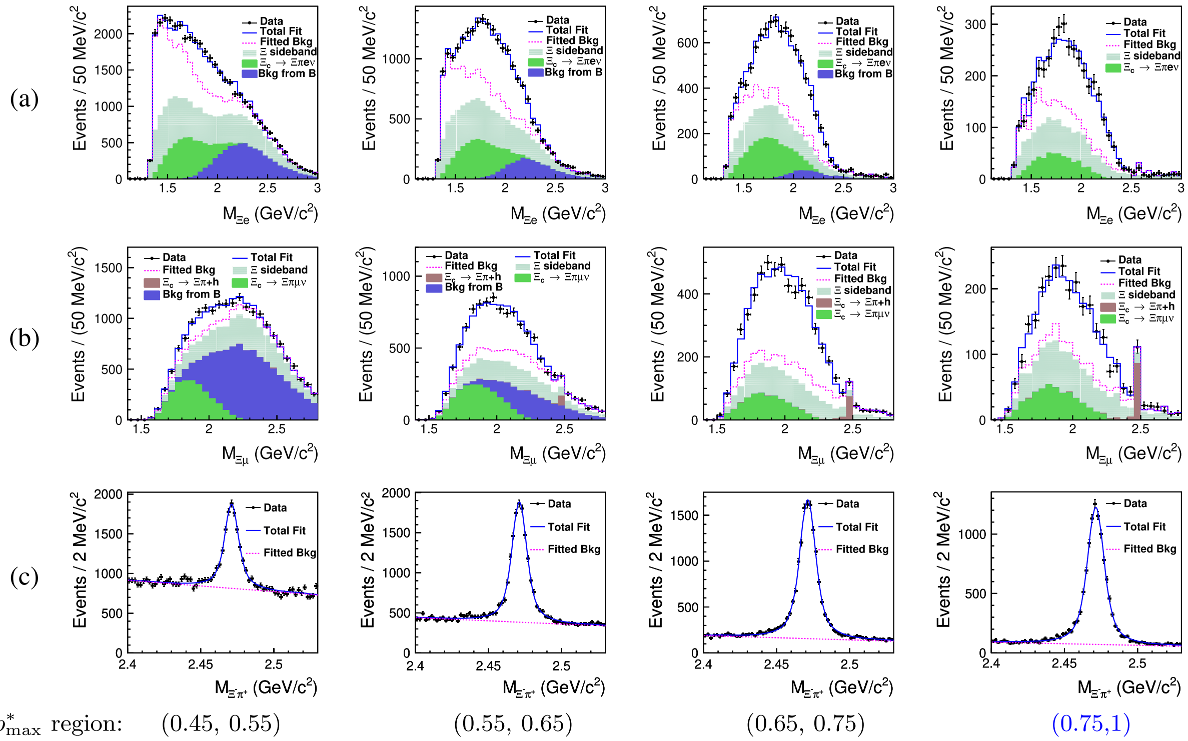

FIG. 1. The fits to the $M_{\Xi^-e^+}$, $M_{\Xi^-\mu^+}$, and $M_{\Xi^-\pi^+}$ distributions of the selected (a) $\Xi_c^0 \to \Xi^- e^+ \nu_e$, (b) $\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$, and (c) $\Xi_c^0 \to \Xi^- \pi^+$ candidates in each $p^*_{\Xi^-X}/p^*_{\max}$ bin listed at the bottom. The points with error bars represent the data from $\sqrt{s} = 10.52$ GeV and 10.58 GeV, the solid blue lines are the best fits, and the violet dashed lines are the fitted total backgrounds. The other components of the fits are indicated in the legends.

while the background shape is represented with a first-order polynomial. Figure 1 shows the fitted results in each $p^*_{\Xi^-X}/p^*_{\max}$ bin labeled at the bottom for (a) $\Xi_c^0 \to \Xi^- e^+ \nu_e$, (b) $\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$, and (c) $\Xi_c^0 \to \Xi^- \pi^+$. The fitted result in each $p^*_{\Xi^-X}/p^*_{\max}$ bin together with the corresponding detection efficiency is listed in Table I. The background sources and fit methods are validated with generic simulated samples.

The Ξ_c^0 semileptonic decay branching fractions are calculated using

$$\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell) \equiv \frac{\varepsilon_{\rm pop}^{\Xi^-\pi^+} \Sigma_i \frac{N_i^{\Xi^-\ell^+}}{\varepsilon_i^{\Xi^-\ell^+}}}{\varepsilon_{\rm pop}^{\Xi^-\ell^+} \Sigma_i \frac{N_i^{\Xi^-\pi^+}}{\varepsilon_i^{\Xi^-\pi^+}}} \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+),$$

where $N_i^{\Xi^-X}$ and $\varepsilon_i^{\Xi^-X}$ are the fitted signal yield and detection efficiency, respectively, in each $p^*_{\Xi^-X}/p^*_{\max}$ bin; $\varepsilon_{\rm pop}^{\Xi^-X}$ is the efficiency of the $p^*_{\Xi^-X}/p^*_{\max} > 0.45$ requirement for each channel and is 0.783, 0.574, and 0.588 for $\Xi_c^0 \to \Xi^- \pi^+$, $\Xi^- e^+ \nu_e$, and $\Xi^- \mu^+ \nu_\mu$, respectively.

Using the results listed in Table I, we obtain $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.31 \pm 0.04 \pm 0.38)\%$, $\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = (1.27 \pm 0.06 \pm 0.37)\%$, and $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = 1.03 \pm 0.05$. Here, the first and second uncertainties are statistical and from $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ [29], respectively.

In the following, $\Xi_c^0 \to \Xi^- \pi^+$ and $\bar{\Xi}_c^0 \to \bar{\Xi}^+ \pi^-$ decays are treated separately to extract decay parameters of α^+ and α^-, and $\mathcal{A}_{CP}$ for $\Xi_c^0(\bar{\Xi}_c^0) \to \Xi^- \pi^+ (\bar{\Xi}^+ \pi^-)$. To obtain

TABLE I. List of the fitted signal yields and the corresponding detection efficiencies in each $p^*_{\Xi^-X}/p^*_{\max}$ bin ($N_i^{\Xi^-X}/\varepsilon_i^{\Xi^-X}$) of data at $\sqrt{s} = 10.52$ GeV and 10.58 GeV. The last column gives the ratios of branching fractions $[\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)]$ in the full $p^*_{\Xi^-X}/p^*_{\max}$ range. Quoted uncertainties are statistical only.

$p^*_f/p^*_{\max}$	(0.45, 0.55)	(0.55, 0.65)	(0.65, 0.75)	> 0.75	$[\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)]$
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	$(5.13 \pm 0.26)\times 10^3/16.5\%$	$(6.08 \pm 0.28)\times 10^3/19.8\%$	$(4.08 \pm 0.21)\times 10^3/21.4\%$	$(1.72 \pm 0.10)\times 10^3/21.3\%$	0.730 ± 0.021
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	$(1.68 \pm 0.15)\times 10^3/6.59\%$	$(3.35 \pm 0.25)\times 10^3/10.36\%$	$(3.15 \pm 0.25)\times 10^3/13.6\%$	$(1.13 \pm 0.14)\times 10^3/15.5\%$	0.708 ± 0.033
$\Xi_c^0 \to \Xi^- \pi^+$	$(8.12 \pm 0.29)\times 10^3/24.2\%$	$(1.20 \pm 0.02)\times 10^4/25.6\%$	$(1.31 \pm 0.02)\times 10^4/26.9\%$	$(1.04 \pm 0.02)\times 10^4/27.13\%$	...

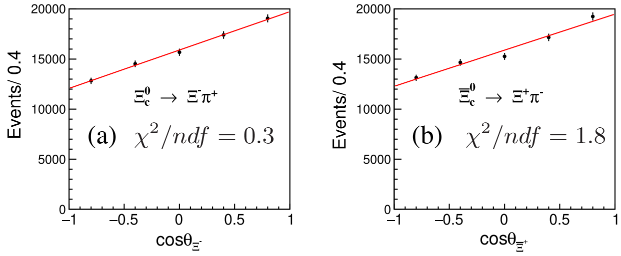

FIG. 2. The maximum-likelihood fits to the efficiency-corrected $\cos\theta_\Xi$ distributions of data to extract (a) $\alpha_{\Xi^-\pi^+}$ and (b) $\alpha_{\bar{\Xi}^+\pi^-}$ for $\Xi_c^0 \to \Xi^-\pi^+$ and $\bar{\Xi}_c^0 \to \bar{\Xi}^+\pi^-$ decays. The points with error bars represent data from the combined samples at $\sqrt{s} = 10.52$ GeV and 10.58 GeV, and the red solid lines are the best fits.

the θ_Ξ distribution, we divided the 2D plane of $p^*_{\Xi\pi}/p^*_{\rm max}$ versus $\cos\theta_\Xi$ into 4×5 bins with the bin edges for $p^*_{\Xi\pi}/p^*_{\rm max}$ and $\cos\theta_\Xi$ set as (0.45,0.55,0.65,0.75,1.0) and $(-1.0, -0.6, -0.2, 0.2, 0.6, 1.0)$, respectively. The detection efficiency in each 2D bin is calculated individually. The number of $\Xi_c^0(\bar{\Xi}_c^0)$ signal events in each 2D bin is obtained by fitting the corresponding $M_{\Xi\pi}$ distribution with the method used in the branching fraction measurements. The number of signal events in each $\cos\theta_\Xi$ bin is the sum of the efficiency-corrected signal yields in corresponding $p^*_{\Xi\pi}/p^*_{\rm max}$ bins. The fitting method was checked using special simulated samples with a range of values of $\mathcal{A}_{CP}$. The final efficiency-corrected $\cos\theta_\Xi$ distributions for (a) $\Xi_c^0 \to \Xi^-\pi^+$ and (b) $\bar{\Xi}_c^0 \to \bar{\Xi}^+\pi^-$ decays are shown in Fig. 2. Using Eq. (1) with $\alpha_{\Xi^-} = -0.376 \pm 0.008$ and $\alpha_{\bar{\Xi}^+} = 0.371 \pm 0.007$ [50], the fits yield $\alpha^+ = -0.64 \pm 0.05$ and $\alpha^- = 0.61 \pm 0.05$, resulting in $\mathcal{A}_{CP} = 0.024 \pm 0.052$. Here, the uncertainties are statistical only.

There are several sources of systematic uncertainties contributing to the branching fraction measurements. Using the $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, $\Lambda \to p\pi$, and $J/\psi \to \ell\ell$ control samples, the particle identification uncertainties ($\sigma_{\rm PID}$) are 0.51–0.55% per pion, 0.55–0.93% per electron, and 0.44–0.84% per muon, depending on the $p^*_{\Xi^-X}/p^*_{\rm max}$ region. The systematic uncertainties associated with tracking efficiency and Ξ^- selection cancel in the branching fraction ratio measurements. We estimate the systematic uncertainties associated with the fitting procedures ($\sigma_{\rm fit}$) for $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ and $\Xi_c^0 \to \Xi^-\pi^+$ separately. For $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ decays, we change the bin width of the $M_{\Xi^-\ell^+}$ spectra by ± 5 MeV$/c^2$, change the Ξ^- mass sidebands from 2 times that of the signal region to 3 times that of the signal region, add the background component from $\Xi_c \to \Xi\pi^+\pi^-\ell^+\nu_\ell$ with its shape taken from MC simulation and yields floated, and take the difference of the fitted signal yields as $\sigma_{\rm fit}$ for each $p^*_{\Xi^-\ell^+}/p^*_{\rm max}$ bin (2.30–4.54% for the electron mode and 2.34–5.10% for the muon mode). For $\Xi_c^0 \to \Xi^-\pi^+$, we estimate $\sigma_{\rm fit}$ by changing the range of the fit and the order of the background polynomial, and take the differences of the fitted signal yields as systematic uncertainties (1.03–1.46% depending on the $p^*_{\Xi^-\pi^+}/p^*_{\rm max}$ region). By using the control sample $\Xi_c^0 \to \Xi^-\pi^+$, the maximum difference in selection efficiency of the requirement $p^*_{\Xi^-\pi^-}/p^*_{\rm max} > 0.45$ between weighted MC simulation based on $p^*_{\Xi^-X}/p^*_{\rm max}$ distribution from data and different signal MC simulations with different fragmentation functions in PYTHIA generator [61] is 3.0%, which is taken as the systematic uncertainty ($\sigma_{\varepsilon^{\rm pop}}$). For semileptonic decays, the uncertainties of the form factors in Ref. [62] introduce a 3.1% (3.6%) uncertainty in the electron (muon) mode ($\sigma_{\rm FF}$). The change of the branching fraction measured with the subdatasets with $p^*_{\Xi^-X}/p^*_{\rm max} > 0.75$ that removes all background from B decay is taken as the uncertainty associated with modeling of the B-decay background ($\sigma_{B\bar{B}}$) which is 2.5% (6.3%) for electron (muon) mode. The systematic uncertainties $\sigma_{\rm PID}$ ($\sigma_{\rm fit}$) are added linearly (in quadrature) weighted by $(N_i^{\Xi^-X}/\varepsilon_i^{\Xi^-X})$ and then summed with $\sigma_{\varepsilon^{\rm pop}}$, $\sigma_{\rm FF}$, and $\sigma_{B\bar{B}}$ in quadrature to yield the total systematic uncertainty ($\sigma_{\mathcal{B}}$) for each Ξ_c^0 decay mode, which yields 4.6%, 7.6%, and 3.1% for the electron, muon, and pion mode, respectively. The final systematic uncertainty on the branching fraction is the sum of the corresponding two $\sigma_{\mathcal{B}}s$ in quadrature, which yields 5.6% for $\mathcal{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)$, and 8.2% for $\mathcal{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$. The uncertainty of 28.9% on $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$ [29] is treated as an independent systematic uncertainty. The total systematic uncertainty for $\mathcal{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$ is 6.8% with the $\sigma_{B\bar{B}}$ negatively correlated.

The sources of systematic uncertainties in $\alpha^\pm$ include fitting procedures ($\sigma^{\alpha^\pm}_{\rm fit}$) and uncertainties on $\alpha_{\Xi^\pm}$ values ($\sigma^{\alpha^\pm}_{\alpha_{\Xi^\mp}}$). $\sigma^{\alpha^\pm}_{\rm fit}$ are estimated to be 0.2% with a toy MC method whose simulated distributions of $\alpha^\pm$ are found to be unbiased. The uncertainties on $\alpha_{\Xi^\pm}$ values are $\sigma^{\alpha^+}_{\alpha_{\Xi^-}} = 2.1\%$ and $\sigma^{\alpha^-}_{\alpha_{\bar{\Xi}^+}} = 1.9\%$ [50], which are the leading systematic uncertainties. The final systematic uncertainties of $\alpha^\pm$ are $\sigma_{\alpha^\pm} = \sqrt{(\sigma^{\alpha^\pm}_{\rm fit})^2 + (\sigma^{\alpha^\pm}_{\alpha_{\Xi^\mp}})^2}$. The systematic uncertainty $\Delta_{\mathcal{A}_{CP}}$ is equal to $2\Delta r/(1-r)^2$. Here $r = \alpha^+/\alpha^-$, $\Delta r = |r| \times \sqrt{\sigma^2_{\alpha^+} + \sigma^2_{\alpha^-}}$. Finally, the systematic uncertainties for α^+, α^-, and $\mathcal{A}_{CP}$ are estimated to be 0.01, 0.01, and 0.014, respectively.

In summary, based on data samples of 89.5 and 711 fb^{-1} collected with the Belle detector at $\sqrt{s} = 10.52$ GeV and $\sqrt{s} = 10.58$, respectively, we measure the branching fractions of the $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ decays, $\Xi_c^0(\bar{\Xi}_c^0) \to \Xi\pi$ decay parameters $\alpha^\pm$, and the corresponding CP-asymmetry parameter $\mathcal{A}_{CP}$. The measured branching fractions are $\mathcal{B}(\Xi_c^0 \to \Xi^-e^+\nu_e) = (1.31 \pm 0.04 \pm 0.07 \pm 0.38)\%$ and $\mathcal{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu) = (1.27 \pm 0.06 \pm 0.10 \pm 0.37)\%$. The ratio $\mathcal{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$ is $1.03\pm$

0.05 ± 0.07, which is consistent with the expectation of LFU [62]. The measured Ξ_c^0 decay parameters are $\alpha^+ = -0.64 \pm 0.05 \pm 0.01$ and $\alpha^- = 0.61 \pm 0.05 \pm 0.01$. The corresponding average absolute value of $\alpha^{\pm}$ is $0.63 \pm 0.03 \pm 0.01$, and the CP-asymmetry parameter $\mathcal{A}_{CP}$ of $\Xi_c^0 \to \Xi^-\pi^+$ decay is measured to be $0.024 \pm 0.052 \pm 0.014$. Here, the first and second uncertainties are statistical and systematic, respectively, while the third uncertainties on branching fractions are due to the uncertainty of $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$ [29]. The precision of the measurements of branching fractions of $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$, and the $\alpha^{\pm}$ of $\Xi_c^0 \to \Xi^-\pi^+$ is greatly improved compared with previous experimental results [27,28,51]. The measured $\mathcal{A}_{CP}$ is consistent with no CP violation. The semileptonic branching fraction $\mathcal{B}(\Xi_c^0 \to \Xi^-\ell^+\nu_\ell)$ is an important input used to constrain parameters of lattice QCD calculations [62] and phenomenological models [4–8] of heavy-flavor baryon decays. As more precise measurements of $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$ become available, the results presented in this Letter will allow the value of $\mathcal{B}(\Xi_c^0 \to \Xi^-\ell^+\nu_\ell)$ to be further improved.

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