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Measurement of the absolute branching fraction of $\Lambda_c^+ \to p K_S^0 \eta$ decays

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ABSTRACT

Based on 586 pb^{-1} of e^+e^- annihilation data collected at a center-of-mass energy of $\sqrt{s} = 4.6$ GeV with the BESIII detector at the BEPCII collider, the absolute branching fraction of $\Lambda_c^+ \to pK_S^0\eta$ decays is measured for the first time to be $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (0.414 \pm 0.084 \pm 0.028)\%$, where the first uncertainty

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is statistical and the second is systematic. The result is compatible with a previous CLEO result on the relative branching fraction $\frac{\mathcal{B}(\Lambda_c^+\to pK_S^0\eta)}{\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)}$, and consistent with theoretical predictions of SU(3) flavor symmetry.

1. Introduction

The lightest charmed baryon, Λ_c^+, was first observed in the 1970s [1,2], but only in the past few years has there been significant progress in precision measurements of its absolute decay rates [3,4]. Driven by these improvements, the theoretical calculations of charmed baryon decays have greatly improved their treatment of non-perturbative effects [5–8]. However, more experimental and theoretical efforts are needed to further improve the understanding of non-factorizable effects, which are non-trivial in the charmed baryon sector [7,9]. More experimental data are also desired to test existing theoretical predictions [10].

The hadronic decay $\Lambda_c^+ \to pK_S^0\eta$ offers important information about the dynamics of charmed baryon decays [11]. The charge-conjugate mode is always implied throughout this Letter. The branching fraction (BF) $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = \mathcal{B}(\Lambda_c^+ \to p\overline{K}^0\eta)/2 = (0.79\pm0.13\ \text{(stat.)}\pm0.13\ \text{(sys.)})\%$ has only been measured relative to $\Lambda_c^+ \to pK^-\pi^+$ [12,13]. However, recent comprehensive theoretical analyses of different BFs for Λ_c^+ decays to three-body final states, which assume SU(3) flavor symmetry, predict that $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta)$ is in the range 0.35% to 0.45% [11,14]. There is a discrepancy of approximately 2 standard deviations between the existing experimental result and those new theoretical calculations. Further, $\Lambda_c^+ \to pK_S^0\eta$ is regarded as an important channel to understand the properties of the intermediate $N(1535)$ resonance [15,16]. The $N(1535)$ resonance is puzzling because it decays to final states that contain strange hadrons, like ηN and $K\Lambda$ [13,15,16], but it does not contain any $\bar{s}s$ component according to the naive constituent quark model. Thus, further measurements of the $\Lambda_c^+ \to pK_S^0\eta$ decays may help to verify SU(3) flavor symmetry and may reveal the intermediate states contributing to these decays.

In this Letter, we present the first absolute measurement of the BF for $\Lambda_c^+ \to pK_S^0\eta$ decays based on an e^+e^- collision data sample corresponding to an integrated luminosity of 586 pb^{-1}, collected at the center-of-mass energy of $\sqrt{s} = 4.6$ GeV with the BESIII detector [17] at the Beijing Electron Positron Collider (BEPCII) [18]. At this energy, the Λ_c^+ baryon is always produced along with a $\bar{\Lambda}_c^-$, and the energy remaining does not allow the production of any additional hadrons. Besides, the previous analysis [19], based on the double tag method and the simultaneous fit along the 12 Λ_c^+ decay channels, has reported the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs in the same data sample, which gives a chance to measure the absolute BF of the other Λ_c^+ decay channels. In this analysis, we use the single tag (ST) method in which the $\Lambda_c^+ \to pK_S^0\eta$ is reconstructed while the $\bar{\Lambda}_c^-$ is not.

2. BESIII detector and Monte Carlo simulation

The BESIII detector is a magnetic spectrometer [17] located at BEPCII [18]. The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive-plate-counter muon-identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% of the 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps.

Samples of simulated events produced with the GEANT4-based [20] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and estimate the backgrounds. The simulation includes the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations modeled with the generator KKMC [21]. Two types of MC samples are generated in this analysis. The signal MC samples, in which the Λ_c^+ decays non-resonantly to $\Lambda_c^+ \to pK_S^0\eta$ while the $\bar{\Lambda}_c^-$ decays into all possible channels, are used to determine the detection efficiency. The inclusive MC sample, which consists of the production of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs and open-charm mesons, the ISR production of vector charmonium(-like) states, and the continuum processes incorporated in KKMC [21], is used to estimate the backgrounds. Known decay modes are modeled with EVTGEN [22] using BFs taken from the PDG [13], and the remaining unknown decays from the charmonium states are modeled with LUNDCHARM [23]. The final-state radiation from charged final-state particles is incorporated using the PHOTOS package [24].

3. Event selection

In this analysis, all the charged tracks are required to satisfy $|\cos\theta| < 0.93$, where θ is the polar angle of the charged track with respect to the axis of the MDC. For the proton, the distance of closest approach to the interaction point (IP) must be within ±10 cm along the MDC axis (V_z) and within ±1 cm in the plane perpendicular to the MDC axis (V_r). The particle identification (PID) algorithm combines the dE/dx information from the MDC and flight time from the TOF to evaluate the likelihood $\mathcal{L}(h)(h = \pi, K, p)$ for the different final state hadron hypotheses; to be classified as a proton we require the charged track satisfies both $\mathcal{L}(p) > \mathcal{L}(\pi)$ and $\mathcal{L}(p) > \mathcal{L}(K)$.

We reconstruct $K_S^0 \to \pi^+\pi^-$ candidates by combining two oppositely charged tracks. For these tracks, the distance of closest approach to the IP must be within ±20 cm along the MDC axis. No requirement on either V_r or the PID likelihood is applied to maximize the efficiency. The two tracks are constrained to a common decay vertex by applying a vertex fit [3], and the corresponding χ^2 is required to be less than 100. The momenta of the $\pi^+\pi^-$ pairs corrected by the vertex fit are used in the following analysis. Further, the distance of the decay vertex of the K_S^0 from the IP is required to be larger than twice the estimated resolution. The invariant mass of the $\pi^+\pi^-$ pairs, $M_{\pi^+\pi^-}$, is required to lie in the mass region (0.487, 0.511) GeV/c^2.

The η candidates are formed by photon pairs with their invariant mass satisfying the requirement 0.500 GeV/c^2 $< \mathrm{M}_{\gamma\gamma} <$ 0.565 GeV/c^2. Here, the γ candidates are reconstructed from clusters in the EMC crystals that are not matched with any charged tracks.

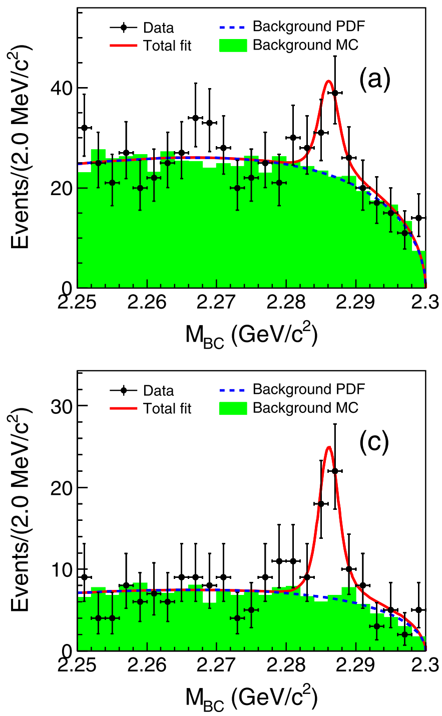

Fig. 1. One-dimensional projection plots of (a) M_{BC} and (b) ΔE distributions, as well as background reduced projection plots of (c) M_{BC} ($|\Delta E| < 0.02$ GeV) and (d) ΔE (2.28 GeV/$c^2 < \mathrm{M_{BC}} < 2.295$ GeV/c^2) with the fit results. Points with error bars are data, the solid red line is the total fit result, the blue-dashed line is the background contribution, and the green histogram is the background distribution from the inclusive MC sample.

The energy deposited in the nearby TOF counters is included in the photon reconstruction. The deposited energy of any cluster is required to be larger than 25 MeV in the barrel region ($|\cos\theta| < 0.8$) or 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$). The measured EMC time of the cluster, which is defined as the shower time recorded by the EMC relative to the event start time, is required to be within $(0, 700)$ ns to suppress electronic noise and energy deposits unrelated to the event. A kinematic fit is applied to constrain $M_{\gamma\gamma}$ to the nominal mass of the η meson [13]. The momenta of the $\gamma\gamma$ pairs corrected by the kinematic fit are used for further analysis.

The Λ_c^+ candidates are formed by all combinations of proton, K_S^0 and η candidates in an event. Two kinematic variables, the energy difference $\Delta E \equiv E_{\Lambda_c^+} - E_{\mathrm{beam}}$ and the beam-constrained mass $M_{\mathrm{BC}} \equiv \sqrt{E_{\mathrm{beam}}^2/c^4 - |\vec{p}_{\Lambda_c^+}|^2/c^2}$, are defined to identify Λ_c^+ candidates. Here, $E_{\Lambda_c^+}$ and $\vec{p}_{\Lambda_c^+}$ are the reconstructed energy and momentum of the Λ_c^+ candidates calculated in the e^+e^- rest frame, and E_{beam} is the average energy of the e^+ and e^- beams. All the candidates are required to satisfy -0.07 GeV $< \Delta\mathrm{E} < 0.07$ GeV and 2.25 GeV/$c^2 < \mathrm{M_{BC}} < 2.3$ GeV/c^2. If more than one candidate in an event satisfies all the above requirements, the best candidate is selected with the following sequence. First, we select candidates that contain the proton with the largest $\mathcal{L}(p)$. Second, if there are still multiple candidates, we select those that contain the K_S^0 with the largest decay length in units of its resolution. Finally, if there are still multiple candidates after the proton and K_S^0 requirements, we select the candidate that contains the η with the smallest χ^2 returned by the kinematic fit. About 16.9% of total events in data have multiple candidates, and the probability to select the correct candidate is 63.1% based on a MC study.

4. Signal yield and BF

To determine the signal yield of $\Lambda_c^+ \to pK_S^0\eta$, an extended unbinned maximum likelihood fit is performed on the two-dimensional distribution of M_{BC} versus ΔE. Based on the K_S^0 sideband (0.02 GeV/$c^2 < |\mathrm{m}(\pi^+\pi^-) - \mathrm{m}(\mathrm{K_S^0})| < 0.03$ GeV/c^2) from data, and inclusive MC studies, no peaking background is found in either the M_{BC} or ΔE signal region. In the fit, the M_{BC} and ΔE background shapes are modeled by an ARGUS function [25] and a second-order Chebyshev polynomial function, respectively. The end point of the ARGUS function is fixed to the beam energy $E_{\mathrm{beam}} = 2.3$ GeV, while all the other parameters in the background function are free. The M_{BC} and ΔE background shapes are treated as uncorrelated based on MC validation. The signal shape is the MC-derived two-dimensional shape convolved with Gaussian functions in each dimension, where the Gaussian functions compensate for the resolution difference between data and MC samples. The parameters of the Gaussian functions for ΔE and M_{BC} are fixed to the values determined from the corresponding one-dimensional fits in data.

Fig. 1 shows the one-dimensional projection plots of the fit results. The signal yield is obtained to be $N_{\mathrm{sig}} = 42.0 \pm 8.5$, where the uncertainty is statistical only. The statistical significance for the signal is 7.3σ, which is evaluated by the change of the likelihood between the nominal fit and the fit without the signal component [3,26]. And the significance including the systematic uncertainties is evaluated to be 5.3σ [27]. The detection efficiency, which is estimated by using the signal MC sample, is $\varepsilon = (17.57 \pm 0.01)\%$. Thus, the absolute BF of $\Lambda_c^+ \to pK_S^0\eta$ can be obtained by

$$\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = \frac{N_{\mathrm{sig}}}{2 \times N_{\Lambda_c^+\bar{\Lambda}_c^-} \times \mathcal{B}_{\mathrm{inter}} \times \varepsilon}\quad , \tag{1}$$

where $\mathcal{B}_{\mathrm{inter}} = \mathcal{B}(K_S^0 \to \pi^+\pi^-) \times \mathcal{B}(\eta \to \gamma\gamma)$ is the product of the BFs of the intermediate states taken from the PDG [13], $N_{\Lambda_c^+\bar{\Lambda}_c^-} = (105.9 \pm 5.3) \times 10^3$ is the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs in data [19], and the factor 2 is the factor related to the charge conjugation. Using Eq. (1), we calculate $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (0.414 \pm 0.084)\%$, where the uncertainty is statistical only.

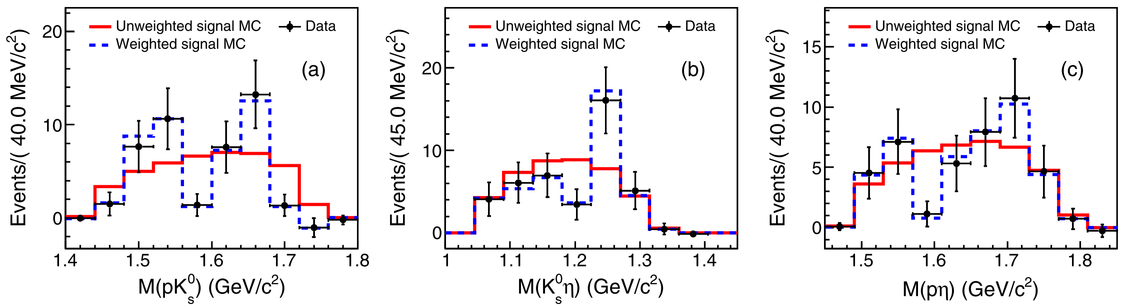

Fig. 2. Distributions of (a) $M_{pK_S^0}$, (b) $M_{K_S^0\eta}$ and (c) $M_{p\eta}$ in data and signal MC samples, in which points with error bars are data after the background subtraction, and the red-solid and blue-dashed histograms show the unweighted and weighted signal MC samples, respectively.

5. Systematic uncertainties

In this work, the systematic uncertainties on the BF measurement include the uncertainties related to the PID and tracking of the proton, the reconstruction of the K_S^0 and η, the two-dimensional fit, the MC modeling, $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ and the BFs of the intermediate states.

The uncertainties related to both the PID and tracking efficiencies of the proton are estimated to be 1%, respectively, based on a study of control samples of $e^+e^- \to p\bar{p}\pi^+\pi^-$ and $e^+e^- \to p\bar{p}\pi^+\pi^-\pi^+\pi^-$ events in data at $\sqrt{s} > 4.23$ GeV [19]. The uncertainty associated with the K_S^0 reconstruction is assigned to be 2.5% based on studies of control samples of $J/\psi \to K^*(892)^\mp K^\pm$ and $J/\psi \to \phi K_S^0 K^\mp\pi^\pm$ decays [19]. We use a control sample of $D^0 \to K^-\pi^+\pi^0$ events to estimate the uncertainty due to the η reconstruction [28,29]. The $\pi^0 \to \gamma\gamma$ reconstruction efficiencies are obtained in data and MC simulations, and an η reconstruction uncertainty of 1.8% is assigned by weighting the efficiency difference to the η momentum distribution of the signal samples.

The uncertainty associated with the two-dimensional fit consists of the uncertainties of the signal and background shapes. To estimate the uncertainty, 20000 pseudo-data-sets are sampled with replacement data according to the bootstrap method [30]. For each pseudo-data-set, a two-dimensional fit is performed, in which the mean values and standard deviations of the two Gaussian functions in the signal shape are randomly varied by $\pm 1\sigma$ around their nominal values, the endpoint of the ARGUS function is randomly varied by ± 0.2 MeV around its nominal value, and the background shape of the ΔE distributions is replaced by a first-order Chebyshev polynomial function. The pull of the fit result $\mathrm{p}(N_{\mathrm{sig}})$ is defined as

$$\mathrm{p}(N_{\mathrm{sig}}) = \frac{N_{\mathrm{sig}}^{\mathrm{pseudo}} - N_{\mathrm{sig}}^{\mathrm{real}}}{\sigma_N^{\mathrm{pseudo}}}, \tag{2}$$

where $N_{\mathrm{sig}}^{\mathrm{real}}$ is the fit yield of real data, $N_{\mathrm{sig}}^{\mathrm{pseudo}}$ and $\sigma_N^{\mathrm{pseudo}}$ are the fit yield and its statistical uncertainty of the pseudo-data, respectively. The distribution of $\mathrm{p}(N_{\mathrm{sig}})$ values is fitted with a Gaussian function, and the mean value is obtained to be -0.1364 ± 0.0074. The bias in $\mathrm{p}(N_{\mathrm{sig}})$ is 13.64% times the statistical uncertainty, which is calculated to be 2.8%, and as no correction for this bias is applied, we use 2.8% as the systematic uncertainty related with the two-dimensional fit.

The uncertainty related to the MC model of the signal process is evaluated by reweighting the signal MC sample, which is generated assuming no intermediate resonances, according to the $M_{pK_S^0}$, $M_{K_S^0\eta}$ and $M_{p\eta}$ invariant mass distributions observed in data. Here, M_{ij} is the invariant mass of the combination of particles i and j.

Table 1
Systematic uncertainties.

Source	Uncertainty (%)
Proton PID	1.0
Proton Tracking	1.0
K_S^0 reconstruction	2.5
η reconstruction	1.8
Two-dimensional fit	2.8
Signal model	2.2
$N_{\Lambda_c^+\bar{\Lambda}_c^-}$	4.6
$\mathcal{B}_{\mathrm{inter}}$	0.5
Total	6.8

Fig. 2 shows the distributions of these invariant masses in data after the background subtraction using the *sPlot* method [31] based on the nominal fitting. The detection efficiency based on the modified MC sample is calculated to be 17.19%, and the relative difference to the nominal efficiency, 2.2%, is taken as the corresponding systematic uncertainty.

The uncertainty of $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ in data is reported to be 4.6% in Ref. [19]. The BFs of intermediate states from the PDG [13] are $\mathcal{B}(K_S^0 \to \pi^+\pi^-) = (69.20 \pm 0.05)\%$ and $\mathcal{B}(\eta \to \gamma\gamma) = (39.41 \pm 0.20)\%$. The uncertainty from these two BFs, which is dominated by the latter one, is 0.5%.

The total systematic uncertainty, which is determined by adding all sources of systematic uncertainties in quadrature, is calculated to be 6.8%. The systematic uncertainties are summarized in Table 1.

6. Summary

Based on 586 pb^{-1} of e^+e^- collision data collected at $\sqrt{s} = 4.6$ GeV with the BESIII detector and the BEPCII collider, the absolute BF for $\Lambda_c^+ \to pK_S^0\eta$ is determined for the first time. The BF is measured to be $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (0.414 \pm 0.084 \pm 0.028)\%$, where the first uncertainty is statistical and the second one is systematic. The statistical significance of this measurement is larger than 7σ, and the significance becomes 5.3σ when both statistical and systematic uncertainties are taken into account. This result is compatible with the CLEO result $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (0.8 \pm 0.2)\%$ [12] within 1.5σ. Our result is consistent with theoretical predictions based on SU(3) symmetry [11,14]. With present statistics, it is not practical to measure any intermediate N^* states, as suggested in Refs. [15,16].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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