Measurement of branching fractions and decay asymmetry parameters for $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Sigma^0 h^+$ ($h = K, \pi$), and search for $CP$ violation in baryon decays
(The Belle Collaboration)

We report a study of $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Sigma^0 h^+$ ($h = K, \pi$) decays based on a data sample of 980 fb$^{-1}$ collected with the Belle detector at the KEKB energy-asymmetric $e^+e^-$ collider. The first results of direct $CP$ asymmetry in two-body singly Cabibbo-suppressed (SCS) decays of charm baryons are measured, $A_{CP}^{\Lambda_c^+}(\Lambda_c^+ \to \Lambda K^+) = +0.021 \pm 0.026 \pm 0.001$ and $A_{CP}^{\Lambda_c^+}(\Lambda_c^+ \to \Sigma^0 K^+) = +0.025 \pm 0.054 \pm 0.004$, where the first uncertainties are statistical and the second systematic. We obtain the most precise branching fractions of SCS $\Lambda_c^+$ decays, $B(\Lambda_c^+ \to \Lambda K^+) = (0.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$ and $B(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$, where the third uncertainties are from the uncertainties on the branching fractions of the reference modes $\Lambda^+ \to \Lambda \pi^+$ and $\Lambda^+ \to \Sigma^0 \pi^+$. The average decay asymmetry parameter for SCS $\Lambda_c^+$ decays, $\alpha(\Lambda_c^+ \to \Lambda K^+) = -0.585 \pm 0.049 \pm 0.018$ and $\alpha(\Lambda_c^+ \to \Sigma^0 K^+) = -0.55 \pm 0.18 \pm 0.09$, are measured for the first time and those for Cabibbo-favored (CF) decays, $\alpha(\Lambda_c^+ \to \Lambda \pi^+) = -0.755 \pm 0.005 \pm 0.003$ and $\alpha(\Lambda_c^+ \to \Sigma^0 \pi^+) = -0.463 \pm 0.016 \pm 0.008$, are measured with an improved precision relative to previous measurements. We search for charm $CP$ violation via the $o$-induced $CP$ asymmetry in SCS $\Lambda_c^+$ decays. We measure $A_{CP}^{\Lambda_c^+}(\Lambda_c^+ \to \Lambda K^+) = -0.023 \pm 0.086 \pm 0.071$ and $A_{CP}^{\Lambda_c^+}(\Lambda_c^+ \to \Sigma^0 K^+) = +0.08 \pm 0.35 \pm 0.14$, which are the first $A_{CP}^{\Lambda_c^+}$ results for SCS decays of charm baryons. We also search for $\Lambda$-hyperon $CP$ violation assuming no $CP$ violation in CF decays $\Lambda_c^+ \to \Lambda \pi^+$ and $\Lambda_c^+ \to \Sigma^0 \pi^+$. We find $A_{CP}^{\Lambda_c^+}(\Lambda_c^+ \to \pi^+\pi^-) = +0.013 \pm 0.007 \pm 0.011$. This is the first time that hyperon $CP$ violation has been measured via charm CF decays. No evidence of baryon $CP$ violation is found.

Keywords: $CP$ violation, charm baryon, singly Cabibbo-suppressed decay, $CP$ asymmetry, branching fraction, decay asymmetry parameter

I. INTRODUCTION

Charge-parity ($CP$) violation is one of the conditions necessary to explain the matter-antimatter asymmetry of the universe [1]. The single complex phase in the Cabibbo-Kobayashi-Maskawa matrix provides the only source of $CP$ violation ($CPV$) in the standard model (SM), but it is not large enough to explain the observed matter-antimatter asymmetry. Baryogenesis, the process by which the baryon-antibaryon asymmetry of the universe developed, is directly related to baryon $CPV$ [2, 3].

Two-body decays of baryons containing a charm quark are sensitive to $CP$ asymmetries, yet are largely unexplored to date. Precise measurements of charm baryon branching fractions also provide useful probes of heavy-baryon dynamics and decay asymmetry parameter measurements can be used to study parity-violating and parity-conserving amplitudes in weak hyperon decays.

To date, $CPV$ has been observed in the open-flavored meson sector (i.e. $K$, $D$ and $B$ mesons), but not yet established in the baryon sector. Since $CPV$ in charm decays is predicted in the SM to be very small [4–6], an observation of $CPV$ in charm decays larger than $10^{-3}$ could indicate new physics beyond the SM [7, 8].

Singly Cabibbo-suppressed (SCS) decays of charm hadrons provide an ideal laboratory for studying $CPV$ as they are a unique window on the physics of decay-rate dynamics in the charm sector [4, 5]. The only observation of CPV in the charm sector was made by the LHCb collaboration in SCS charm meson decays, $D^0 \to h^+h^-$ ($h = K, \pi$ throughout this paper) [9]. $CP$ asymmetry measurements in SCS charm baryon decays are experimentally more challenging than in charm meson decays and relatively unexplored. The direct $CP$ asymmetry, taking $\Lambda_c^+$ decays as an example, is defined as

$$A_{CP}^{\Lambda_c^+} = \frac{\Gamma(\Lambda_c^+ \to f) - \Gamma(\Lambda_c^+ \to \bar{f})}{\Gamma(\Lambda_c^+ \to f) + \Gamma(\Lambda_c^+ \to \bar{f})},$$

where $\Gamma(\Lambda_c^+ \to f)$ and $\Gamma(\Lambda_c^+ \to \bar{f})$ are the partial decay widths for the final state $f$ and its $CP$-conjugate state $\bar{f}$. Searches for direct $CPV$ in charm baryon decays were made by LHCb in $\Lambda_c^+ \to p\phi^+\pi^-$ [10] and $\Xi^+_c \to pK^-\pi^+$ [11]. No direct $CPV$ searches in two-body SCS decays of charm baryons have been made to date.

Theoretical $CPV$ predictions in two-body decays are more straightforward than in multi-body decays, which are complicated by plentiful intermediate processes. Direct $CP$ asymmetry measurements for two-body SCS decays of charm baryons provide useful constraints on theoretical predictions for CPV in the charm baryon sector.

Since the $\Lambda_c^+$ was discovered, many efforts have been made to predict the BFs of its hadronic decays using phenomenological models such as current algebra [12], pole model [13, 14] and SU(3)$_F$ symmetry [15, 16]. The non-factorizable contributions in charm baryon decays, arising from $W$-exchange or internal $W$-emission diagrams, play an essential role [14]. For example, there is only the non-factorization contribution in $\Lambda_c^+ \to \Sigma^0 K^+$, while the factorization contribution is dominant in $\Lambda_c^+ \to \Lambda K^+$. Unlike semileptonic decays that can be calculated precisely, the theoretical predictions for hadronic weak decay rate of charm baryons are nontrivial due to non-perturbative strong dynamics, which complicate the calculation of non-factorizable contributions, and the lack

arXiv:2208.08695v1 [hep-ex] 18 Aug 2022
of knowledge on baryon structure [17, 18].

Experimentally, studies of charm baryon decays are more challenging than those of charm mesons due to lower production rates. The current world average BFs, $B(\Lambda_c^+ \rightarrow \Lambda K^+) = (6.1 \pm 1.2) \times 10^{-4}$ and $B(\Lambda_c^+ \rightarrow \Sigma^0 p^+) = (5.2 \pm 0.8) \times 10^{-4}$ [19], rely on measurements with partial datasets from Belle and BaBar [20, 21]. We perform a measurement with the full Belle dataset.

The decay asymmetry parameter $\alpha$ was introduced by Lee and Yang to study the parity-violating and parity-conserving amplitudes in weak hyperon decays [22]. In a weak decay of a spin 1/2 baryon into a spin 1/2 baryon and a pseudoscalar meson, $\alpha = 2 \cdot \text{Re}(S^* P)/(|S|^2 + |P|^2)$, where $S$ and $P$ denote the parity-violating S-wave and parity-conserving P-wave amplitudes, respectively. A measurement of $\alpha$ in $\Lambda_c^+$ decays is a necessary input for various dynamical modes. It would also improve the knowledge of contributions from parity-violating and parity-conserving amplitudes in two-body $\Lambda_c^+$ decays and the dynamical properties of $\Lambda_c^+$ decays: for example the relative amplitude between S-wave and P-wave is helpful to constrain phenomenological models. Most theoretical predictions for $\alpha$ of $\Lambda_c^+ \rightarrow \Lambda \pi^+$ are in good agreement with experimental results, while those for $\alpha$ in $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$ are not [12–16, 19]. Experimentally, the $\alpha$-parameters for SCS decays of charm baryons are unexplored.

Since $\alpha$ is CP-odd, the $\alpha$-induced CP asymmetry is defined as

$$A_{\alpha CP}^\Lambda = \frac{\alpha_{\Lambda_c^+} - \overline{C} \alpha_{\Lambda_c^+} \overline{C}^\dagger}{\alpha_{\Lambda_c^+} + \overline{C} \alpha_{\Lambda_c^+} \overline{C}^\dagger} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\Sigma^-}}{\alpha_{\Lambda_c^+} + \alpha_{\Sigma^-}},$$

where $\overline{C}$ denotes the CP conjugation operator. In the case that $A_{\alpha CP}^{dir}$ is zero, $A_{\alpha CP}^\Lambda$ is given by the CPV in $\text{Re}(S^* P)$. Therefore, $A_{\alpha CP}^\Lambda$ provides an observable complementary to the $A_{\alpha CP}^{dir}$ induced by decay widths. To date, there is only one $A_{\alpha CP}^\Lambda$ measurement for hadronic $\Lambda_c^+$ decays, $A_{\alpha CP}^\Lambda(\Lambda_c^+ \rightarrow \Lambda \pi^+) = -0.07 \pm 0.22$, from the FOCUS experiment [23]. Using the high-statistics $\Lambda_c^+$ sample at Belle, we make the first measurements of $A_{\alpha CP}^\Lambda$ in $\Lambda_c^+ \rightarrow \Lambda K^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 h^+$ decays and measure $A_{\alpha CP}^\Lambda$ with improved precision in $\Lambda_c^+ \rightarrow \Lambda \pi^+$.

CPV in hyperon decays is predicted to be at the level of $O(10^{-3})$ or smaller in the SM [24, 25] and can be enhanced to reach the level of $10^{-3}$ in some new physics models [26–29]. The world average value of $A_{\alpha CP}^\Lambda(\Lambda \rightarrow p \pi^-) = -0.0024 \pm 0.0044$ [19, 30], is dominated by a measurement by BESIII in $J/\psi \rightarrow \Lambda \Lambda$ based on 10 billion $J/\psi$ events [30]. In this analysis, we search for CP-violating CPV with the novel and complementary method proposed in Ref. [31]. The total $\alpha$-induced CP asymmetry for $\Lambda_c^+ \rightarrow \Lambda \pi^+$, $\Lambda \rightarrow p \pi^-$ and $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$, $\Sigma^0 \rightarrow \Lambda \gamma$, $\Lambda \rightarrow p \pi^-$ decay chains is determined according to

$$A_{\alpha CP}^\Lambda(\text{total}) = \frac{\alpha_{\Lambda_c^+} \alpha_{\Sigma^-} - \alpha_{\Sigma^-} \alpha_{\Lambda_c^+}}{\alpha_{\Lambda_c^+} \alpha_{\Sigma^-} + \alpha_{\Sigma^-} \alpha_{\Lambda_c^+}},$$

where $\alpha_-$ and $\alpha_+$ are the decay asymmetry parameters of $\Lambda \rightarrow p \pi^-$ and $\Lambda \rightarrow \overline{p} \pi^+$, respectively [19]. Under the assumption that $\alpha_{\Lambda_c^+} = -\alpha_{\Sigma^-}$ for these CF $\Lambda_c^+$ decays, which is the expected result in the SM, $A_{\alpha CP}^\Lambda(\text{total}) = A_{\alpha CP}^\Lambda(\Lambda \rightarrow p \pi^-)$.

In this paper, we report the direct CP asymmetries and the BFs for SCS decays $\Lambda_c^+ \rightarrow \Lambda K^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 K^+$, using the CF decays $\Lambda_c^+ \rightarrow \Lambda \pi^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$ as reference modes. We also measure $\alpha$ and $A_{\alpha CP}^\Lambda$ in these four decays and search for $\Lambda$-hyperon CPV in the CF $\Lambda_c^+$ decays. Inclusion of charge conjugate states is implicit, unless otherwise stated.

## II. DETECTOR AND DATA SET

This analysis is based on the full data set recorded by the Belle detector [32] operating at the KEKB [33] asymmetric-energy $e^+e^-$ collider. This data sample corresponds to a total integrated luminosity of 980 $fb^{-1}$ collected at or near the $Y(nS)$ ($n = 1, 2, 3, 4, 5$) resonances. The Belle detector is a large-solid-angle magnetic spectrometer consisting of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) consisting of CsI(Tl) crystals. These components are all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. The iron flux-return of the magnet is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [32].

Monte Carlo (MC) simulated events are generated with EVTGEN [34] and PYTHIA [35], and are subsequently processed through a full detector simulation based on GEANT3 [36]. Final-state radiation from charged particles is included at event generation using PHOTOS [37]. Signal $\Lambda_c^+$ baryons are produced via the inclusive process $e^+e^- \rightarrow c\overline{c} \rightarrow \Lambda_c^+ + \text{anything}$ and $\Lambda_c^+ \rightarrow \Lambda h^+$, $\Sigma^0 h^+$ decays, where $\Sigma^0 \rightarrow \Lambda \gamma$ and $\Lambda \rightarrow p \pi^-$. 

## III. MEASUREMENT METHODS

The raw asymmetry in the decays of $\Lambda_c^+ \rightarrow f$ and $\Lambda_c^- \rightarrow \overline{f}$ is defined with signal yields $N$ as follows:

$$A_{\text{raw}} = \frac{N(\Lambda_c^+ \rightarrow f) - N(\Lambda_c^- \rightarrow \overline{f})}{N(\Lambda_c^+ \rightarrow f) + N(\Lambda_c^- \rightarrow \overline{f})}.$$
Several sources contribute to the raw asymmetry, which for \( \Lambda^+_c \to \Lambda K^+ \) is given by
\[
A_{\text{raw}} = A_{\text{FB}}^{\Lambda^+_c} + A_{\text{CP}}^{\Lambda^+_c \to \Lambda K^+} + A_{\text{CP}}^{\Lambda^+_c \to \pi^+ \pi^-} + A_\varepsilon^\Lambda + A_\varepsilon^{K^+},
\]
where all terms are small (< 1%): \( A_{\text{FB}}^{\Lambda^+_c} \) is the forward-backward asymmetry of \( \Lambda^+_c \) production due to \( \gamma Z^0 \) interference and higher-order QED effects in \( e^+ e^- \to \ell^+ \ell^- \) collisions [38], \( A_{\text{CP}}^{\Lambda^+_c \to \Lambda K^+} \) is the direct CP asymmetry associated with the \( \Lambda^+_c \) decay; \( A_{\text{CP}}^{\Lambda^+_c \to \pi^+ \pi^-} \) is the direct CP asymmetry associated with the \( \Lambda \) decay; \( A_\varepsilon^\Lambda \) is the detection asymmetry resulting from differences in the reconstruction efficiency between \( \Lambda \) and \( \Xi^+ \); and \( A_\varepsilon^{K^+} \) is the detection asymmetry resulting from differences in reconstruction efficiencies between \( K^+ \) and its anti-particle \( K^- \).

The reference mode \( \Lambda^+_c \to \Lambda \pi^+ \) and signal mode have nearly the same \( \Lambda \) kinematic distributions, including the \( \Lambda \) decay length, the polar angle with respect to the direction opposite the positron beam and the momentum of the proton and pion in the laboratory reference frame. Asymmetries common between the reference and signal modes therefore cancel such that \( A_{\text{raw}} = A_{\text{CP}}^{\Lambda^+_c \to \Lambda K^+} + A_\varepsilon^\Lambda \). We weight \( \Lambda^+_c \) candidates with factors \( 1 \mp A_{\text{FB}}^{\Lambda^+_c} \) to remove the \( K^+ \) or \( \pi^+ \) detection asymmetry from the raw asymmetry in \( \Lambda^+_c \to \Lambda K^+ \) and \( \Lambda^+_c \to \Lambda \pi^+ \).

Here \( A_{\text{CP}}^{\Lambda^+_c \to \Lambda K^+} \) depends on the cosine of the polar angle and transverse momentum of the \( h^+ \) tracks in the laboratory frame and was determined at Belle using \( D^0 \to K^+ \pi^+ \) and \( D^+_s \to \phi \pi^+ \) events for \( A_\varepsilon^{K^+} \) [39] and \( D^+ \to K^- \pi^+ \pi^+ \) and \( D^0 \to K^- \pi^+ \pi^0 \) events for \( A_\varepsilon^{\pi^+} \) [40].

The difference of the corrected raw asymmetries is
\[
A_{\text{corr}}^{\Lambda^+_c \to \Lambda K^+} - A_{\text{corr}}^{\Lambda^+_c \to \Lambda \pi^+} = A_{\text{dir}}^{\Lambda^+_c \to \Lambda K^+} - A_{\text{dir}}^{\Lambda^+_c \to \Lambda \pi^+}.
\]

Since CP is well conserved in CF charm decays not involving a \( K_L \) or \( K_S \) in the final-state in the SM, \( A_{\text{dir}}^{\Lambda^+_c \to \Lambda K^+} \) can be set to be zero. Thus, the measured asymmetry difference in Eq. (6) is equal to \( A_{\text{dir}}^{\Lambda^+_c \to \Lambda \pi^+} \) for \( \Lambda^+_c \to \Lambda K^+ \).

The branching fractions of signal modes are measured relative to those of the reference modes using
\[
\frac{B_{\text{sig}}}{B_{\text{ref}}} = \frac{N_{\text{sig}}/\varepsilon_{\text{sig}}}{N_{\text{ref}}/\varepsilon_{\text{ref}}}.
\]

For \( \Lambda^+_c \to \Lambda h^+ \) decays, the differential decay rate depends on \( \alpha \) parameters and one helicity angle as
\[
dN \over d \cos \theta_\Lambda \propto 1 + \alpha_{\Lambda^+_c} \cos \theta_\Lambda,
\]
where \( \alpha_{\Lambda^+_c} \) is the decay asymmetry parameter of \( \Lambda^+_c \to \Lambda h^+ \), and \( \theta_\Lambda \) is the angle between the proton momentum and the direction opposite the \( \Lambda^+_c \) momentum in the \( \Lambda \) rest frame, as illustrated in Fig. 1 (top). For \( \Lambda^+_c \to \Sigma^0 h^+ \) decays, considering \( \alpha (\Sigma^0 \to \gamma \Lambda) \) is zero due to parity conservation for an electromagnetic decay, the differential decay rate related to the \( \alpha \) parameters and helicity angles is given by
\[
dN \over d \cos \theta_{\Sigma^0}d \cos \theta_\Lambda \propto 1 - \alpha_{\Lambda^+_c} \cos \theta_{\Sigma^0} \cos \theta_\Lambda,
\]
where \( \theta_\Lambda \) (\( \theta_{\Sigma^0} \)) is the angle between the proton (\( \Lambda \)) momentum and the direction opposite the \( \Sigma^0 \) (\( \Lambda^+_c \)) momentum in the \( \Lambda \) (\( \Sigma^0 \)) rest frame, as illustrated in Fig. 1 (bottom).

\[\text{FIG. 1. Schematic plot showing the helicity angles: (top) } \theta_\Lambda \text{ and } \theta_\Lambda \text{ in } \Lambda^+_c \to \Lambda \pi^+, \Lambda \to p \pi^-; \text{ and (bottom) } \theta_{\Sigma^0} \text{ and } \theta_\Lambda \text{ in } \Lambda^+_c \to \Sigma^0 \pi^+, \Sigma^0 \to \gamma \Lambda, \Lambda \to p \pi^- \text{.} \]

\[\text{IV. EVENT SELECTION AND OPTIMIZATION} \]

We improve the invariant mass resolution by calculating the corrected mass difference wherever the final state includes a hyperon. Taking \( \Lambda^+_c \to \Lambda h^+ \) as an example, the corrected mass is \( M(\Lambda^+_c) = M_{\Lambda^+_c} - M_{\Lambda} + m_H \) where \( M_X \) is the invariant mass of reconstructed particle \( X \) and \( m_X \) represents its nominal mass [19]. The event selection criteria are optimized with a figure-of-merit (FOM), which is defined as \( S/\sqrt{S + B} \) where \( S \) and \( B \) are the expected signal and background yields in the signal region. The signal region is defined as \( |M(\Lambda^+_c) - m_{\Lambda^+_c}| < 15 \text{ MeV/c}^2 \), corresponding to 2.5 standard deviations in the \( M(\Lambda^+_c) \) resolution.
The particle identification (PID) likelihood for a given particle hypotheses, $L_i$ ($i = \pi, K, p$), is calculated from the photon yield in the ACC, energy-loss measurements in the CDC, and time-of-flight information from the TOF [41]. Charged tracks satisfying $R(K|\pi) = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.7$, are identified as kaons. All other tracks are identified as pions. The highly proton-like tracks with $R(p|K) > 0.8$ and $R(p|\pi) > 0.8$ are rejected as $h^+$ candidates for signal modes and reference modes, respectively. To suppress the background from $\Lambda^+\Sigma^0$ semileptonic decays, tracks that are highly electron-like ($\mathcal{L}_e/(\mathcal{L}_e + \mathcal{L}_{\text{non-}\ell}) > 0.95$) or muon-like ($\mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K) > 0.95$) are rejected. The electron and muon likelihoods depend primarily on the information from the ECL and KLM, respectively [42, 43].

PID requirements have a signal efficiency of about 83% for signal modes and 96% for reference modes and a background-rejection rate of 44% and 9%, respectively. We require the $h^+$ candidate to have at least two hits in the SVD to improve its impact parameter resolution with respect to the interaction point.

The $\Lambda$ candidates are reconstructed from one $p$ and one $\pi$ candidate, which a fit requires to originate from a common vertex. We require $|M_\Lambda - m_\Lambda| < 3$ MeV/c², corresponding to approximately 2.5 standard deviations of the $M_\Lambda$ resolution. Proton candidates are required to have $R(p|K) > 0.2$. To suppress the non-$\Lambda$ background, we calculate the significance of the $\Lambda$ displacement vector, relative to the production vertex, onto its momentum direction. The corresponding uncertainty $\sigma_L$ is calculated by propagating uncertainties in the vertices and the $\Lambda$ momentum, including their correlations. We require $L/\sigma_L > 4$ to suppress the non-$\Lambda$ background. The signal efficiency loss due to this requirement is 5% for all decay modes and the background rejection rate is 22% for $\Lambda^+\rightarrow\Lambda K^+$, 35% for $\Lambda^+\rightarrow\Lambda\pi^+$, 19% for $\Lambda^+\rightarrow\Sigma^0 K^+$ and 23% for $\Lambda^+\rightarrow\Sigma^0\pi^+$.

Photon candidates are identified as energy clusters in the ECL that are not associated with any charged track. The ratio of the energy deposited in the 3×3 array of crystals centered on the crystal with the highest energy to the energy deposited in the corresponding 5×5 array is required to be greater than 0.85. Candidate $\Sigma^0\rightarrow\Lambda\gamma$ decays are formed by combining the $\Lambda$ candidate with a photon candidate that has an ECL cluster energy above 0.1 GeV. The $\Sigma^0$ candidate is required to have $|M(\Sigma^0) - m_{\Sigma^0}| < 6$ MeV/c², corresponding to 1.5 standard deviations of the $M(\Sigma^0)$ resolution.

Candidate $\Lambda^+\rightarrow\Lambda h^+$ and $\Lambda^+\rightarrow\Sigma^0 h^+$ decays are reconstructed by combining $\Lambda$ or $\Sigma^0$ candidate with a $h^+$ candidate. A fit constrains the $\Lambda$ and $h^+$ candidates to originate from a common vertex and the $\chi^2$ of the fit is required to be less than 9. To suppress combinatorial backgrounds, the normalized momentum $x_p = p^*c/\sqrt{s/4 - M^2(\Lambda^c)} \cdot c^2$ is required to be greater than 0.5, where $p^*$ is the $\Lambda^c$ momentum in $e^+e^-$ center-of-mass frame and $\sqrt{s}$ is the center-of-mass energy.

After applying the optimized requirements, the $\Lambda^+$ candidate multiplicity is greater than one for 1%, 7%, and 11% of events for $\Lambda^+\rightarrow\Lambda K^+$, $\Lambda^+\rightarrow\Lambda\pi^+$, $\Sigma^0 K^+$, and $\Sigma^0\pi^+$, respectively. For modes including a $\Sigma^0$, the multiplicity is predominantly from multiple photons. We perform a best candidate selection (BCS) for events with multiple candidates by retaining candidates with the smallest sum of $\chi^2$ from the vertex fits of the $\Lambda$ and $\Lambda^+$ candidates for $\Lambda^+\rightarrow\Lambda h^+$ modes. For $\Lambda^+\rightarrow\Sigma^0 h^+$ modes, an additional term given by $(M(\Sigma^0) - m_{\Sigma^0})^2/\sigma_M^2$, where $\sigma_M = 4$ MeV/c², is the $\Sigma^0$ mass resolution, is added. The BCS has a signal efficiency of 60% for events with multiple candidates and does not introduce any peaking backgrounds.

V. DIRECT CP ASYMMETRY

The signal probability density function (PDF) uses a sum of three or four asymmetric Gaussian functions for SCS or CF modes, respectively. These Gaussian functions share a common mean parameter but have different width parameters. For modes that include a $\Sigma^0$, an additional component denoted broken-$\Sigma^0$ signal, which is the signal decay but with the $\gamma$ in $\Sigma^0\rightarrow\Lambda\gamma$ replaced by a random photon in the event, is added into the signal and its shape and ratio to the total signal is fixed according to the results of a fit to the MC sample. The signal parameters are fixed to the fitted results of truth-matched signal, but with a common shift ($\delta_\nu$) for the mean parameter and a common scaling factor ($k_\nu$) for all width parameters to account for discrepancies between the experimental data and simulated samples.

The background PDF is constructed from a sum of empirical shapes based on truth-matched background events in simulation and a second-order polynomial function for $\Lambda^+\rightarrow\Lambda K^+$ or a third-order polynomial for the other modes. For $\Lambda^+\rightarrow\Lambda K^+$, the empirical backgrounds include $\Lambda^+\rightarrow\Lambda\pi^+$ decays with the $\pi^+$ misidentified as a $K^+$, a feed-down background from $\Lambda^+\rightarrow\Sigma^0 K^+$ with a missing $\gamma$, and a wide enhancement of $\Lambda^+\rightarrow\Sigma^0\pi^+$ with a misidentified $\pi^+$ and a missing $\gamma$. For $\Lambda^+\rightarrow\Lambda\pi^+$, the empirical backgrounds include a feed-down background from $\Lambda^+\rightarrow\Sigma^0\pi^+$, and a feed-down $\Xi^-$ background from $\Xi^0\rightarrow\Xi^0\pi^+$ where $\Xi^0\rightarrow\Lambda\pi^-$ with one missing pion. For $\Lambda^+\rightarrow\Sigma^0 K^+$, the empirical backgrounds include a background from $\Lambda^+\rightarrow\Sigma^0\pi^+$ with a misidentified $\pi^+$ and a feed-down background from $\Lambda^+\rightarrow\Xi^0 K^+$ where $\Xi^0\rightarrow\Lambda\pi^0, \pi^0\rightarrow\gamma\gamma$ with one missing photon. For $\Lambda^+\rightarrow\Sigma^0\pi^+$, the empirical backgrounds include a reflection background from $\Lambda^+\rightarrow\Lambda\pi^+$ where $\Lambda$ is combined with a random $\gamma$ to form fake $\Sigma^0$ candidate. The yields
of each component and the parameters of the polynomial functions are floated to account for discrepancies between the experimental data and simulated samples.

We perform an unbinned extended maximum likelihood fit on the $M(\Lambda^+_c)$ distributions of the weighted $\Lambda^+_c$ and $\bar{\Lambda}^-_c$ samples simultaneously to measure the corrected raw asymmetry differences. In the fit, the mass resolution of $\Lambda^+_c$ and $\bar{\Lambda}^-_c$ are allowed to differ. The fit projections are shown in Fig. 2 for $\Lambda^+_c \to \Lambda h^+$ and in Fig. 3 for $\Lambda^+_c \to \Sigma^0 h^+$, along with the distribution of pull values, defined as $(N_{\text{data}} - N_{\text{fit}})/\sqrt{N_{\text{data}}}$. The fitted $A^{\text{corr}}_{\text{raw}}$ values are

$$A^{\text{corr}}_{\text{raw}}(\Lambda^+_c \to \Lambda K^+) = (+3.66 \pm 2.59)\%,$$  \hspace{1cm} (10)

$$A^{\text{corr}}_{\text{raw}}(\Lambda^+_c \to \Lambda \pi^+) = (+1.55 \pm 0.30)\%,$$  \hspace{1cm} (11)

$$A^{\text{corr}}_{\text{raw}}(\Lambda^+_c \to \Sigma^0 \pi^+) = (+8.60 \pm 5.34)\%,$$  \hspace{1cm} (12)

$$A^{\text{corr}}_{\text{raw}}(\Lambda^+_c \to \Sigma^0 h^+) = (+6.11 \pm 0.40)\%.$$  \hspace{1cm} (13)

Using Eq. (6), we measure the $CP$ asymmetries:

$$A^{\text{dir}}_{CP}(\Lambda^+_c \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%,$$  \hspace{1cm} (14)

$$A^{\text{dir}}_{CP}(\Lambda^+_c \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%.$$  \hspace{1cm} (15)

where the first uncertainties are statistical and the second are systematic, which are discussed in detail below. No evidence of charm $CP$ violation is found. This is the first direct $CP$ asymmetry measurement for SCS two-body decays of charm baryons.

VI. BRANCHING FRACTION

To measure the branching fraction, we perform a fit to the $M(\Lambda^+_c)$ distribution for the combined $\Lambda^+_c$ and $\bar{\Lambda}^-_c$ sample. The fitted signal yields are listed in Table I, along with the reconstruction efficiency ratio for the SCS modes relative to the CF modes. The efficiency is determined based on signal MC events, which are produced with a special angular distribution using our measured $\alpha$ values. An event-by-event correction (typically 0.3% and 2.8%) is applied to account for discrepancies in the $K^+$ and $\pi^+$ PID efficiencies between data and simulation. These correction factors depend on the momentum and polar angle of tracks and are determined using a sample of $D^{*+} \to [D^0 \to K^- \pi^+]\pi^+$ decays. Additional details are given in the supplementary materials.

Using the fitted yields and efficiency ratios, we calculate the branching fraction ratios according to Eq.(7) as

$$B(\Lambda^+_c \to \Lambda K^+) \over B(\Lambda^+_c \to \Lambda \pi^+) = (5.05 \pm 0.13 \pm 0.09)\%,$$  \hspace{1cm} (16)

$$B(\Lambda^+_c \to \Sigma^0 K^+) \over B(\Lambda^+_c \to \Sigma^0 \pi^+) = (2.78 \pm 0.15 \pm 0.05)\%.$$  \hspace{1cm} (17)

where the first uncertainties are statistical and the second are systematic. Systematic uncertainties are described in detail in Sec. IX. Multiplying the branching fraction results by the world average values for the branching fraction of the appropriate reference mode, $B(\Lambda^+_c \to \Lambda \pi^+) = (1.30 \pm 0.07)\%$ and $B(\Lambda^+_c \to \Sigma^0 \pi^+) = (1.29 \pm 0.07)\%$ [19], we measure the absolute branching fraction for the SCS decays,

$$B(\Lambda^+_c \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35 \times 10^{-4},$$  \hspace{1cm} (18)

$$B(\Lambda^+_c \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19 \times 10^{-4},$$  \hspace{1cm} (19)

where the first uncertainties are statistical, the second are systematic, and the third are from the uncertainties on the branching fractions for the reference modes [19]. These results are consistent with current world average values [19], but with significantly improved precision.

VII. DECAY ASYMMETRY PARAMETER $\alpha$

To extract the $\alpha$ parameter, the $\cos \theta_A$ distributions of $\Lambda^+_c \to \Lambda h^+$ modes are divided into 10 bins of uniform width. The $\cos \theta_{\Sigma^0}$ versus $\cos \theta_A$ distributions for $\Lambda^+_c \to \Sigma^0 h^+$ modes are similarly divided into $5 \times 5$ bins for $\Lambda^+_c \to \Sigma^0 K^+$ and $6 \times 6$ bins for $\Lambda^+_c \to \Sigma^0 \pi^+$, since the latter mode has much greater statistics. To extract the per-bin yield, we fit the $M(\Lambda^+_c)$ distribution with signal parameters and background polynomial parameters fixed according to the fit to the full sample integrated over helicity angles. In the $\Lambda^+_c \to \Sigma^0 h^+$ modes, the ratio of broken-$\Sigma^0$ signal to total signal depending on the $\cos \theta_{\Sigma^0}$ bin is fixed to the truth-matched results in simulation. In the $\Lambda^+_c \to \Sigma^0 \pi^+$ mode, the shape of the reflection background $\Lambda^+_c \to \Lambda \pi^+$ is found to depend on the $\cos \theta_{\Sigma^0}$ bins and its shape in each bin is fixed to the results from a fit to simulation.

The fitted signal yields are corrected bin-by-bin with the signal efficiencies, which are determined based on signal MC events produced with our measured angular distribution. These distributions are fitted according to Eqs.(8, 9) and the fit results are shown in Fig. 4 for $\Lambda^+_c \to \Lambda h^+$ and Fig. 5 for $\Lambda^+_c \to \Sigma^0 h^+$. The fitted slope

| Channel | $N_{\text{sig}}$ | $\varepsilon_{\text{sig}}/\varepsilon_{\text{ref}}$ | $B_{\text{ref}}$/B_{\text{raw}} (%) | W.A. (%) |
|--------|-----------------|-----------------|----------------|--------|
| $\Lambda^+_c \to \Lambda K^+$ | 11175 ± 296 | 0.836 | 5.05 ± 0.13 ± 0.09 | 4.7 ± 0.9 |
| $\Lambda^+_c \to \Lambda \pi^+$ | 26470 ± 787 | 0.805 | 2.78 ± 0.15 ± 0.05 | 4.0 ± 0.6 |
| $\Lambda^+_c \to \Sigma^0 K^+$ | 2335 ± 132 | 0.835 | 2.78 ± 0.15 ± 0.05 | 4.0 ± 0.6 |
| $\Lambda^+_c \to \Sigma^0 \pi^+$ | 105018 ± 475 | 0.835 | 2.78 ± 0.15 ± 0.05 | 4.0 ± 0.6 |

TABLE I. The fitted yield ($N_{\text{sig}}$), efficiency ($\varepsilon$) ratio, and ratio of branching fractions ($B$) for signal modes ($\Lambda^+_c \to \Lambda K^+, \Sigma^0 K^+$) relative to reference modes ($\Lambda^+_c \to \Lambda \pi^+, \Sigma^0 \pi^+$), compared with the world average values (W.A.) [19].
factors \( \alpha_{\Lambda^+} \alpha_- \) are

\[
\alpha_{\text{avg}}(\Lambda_+^+ \to \Lambda K^+) \cdot \alpha_{\text{avg}} = -0.441 \pm 0.037, \quad (20)
\]

\[
\alpha_{\text{avg}}(\Lambda_c^+ \to \Lambda \pi^+) \cdot \alpha_{\text{avg}} = -0.570 \pm 0.004, \quad (21)
\]

\[
\alpha_{\text{avg}}(\Lambda_c^+ \to \Sigma^0 K^+) \cdot \alpha_{\text{avg}} = -0.41 \pm 0.14, \quad (22)
\]

\[
\alpha_{\text{avg}}(\Lambda_c^+ \to \Sigma^0 \pi^+) \cdot \alpha_{\text{avg}} = -0.354 \pm 0.012, \quad (23)
\]

where only statistical uncertainties are given. The subscript (superscript) ‘avg’ denotes the averaged \( \alpha \) value for the combined \( \Lambda_+^+ \) (\( \Lambda \)) and \( \Lambda_c^- \) (\( \overline{\Lambda} \)) decays. Dividing these results by the most precise \( \alpha_{\text{avg}} = 0.754 \pm 0.0022 \) from BESIII [30] gives the final decay asymmetry parameters \( \alpha_{\text{avg}} \) for the combined \( \Lambda_+^+ \) and \( \Lambda_c^- \) sample,

\[
\alpha_{\text{avg}}(\Lambda_+^+ \to \Lambda K^+) = -0.585 \pm 0.049 \pm 0.018, \quad (24)
\]

\[
\alpha_{\text{avg}}(\Lambda_+^+ \to \Lambda \pi^+) = -0.755 \pm 0.005 \pm 0.003, \quad (25)
\]

\[
\alpha_{\text{avg}}(\Lambda_+^+ \to \Sigma^0 K^+) = -0.55 \pm 0.18 \pm 0.09, \quad (26)
\]

\[
\alpha_{\text{avg}}(\Lambda_+^+ \to \Sigma^0 \pi^+) = -0.463 \pm 0.016 \pm 0.008, \quad (27)
\]

where the first uncertainties are statistical and the second are systematic, which are described in detail in Sec. IX.

The measured values of \( \alpha \) for the \( \Lambda_+^+ \to \Lambda K^+ \) and \( \Lambda_+^+ \to \Sigma^0 K^+ \) modes are the first \( \alpha \) results for SCS decays of charm baryons. The measured values of \( \alpha \) for the \( \Lambda_+^+ \to \Lambda \pi^+ \) and \( \Lambda_+^+ \to \Sigma^0 \pi^+ \) modes are consistent with the current world average values [19], but with significantly improved precision.

**VIII. \( \alpha \)-INDUCED \( CP \) ASYMMETRY**

We separate the \( \Lambda_c^+ \) and \( \overline{\Lambda}_c^- \) samples and measure \( \alpha_{\Lambda_c^+} \) and \( \alpha_{\overline{\Lambda}_c^-} \) with the same method described above. The signal shape parameters for individual bins of helicity angles are fixed to the fitted results in the full sample integrated over helicity angles for \( \Lambda_c^+ \) and \( \overline{\Lambda}_c^- \) separately. The helicity angle distributions for the \( \Lambda_c^+ \) and \( \overline{\Lambda}_c^- \) samples are fitted separately, and the fitted slope factors, \( \alpha_{\Lambda_c^+} \alpha_- \) and \( \alpha_{\overline{\Lambda}_c^-} \alpha_+ \), are listed in Table II. Additional details are given in the supplementary materials.

Using the precise results \( \alpha_-(\Lambda \to p\pi^-) = 0.7519 \pm 0.0041 \) and \( \alpha_+(\overline{\Lambda} \to \overline{p}\pi^+) = -0.7559 \pm 0.0046 \) measured...
by BESIII [30], we measure four \( \alpha \)-induced \( CP \) asymmetries as listed in Table II, where \( A_{\text{CP}}^{\alpha} \) for \( \Lambda_c^+ \to \Lambda K^+ \), \( \Lambda_c^+ \to \Sigma^0 K^+ \), and \( \Lambda_c^+ \to \Sigma^0 \pi^+ \) are measured for the first time. The measured \( A_{\text{CP}}^{\alpha} \) for \( \Lambda_c^+ \to \Lambda \pi^+ \) is consistent with previous results, but with much better precision.

We search for hyperon CPV in \( \Lambda \to p\pi^- \) according to Eq.(3). Using the fitted slopes \( \alpha_{\Lambda^+} \alpha_{\Lambda^-} \) and \( \alpha_{\Lambda_c^+} \alpha_{\Lambda_c^-} \) from Fig. 4 for \( \Lambda_c^+ \to \Lambda \pi^+ \) and from Fig. 5 for \( \Lambda_c^+ \to \Sigma^0 \pi^+ \), the \( \alpha \)-induced \( CP \) asymmetry of \( \Lambda \to p\pi^- \) is measured to be \( +0.0169 \pm 0.0073 \pm 0.0120 \) in \( \Lambda_c^+ \to \Lambda \pi^+ \) and \( -0.026 \pm 0.034 \pm 0.030 \) in \( \Lambda_c^+ \to \Sigma^0 \pi^+ \). Finally, their average value is calculated to be

\[
A_{\text{CP}}^{\alpha}(\Lambda \to p\pi^-) = +0.013 \pm 0.007 \pm 0.011. \tag{28}
\]

This is the first measurement of hyperon CPV searches in CF charm decays. No evidence of \( \Lambda \)-hyperon CPV is found.

**IX. SYSTEMATIC UNCERTAINTIES**

Most of the systematic uncertainties for the direct \( CP \) asymmetry cancel since they affect both \( \Lambda_c^+ \) and \( \Lambda_c^- \) decays. The remaining sources of systematic uncertainty are listed in Table III. The uncertainty due to each charged track asymmetry map is evaluated by varying the asymmetry value bin-by-bin by its uncertainty (\( \pm 1\sigma \))
TABLE II. The fitted slopes $\alpha_{\Lambda_c^+}$ and $\alpha_{\Xi_c^-}$ for individual $\Lambda_c^+$ and $\Xi_c^-$ samples using the most precise $\alpha$ from EShI recently [30], and the corresponding $\alpha$-induced CP asymmetry $A_{CP}^\alpha$, comparing with current world averages (W.A.) [19].

| Channel          | $\alpha_{\Lambda_c^+}$ | $\alpha_{\Lambda_c^-}$ | $\alpha_{\Xi_c^+}$ | $\alpha_{\Xi_c^-}$ | $A_{CP}^\alpha$ | W.A. $A_{CP}^\alpha$ |
|------------------|-------------------------|-------------------------|---------------------|---------------------|------------------|---------------------|
| $\Lambda_c^+ \to \Lambda K^+$ | $-0.418 \pm 0.053$ | $-0.442 \pm 0.053$ | $-0.566 \pm 0.071$ | $0.028$ | $0.592 \pm 0.070 \pm 0.079$ | $-0.023 \pm 0.086 \pm 0.071$ |
| $\Lambda_c^+ \to \Sigma^0 K^+$ | $-0.582 \pm 0.006$ | $-0.565 \pm 0.006$ | $-0.784 \pm 0.008$ | $0.006$ | $0.754 \pm 0.008 \pm 0.018$ | $+0.020 \pm 0.007 \pm 0.013 \mp 0.07 \pm 0.22$ |
| $\Lambda_c^+ \to \Sigma^0 \pi^+$ | $-0.43 \pm 0.18$ | $-0.37 \pm 0.21$ | $-0.58 \pm 0.24 \pm 0.09$ | $0.49 \pm 0.28 \pm 0.14$ | $+0.08 \pm 0.35 \pm 0.14$ | $-0.023 \pm 0.034 \pm 0.030$ |

and the nominal value is taken as a systematic uncertainty. The total systematic uncertainty is determined from the sum of all contributions in quadrature to be $+1.2 \times 10^{-3}$ for $A_{CP}^\alpha(\Lambda_c^+ \to \Lambda K^+)$ and $+3.0 \times 10^{-3}$ for $A_{CP}^\alpha(\Lambda_c^+ \to \Sigma^0 K^+)$. And considering the statistical uncertainties of $A_{CP}^\alpha$ results are larger than 1%, we assign 0.1% and 0.4% as the final systematic uncertainties of $A_{CP}^\alpha(\Lambda_c^+ \to \Lambda K^+)$ and $A_{CP}^\alpha(\Lambda_c^+ \to \Sigma^0 K^+)$, respectively.

TABLE III. The absolute systematic uncertainties (in units of $10^{-3}$) for CP asymmetry $A_{CP}^\alpha$.

| Sources                  | $A_{CP}^\alpha(\Lambda_c^+ \to \Lambda K^+)$ | $A_{CP}^\alpha(\Lambda_c^+ \to \Sigma^0 K^+)$ |
|--------------------------|---------------------------------------------|---------------------------------------------|
| $A_{CP}^\alpha$ map       | $+0.8$                                      | $+0.4$                                      |
| $A_{CP}^\alpha$ map       | $+0.4$                                      | $+0.5$                                      |
| Signal shape              | $+0.5$                                      | $+1.4$                                      |
| Background shape          | $-0.2$                                      | $-3.1$                                      |
| Fit bias                  | $+0.6$                                      | $+2.6$                                      |
| Total                     | $+1.2$                                      | $+4.0$                                      |

For the branching fraction ratio measurement, most systematic uncertainties cancel since they affect both the signal and reference modes. The remaining systematic uncertainties are listed in Table IV. Using the $D^+ \to [D^0 \to K^- \pi^+]\pi^+$ control sample, the PID uncertainties are estimated to be 0.9% for $\Lambda_c^+ \to \Lambda K^+$, 0.8% for $\Lambda_c^+ \to \Lambda \pi^+$, 0.9% for $\Lambda_c^+ \to \Sigma^0 K^+$, and 0.8% for $\Lambda_c^+ \to \Sigma^0 \pi^+$. Since the kaon and pion PID efficiency use the same control sample, we assign 1.7% as the systematic uncertainty for both branching fraction ratios. The systematic uncertainties associated with the fixed parameters in the signal-yield fit is determined according to the same method as for $A_{CP}^\alpha$ to be 0.2% and 0.4% for the $\Lambda$- and $\Sigma^0$-involved modes, respectively. In modes that include a $\Sigma^0$, the broken-$\Sigma^0$ signal has a fixed ratio to signal based on MC simulation. The $M(\Lambda_c^\pm)$ distributions of the MC sample and experimental data in $M(\Sigma^0)$ sideband region have nearly same shapes, which suggests that the MC simulation is reliable for this broken-$\Sigma^0$ signal. We vary its ratio in the $M(\Lambda_c^\pm)$ fit by $\pm 10\%$ and the larger deviation, 0.1%, is assigned as a conservative estimate. We consider the effects of the $\Xi_c$ background shape in the two CF modes by parameterizing it separately from the other backgrounds. The difference in the fitted signal yield is 0.3% for $\Lambda_c^+ \to \Lambda \pi^+$ and 0.1% for...
\(\Lambda^+ \rightarrow \Sigma^0\pi^+\). Since the multiplicity of events for modes that include a \(\Lambda\) is small, we remove events with multiple candidates and repeat the measurement. For modes that include a \(\Sigma^0\), an alternative BCS method is applied to select the candidate with highest momentum \(\gamma\) from the \(\Sigma^0\) decay. The resulting changes in the branching fraction measurement are assigned as systematic uncertainties. The \(\alpha\) value used in signal MC production is varied by its uncertainty and the resulting change in the efficiency is assigned as a systematic uncertainty. A systematic uncertainty due to limited MC statistics is also considered. The total systematic uncertainty is determined by adding the uncertainties from all sources in quadrature, as given in Table IV.

### Table IV. Relative systematic uncertainties (in units of \%) for branching fractions.

| Sources                     | \(B(\Lambda_c^+ \rightarrow \Lambda\pi^+)\) | \(B(\Lambda_c^+ \rightarrow \Sigma^0K^+)\) | \(B(\Lambda_c^+ \rightarrow \Sigma^0\pi^+)\) |
|-----------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| PID efficiency correction   | 1.7                                      | 1.7                                      | 1.7                                      |
| Signal shape                | 0.2                                      | 0.4                                      | 0.4                                      |
| Background shape            | 0.3                                      | 0.1                                      | 0.1                                      |
| BCS effect                  | 0.1                                      | 0.4                                      | 0.4                                      |
| Efficiency ratio            | 0.2                                      | 0.4                                      | 0.4                                      |
| Total                       | 1.7                                      | 1.8                                      | 1.8                                      |

For the \(\alpha\) and \(A_{CP}^\alpha\) measurements, we consider the systematic uncertainty due to the number of helicity angle bins, the efficiency curve, the fit bias, and the quoted uncertainty on \(\alpha_\pi\). We change the number of helicity angle bins from 10 to 8 or 12 for \(\Lambda_c^+ \rightarrow \Lambda h^+\), from 5×5 to 4×4 or 6×6 for \(\Lambda_c^+ \rightarrow \Sigma^0K^+\), and from 6×6 to 5×5 or 7×7 for \(\Lambda_c^+ \rightarrow \Sigma^0\pi^+\). The \(\alpha\) value used in signal MC production is varied by its uncertainty. The resulting changes in \(\alpha\) or \(A_{CP}^\alpha\) are assigned as systematic uncertainties. We consider the possible fit bias for \(\alpha\) and \(A_{CP}^\alpha\) with a linearity test, in which we replace the signal events in the MC sample with events produced with a special angular distribution using five \(\alpha\) values. A linear fit is applied to the measured \(\alpha\) distribution versus the generated values. The fitted slopes consistent with one indicate no fit bias. The relative shift between the fitted linear function and the nominal value is taken as a systematic uncertainty. The quoted uncertainties of \(\alpha_{\text{avg}}\) and \(\alpha_\pi\) of \(\Lambda \rightarrow p\pi^-\) are assigned as systematic uncertainties. The total systematic uncertainties for \(\alpha_{\text{avg}}/ \alpha_{\pi^+}/ A_{CP}^\alpha/A_{CP}^\alpha(\Lambda)\) are taken as the sum in quadrature of all contributions, as listed in Table V.

x. Summary

In conclusion, based on the 980 fb\(^{-1}\) data set collected with the Belle detector, we make the first measurement of the direct \(CP\) asymmetry in \(\Lambda\) decays of charm baryons, \(A_{CP}^\alpha(\Lambda^+ \rightarrow \Lambda K^+) = +0.021 \pm 0.026 \pm 0.001\) and \(A_{CP}^\alpha(\Lambda_c^+ \rightarrow \Sigma^0K^+) = +0.025 \pm 0.054 \pm 0.004\). The relative branching fractions are measured to be, \(B(\Lambda^+ \rightarrow \Lambda K^+)/B(\Lambda^+ \rightarrow \Lambda\pi^+) = (5.05 \pm 0.13 \pm 0.09)\%\) and \(B(\Lambda_c^+ \rightarrow \Sigma^0K^+)/B(\Lambda_c^+ \rightarrow \Sigma^0\pi^+) = (2.78 \pm 0.15 \pm 0.05)\%\), which supersede previous Belle measurements [20]. Using the world average values for the branching fractions for \(\Lambda_c^+ \rightarrow \Lambda\pi^+\) and \(\Lambda_c^+ \rightarrow \Sigma^0\pi^+\), we measure \(B(\Lambda_c^+ \rightarrow \Lambda K^+) = [6.57 \pm 0.17 \pm 0.11 \pm 0.35] \times 10^{-4}\) and \(B(\Lambda_c^+ \rightarrow \Sigma^0K^+) = [3.58 \pm 0.19 \pm 0.06 \pm 0.19] \times 10^{-4}\). These results are the most precise to date and significantly improve the precision of the world average values [19].

We measure the averaged decay asymmetry parameters \(\alpha(\Lambda_c^+ \rightarrow \Lambda K^+) = -0.585 \pm 0.049 \pm 0.018\) and \(\alpha(\Lambda_c^+ \rightarrow \Sigma^0K^+) = -0.55 \pm 0.18 \pm 0.09\) for the first time. We measure \(\alpha(\Lambda_c^+ \rightarrow \Lambda\pi^+) = -0.755 \pm 0.005 \pm 0.003\) and \(\alpha(\Lambda_c^+ \rightarrow \Sigma^0\pi^+) = -0.463 \pm 0.016 \pm 0.008\), which are consistent with previous measurements [19] but with improved precision. We also determine the \(\alpha\)-parameter for \(\Lambda_c^+\) and \(\Xi_c^+\) individually and search for \(CP\) violation via the \(\alpha\)-induced \(CP\) asymmetry in \(\Lambda_c^+ \rightarrow \Lambda\pi^+\) and \(\Lambda_c^+ \rightarrow \Sigma^0\pi^+\) decays, and determine \(A_{CP}^\alpha(\Lambda \rightarrow p\pi^-) = +0.013 \pm 0.007 \pm 0.011\) by combining the two modes. No evidence of \(p\pi^-\) \(CP\) violation is found. The method used in our \(A_{CP}^\alpha(\Lambda \rightarrow p\pi^-)\) measurement can be applied to other hyperons, such as \(A_{CP}^\alpha(\Xi^0_{b0} \rightarrow \Lambda\pi^0)\) in \(\Lambda_c^+ \rightarrow \Xi^0K^+\) and \(\Xi_c^{+0}_{b0} \rightarrow \Xi^0\pi^+\). Our measurement is a milestone for hyperon \(CP\) violation in charm CF decays and this method is promising for precise measurements of hyperon \(CP\) violation at Belle II and LHCb.

CONFIDENT OF INTEREST

The authors declare that they have no conflict of interest.

ACKNOWLEDGMENTS

L. K. Li and W. Shan warmly thank Prof. Fu-Sheng Yu, Dr. Di Wang, Prof. Chao-Qiang Geng, Dr. Chia-Wei Liu, and Dr. Xian-Wei Kang for valuable and helpful discussions. We thank the KEKB group for the excellent operation of the accelerator, and the KEK cryogenics group for the efficient operation of the solenoid.
Total 1.8/2.8/7.9/7.1 0.3/0.6/1.8/1.3/1.20 8.6/9.0/14.4/14.4 0.8/2.3/3.5/3.0/3.0

APPENDIX A. SUPPLEMENTARY MATERIALS

Supplementary materials to this article can be found online at xxxxx (to be added by the publisher).

1. A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967).
2. A. D. Sakharov, Sov. Phys. Usp. 34, 417 (1991).
3. M. E. Shaposhnikov, Nucl. Phys. B 287, 757 (1987).
4. J. Brod, A. L. Kagan, and J. Zupan, Phys. Rev. D 86, 014023 (2012).
5. H.-Y. Cheng and C.-W. Chiang, Phys. Rev. D 85, 034036 (2012).
6. H.-n. Li, C.-D. Lu, and F.-S. Yu, Phys. Rev. D 86, 036012 (2012).
7. Y. Grossman, A. L. Kagan, and Y. Nir, Phys. Rev. D 75, 036008 (2007).
8. Y. Grossman, A. L. Kagan, and J. Zupan, Phys. Rev. D 85, 114036 (2012).
9. R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 122, 211803 (2019).
10. R. Aaij et al. (LHCb Collaboration), J. High Energ. Phys. 2018, 182 (2018).
11. R. Aaij et al. (LHCb Collaboration), Eur. Phys. J. C 80, 986 (2020).
12. T. Uppal, R. C. Verma, and M. P. Khanna, Phys. Rev. D 49, 3417 (1994).
13. H.-Y. Cheng, X.-W. Kang, and F. Xu, Phys. Rev. D 97, 074028 (2018).
14. J. Zou, F. Xu, G. Meng, and H.-Y. Cheng, Phys. Rev. D 101, 014011 (2020).
15. C. Q. Geng, Y. K. Hsiao, Y.-H. Lin, and L.-L. Liu, Phys. Lett. B 776, 265 (2018).
16. C. Q. Geng, C.-W. Liu, and T.-H. Tsai, Phys. Lett. B 794, 19 (2019).
17. R. Konik and N. Isgur, Phys. Rev. D 21, 1868 (1980).
18. H.-Y. Cheng, Chin. J. Phys. 78, 324 (2022).
19. R. L. Workman et al. (Particle Data Group), Prog. Theo. Exp. Phys. 2022, 083C01 (2022).
20. K. Abe et al. (Belle Collaboration), Phys. Lett. B 524, 33 (2002).
21. B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 75, 052002 (2007).
22. T. D. Lee and C.-N. Yang, Phys. Rev. 108, 1645 (1957).
23. J. M. Link et al. (FOCUS Collaboration), Phys. Lett. B 634, 165 (2006).
24. J. F. Donoghue and S. Pakvasa, Phys. Rev. Lett. 55, 162 (1985).
25. J. F. Donoghue, X.-G. He, and S. Pakvasa, Phys. Rev. D 34, 833 (1986).
26. D. Chang, X.-G. He, and S. Pakvasa, Phys. Rev. Lett. 74, 3927 (1995).
27. X.-G. He, H. Murayama, S. Pakvasa, and G. Valencia, Phys. Rev. D 61, 071701 (2000).
28. C.-H. Chen, Phys. Lett. B 521, 315 (2001).
29. J. Tandeau, Phys. Rev. D 69, 076008 (2004).
30. M. Ablikim et al. (BESIII Collaboration), arXiv:2204.11058 [hep-ex].
31. J.-P. Wang and F.-S. Yu, arXiv:2208.01589 [hep-ph].
32. A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Meth. A 1018, 021601 (2012).
33. B. Aubert et al. (BaBar Collaboration), Nucl. Instrum. Meth. A 524, 33 (2002).