Observation of Λ_{c}^{+}→nK_{S}^{0}π^{+}

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Observation of $\Lambda_c^+ \to nK_S^0\pi^+$

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We report the first direct measurement of decays of the Λ_c^+ baryon involving the neutron. The analysis is performed using 567 pb^{-1} of e^+e^- collision data collected at $\sqrt{s} = 4.599$ GeV with the BESIII detector at the BEPCII collider. We observe the decay $\Lambda_c^+ \to nK_S^0\pi^+$ and measure the absolute branching fraction to be $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82 \pm 0.23(\mathrm{stat}) \pm 0.11(\mathrm{syst}))\%$. A comparison to $\mathcal{B}(\Lambda_c^+ \to p(\bar{K}\pi)^0)$ provides an important test of isospin symmetry and final state interactions.

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The ground-state charmed baryon Λ_c^+ decays eventually into a proton or a neutron, each taking about half of the total branching fraction (BF) [1]. However, to date no direct measurement of the decay modes involving a neutron has been performed. It has been argued that isospin symmetry works well in the charmed baryon sector [2]. Comparing BFs of the final states with a neutron to the final states with a proton provides an important observable in testing isospin symmetry in Λ_c^+ three-body decays [2]. The decay $\Lambda_c^+ \to n\bar{K}^0\pi^+$ is the most favored decay of the Λ_c involving a neutron. Under the isospin symmetry, its amplitude is related to those of the most favored proton modes $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to p\bar{K}^0\pi^0$ as $\mathcal{A}(n\bar{K}^0\pi^+) + \mathcal{A}(pK^-\pi^+) + \sqrt{2}\mathcal{A}(p\bar{K}^0\pi^0) = 0$. Hence, precise measurement of the BF for $\Lambda_c^+ \to n\bar{K}^0\pi^+$ provide stringent test on the isospin symmetry in the charmed baryon decays by examining this triangle relation.

Furthermore, study of $\Lambda_c^+ \to n\bar{K}^0\pi^+$ is important to explore the decay mechanism of the Λ_c^+, especially the factorization scheme and the involved final state interaction [2, 3]. In the three-body Λ_c^+ decay to $N\bar{K}\pi$, the total decay amplitudes can be decomposed into two isospin amplitudes of the $N\bar{K}$ system as isosinglet ($I^{(0)}$) and isospin-one ($I^{(1)}$). In the factorization limit, the color-allowed tree diagram, in which the π^+ is emitted and the $N\bar{K}$ is an isosinglet, dominates $I^{(0)}$, and $I^{(1)}$ is expected to be small compared to $I^{(0)}$ as it can only proceed through the color-suppressed tree diagrams. Though the factorization scheme is spoiled in charmed meson decays, whether this scheme is valid in the charmed baryon Λ_c^+ decays is of great interest to both theorists and experimentalists and strongly deserves the experimental investigation. The measurement of BF for $\Lambda_c^+ \to n\bar{K}^0\pi^+$ can validate or falsify this scheme. Together with the $\Lambda_c^+ \to p(\bar{K}\pi)^0$, the $\Lambda_c^+ \to n\bar{K}^0\pi^+$ can be used to determine the magnitudes of the two isospin amplitudes and their phase difference, which provides crucial information on the final state interaction. In addition, hight statistics data will facilitate to understand the resonant structures [4, 5] in the three-body Λ_c decays and test the SU(3) flavor symmetry [2]. Throughout the paper, charge conjugate modes are always implied.

This Letter reports on the observation of the final states with a neutron $\Lambda_c^+ \to nK_S^0\pi^+$. The data analyzed correspond to 566.93 ± 0.11 pb^{-1} [6] of e^+e^- annihilations accumulated with the BESIII experiment at $\sqrt{s} = 4.599$ GeV [7]. This energy is slightly above the mass threshold of a $\Lambda_c^+\bar{\Lambda}_c^-$ pair, at which $\Lambda_c^+\bar{\Lambda}_c^-$ are produced in pairs and no additional hadron is kinematically allowed. The analysis technique in this work, which was first applied in the Mark III experiment [8], is specific for charm hadron pairs produced near threshold. First, we select a data sample of $\bar{\Lambda}_c^-$ baryons by reconstructing exclusive hadronic decays, called the single tag (ST) sample. Then, we search for $\Lambda_c^+ \to nK_S^0\pi^+$ in the system recoiling against the ST $\bar{\Lambda}_c^-$ baryons, called the double tag (DT) sample. In the final state $nK_S^0\pi^+$, the neutron is not detected, and its kinematics is deduced by four-momenta conservation. The absolute BF of $\Lambda_c^+ \to nK_S^0\pi^+$ is then determined from the probability of detecting the process $\Lambda_c^+ \to nK_S^0\pi^+$ in the ST sample. This method provides a clean and straightforward BF measurement independent of the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ events produced.

The BESIII detector is a cylindrical detector with a solid-angle coverage of 93% of 4π that operates at the BEPCII collider. It consists of a Helium-gas based main drift chamber (MDC), a plastic scintillator time-of-flight (TOF) system, a CsI (Tl) electromagnetic calorimeter (EMC), a superconducting solenoid providing a 1.0 T magnetic field and a muon counter. The charged particle momentum resolution is 0.5% at a transverse momentum of 1 GeV/c. The photon energy resolution in EMC is 2.5% in the barrel and 5.0% in the end-caps at energies of 1 GeV. More details about the design and performance of the detector are given in Ref. [9].

A GEANT4-based [10] Monte Carlo (MC) simulation package, which includes a description of the detector geometry and the detector response, is used to determine the detection efficiency and to estimate potential backgrounds. Signal MC samples of a Λ_c^+ baryon decaying only to $nK_S^0\pi^+$ together with a $\bar{\Lambda}_c^-$ decaying only to the studied tag modes are generated by the MC event generator KKMC [11] using EVTGEN [12], including the effects of initial-state radiation (ISR) [13]. Final-state radiation (FSR) off the charged tracks is simulated with the PHOTOS package [14]. The $\Lambda_c^+ \to nK_S^0\pi^+$ decay is simulated using a phase space model since the two-body invariant mass spectra found in data for $M_{n\pi^+}$, $M_{nK_S^0}$ and $M_{K_S^0\pi^+}$ show no obvious structure. To study backgrounds, inclusive MC samples consisting of generic $\Lambda_c^+\bar{\Lambda}_c^-$ events, $D^*_{(s)}\bar{D}^{(*)}_{(s)} + X$ production, ISR return to the charmonium(-like) ψ states at lower masses, and QED processes are generated. All decay modes of the Λ_c, ψ and $D_{(s)}$ as specified in the Particle Data Group (PDG) [1] are simulated by the EVTGEN MC generator, while the unknown decays of the ψ states are generated with LUNDCHARM [15].

The ST $\bar{\Lambda}_c^-$ baryons are reconstructed using eleven hadronic decay modes as listed in the first column of Table I, where the intermediate particles K_S^0, $\bar{\Lambda}$, $\bar{\Sigma}^0$, $\bar{\Sigma}^-$ and π^0 are reconstructed through their decays of $K_S^0 \to \pi^+\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Sigma}^0 \to \gamma\bar{\Lambda}$ with $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Sigma}^- \to \bar{p}\pi^0$ and $\pi^0 \to \gamma\gamma$, respectively.

Charged tracks are required to have polar angles within $|\cos\theta| < 0.93$, where θ is the polar angle of the charged track with respect to the beam direction. Their distances of closest approach to the interaction point (IP) are required to be less than 10 cm along the beam direction and less than 1 cm in the perpendicular plane. Tracks originating from K_S^0 and Λ decays are not subjected to these distance requirements. To discriminate pions from kaons, the specific ionization energy loss (dE/dx) in the MDC and TOF information are used to obtain particle identification (PID) probabilities for the pion ($\mathcal{L}_\pi$) and kaon ($\mathcal{L}_K$) hypotheses. Pion and kaon candidates are selected using $\mathcal{L}_\pi > \mathcal{L}_K$ and $\mathcal{L}_K > \mathcal{L}_\pi$, respectively. For proton identification, information from dE/dx, TOF, and EMC are combined to calculate the PID probability $\mathcal{L}'$, and a charged track satisfying $\mathcal{L}'_p > \mathcal{L}'_\pi$ and $\mathcal{L}'_p > \mathcal{L}'_K$ is identified as a proton candidate.

Photon candidates are reconstructed from isolated clusters in the EMC in the regions $|\cos\theta| \leq 0.80$ (barrel) and $0.86 \leq |\cos\theta| \leq 0.92$ (end cap). The deposited energy of a neutral cluster is required to be larger than 25 (50) MeV in barrel(end cap) region, and the angle between the photon candidate and the nearest charged track must be larger than 10°. To suppress electronic noise and energy deposits unrelated to the events, the difference between the EMC time and the event start time is required to be within (0, 700) ns. To reconstruct π^0 candidates, the invariant mass of the accepted photon pair is required to be within (0.110, 0.155) GeV/c^2. A kinematic fit is performed to constrain the $\gamma\gamma$ invariant mass to the nominal π^0 mass [1], and the χ^2 of the kinematic fit is required to be less than 20. The fitted momenta of the π^0 are used in the further analysis.

To reconstruct K_S^0 and $\bar{\Lambda}$ candidates, a vertex-constrained fit is applied to $\pi^+\pi^-$ and $\bar{p}\pi^+$ combinations, and the fitted track parameters are used in the further analysis. The signed decay length L of the secondary vertex to the IP is also required to be larger than zero. The same PID requirements as mentioned before are applied to the proton candidate, but not to the π candidate. The invariant masses $M_{\pi^+\pi^-}$, $M_{\bar{p}\pi^+}$, $M_{\gamma\bar{\Lambda}}$ and $M_{\bar{p}\pi^0}$ are required to be within (0.485, 0.510) GeV/c^2, (1.110, 1.121) GeV/c^2, (1.179, 1.205) GeV/c^2 and (1.173, 1.200) GeV/c^2 to select candidates for K_S^0, $\bar{\Lambda}$, $\bar{\Sigma}^0$ and $\bar{\Sigma}^-$ candidates, respectively.

For the ST mode $\bar{p}K_S^0\pi^0$, the backgrounds involving $\bar{\Lambda}$ and $\bar{\Sigma}^-$ are rejected by rejecting any event with $M_{\bar{p}\pi^+} \in (1.105, 1.125)$ GeV/c^2 and $M_{\bar{p}\pi^0} \in (1.173, 1.200)$ GeV/c^2. For the ST modes of $\bar{\Lambda}\pi^+\pi^-\pi^-$ and $\bar{\Sigma}^-\pi^+\pi^-$, the backgrounds involving K_S^0 and Λ as intermediate states are suppressed by requiring $M_{\pi^+\pi^-} \notin (0.480, 0.520)$ GeV/c^2 and $M_{\bar{p}\pi^+} \notin (1.105, 1.125)$ GeV/c^2.

The ST $\bar{\Lambda}_c^-$ signal candidates are identified using the variable of beam constrained mass, $M_{\rm BC} \cdot c^2 \equiv \sqrt{E_{\rm beam}^2 - |\overrightarrow{p}_{\bar{\Lambda}_c^-} \cdot c|^2}$, where $E_{\rm beam}$ is the beam energy and $\overrightarrow{p}_{\bar{\Lambda}_c^-}$ is the momentum of the $\bar{\Lambda}_c^-$ candidate. To improve the signal purity, the energy difference $\Delta E \equiv E_{\rm beam} - E_{\bar{\Lambda}_c^-}$ for each candidate is required to be within approximately $\pm 3\sigma_{\Delta E}$ around the ΔE peak, where $\sigma_{\Delta E}$ is the ΔE resolution and $E_{\bar{\Lambda}_c^-}$ is the reconstructed $\bar{\Lambda}_c^-$ energy. The explicit ΔE requirements for the different modes are listed in Table I. The yield of each tag mode is obtained from fits to the $M_{\rm BC}$ distributions in the signal region $(2.280, 2.296)$ GeV/c^2, which is the same as in Ref. [16]. The yields of reconstructed singly tagged $\bar{\Lambda}_c^-$ baryons are listed in Table I. Finally, we obtain the total ST yield summed over all 11 modes to be $N_{\bar{\Lambda}_c^-}^{\rm tot} = 14415 \pm 159$, where the error is statistical only.

TABLE I. ST modes, ΔE requirements and ST yields $N_{\bar{\Lambda}_c^-}$ in data. The errors are statistical only.

Mode	ΔE (GeV)	$N_{\bar{\Lambda}_c^-}$
$\bar{p}K_S^0$	$[-0.025,\ 0.028]$	1066 ± 33
$\bar{p}K^+\pi^-$	$[-0.019,\ 0.023]$	5692 ± 88
$\bar{p}K_S^0\pi^0$	$[-0.035,\ 0.049]$	593 ± 41
$\bar{p}K^+\pi^-\pi^0$	$[-0.044,\ 0.052]$	1547 ± 61
$\bar{p}K_S^0\pi^+\pi^-$	$[-0.029,\ 0.032]$	516 ± 34
$\bar{\Lambda}\pi^-$	$[-0.033,\ 0.035]$	593 ± 25
$\bar{\Lambda}\pi^-\pi^0$	$[-0.037,\ 0.052]$	1864 ± 56
$\bar{\Lambda}\pi^-\pi^+\pi^-$	$[-0.028,\ 0.030]$	674 ± 36
$\bar{\Sigma}^0\pi^-$	$[-0.029,\ 0.032]$	532 ± 30
$\bar{\Sigma}^-\pi^0$	$[-0.038,\ 0.062]$	329 ± 28
$\bar{\Sigma}^-\pi^+\pi^-$	$[-0.049,\ 0.054]$	1009 ± 57
All tags		14415 ± 159

Candidates for the decay $\Lambda_c^+ \to nK_S^0\pi^+$ are selected from the remaining tracks recoiling against the ST $\bar{\Lambda}_c^-$ candidates. A pion with charge opposite to the ST $\bar{\Lambda}_c^-$ is selected, and a K_S^0 candidate is selected with the same selection criteria as described above but without the $M_{\pi^+\pi^-}$ mass requirement. If more than one K_S^0 candidate is formed, the one with the largest decay length significance L/σ_L is retained, where σ_L is the vertex resolution of L.

Since the neutron is not detected, we use a kinematic variable

$$M_{\rm miss}^2 \equiv E_{\rm miss}^2/c^4 - |\overrightarrow{p}_{\rm miss}|^2/c^2$$

to obtain information on the missing neutron, where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and momentum carried by the neutron, respectively, which are calculated by $E_{\rm miss} \equiv E_{\rm beam} - E_{K_S^0} - E_{\pi^+}$ and $\vec{p}_{\rm miss} \equiv \vec{p}_{\Lambda_c^+} - \vec{p}_{K_S^0} - \vec{p}_{\pi^+}$, where $\vec{p}_{\Lambda_c^+}$ is the momentum of the Λ_c^+ baryon, $E_{K_S^0}$ ($\vec{p}_{K_S^0}$) and E_{π^+} ($\vec{p}_{\pi^+}$) are the energies (momenta) of the K_S^0 and π^+, respectively. Here, the momentum $\vec{p}_{\Lambda_c^+}$ is given by $\vec{p}_{\Lambda_c^+} = -\hat{p}_{\rm tag}\sqrt{E_{\rm beam}^2/c^2 - m_{\bar{\Lambda}_c^-}^2 c^2}$, where $\hat{p}_{\rm tag}$ is the direction of the momentum of the ST $\bar{\Lambda}_c^-$ and $m_{\bar{\Lambda}_c^-}$ is the nominal $\bar{\Lambda}_c^-$ mass [1]. If the K_S^0 and π^+ from the decay $\Lambda_c^+ \to nK_S^0\pi^+$ are correctly identified, the $M_{\rm miss}^2$ is expected to peak around the nominal neutron mass

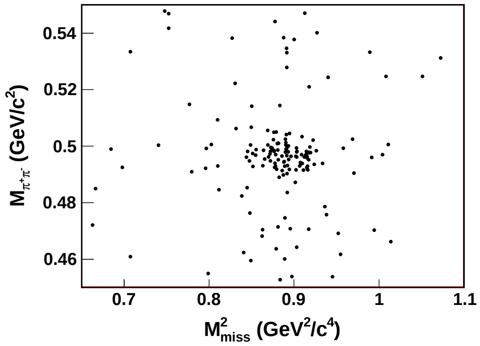

FIG. 1. Scatter plot of $M_{\pi^+\pi^-}$ versus $M^2_{\rm miss}$ for $\Lambda_c^+ \to nK_S^0\pi^+$ observed from data.

squared.

The scatter plot of $M_{\pi^+\pi^-}$ versus $M^2_{\rm miss}$ for the $\Lambda_c^+ \to nK_S^0\pi^+$ candidates in data is shown in Fig. 1, where a cluster of events in the signal region is clearly visible. According to MC simulations, the dominant backgrounds are from the decays $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$ with $\Sigma^\pm \to n\pi^\pm$, which have the same final state as signal. These background events form a peaking background in $M^2_{\rm miss}$, but are distributed flat in $M_{\pi^+\pi^-}$. Backgrounds from non-Λ_c^+ decays are estimated by examining the ST candidates in the $M_{\rm BC}$ sideband $(2.252, 2.272)$ GeV/c^2 in data, whose area is 1.6 times larger than the background area in the signal region.

To obtain the yield of $\Lambda_c^+ \to nK_S^0\pi^+$ events, we perform a two-dimensional unbinned maximum likelihood fit to the $M^2_{\rm miss}$ and $M_{\pi^+\pi^-}$ distributions in both $M_{\rm BC}$ signal and sideband regions simultaneously. As verified with MC simulations, we model the $M_{\pi^+\pi^-}$ and $M^2_{\rm miss}$ distributions with a product of two one-dimensional probability density functions, one for each dimension. The signal functions for $M^2_{\rm miss}$ and $M_{\pi^+\pi^-}$ are both described by double Gaussian functions. The peaking background in the $M^2_{\rm miss}$ distribution is described by a double Gaussian function with parameters fixed according to MC simulations, and the flat distribution in the $M_{\pi^+\pi^-}$ spectrum is described by a constant function. The non-Λ_c^+ decay background is modelled by a second-order polynomial function in the $M^2_{\rm miss}$ distribution and a Gaussian function plus a second-order polynomial function in the $M_{\pi^+\pi^-}$ distribution, in which the parameters and the normalized background yields are constrained by the events in $M_{\rm BC}$ sideband in the simultaneous fit. The fit procedure is validated by analyzing a large ensemble of MC-simulated samples, in which the pull distribution of the fitted yields is in good agreement with the normal distribution. Projections of the final fit to data are shown in Fig. 2. From the fit, we obtain $N^{\rm obs}_{nK_S^0\pi^+} = 83.2 \pm 10.6$, where the error is statistical only.

The absolute branching fraction for $\Lambda_c^+ \to nK_S^0\pi^+$ is

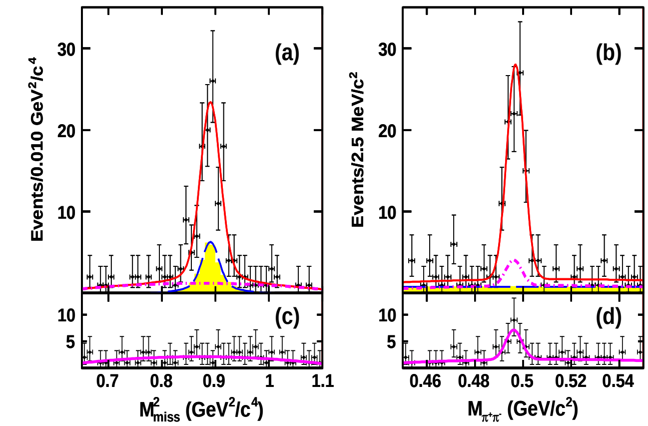

FIG. 2. Simultaneous fit to $M^2_{\rm miss}$ and $M_{\pi^+\pi^-}$ of events in (a, b) the $\bar{\Lambda}_c^-$ signal region and (c, d) sideband regions. Data are shown as the dots with error bars. The long-dashed lines (blue) show the Λ_c^+ backgrounds while the dot-dashed curves (pink) show the non-Λ_c^+ backgrounds. The (red) solid curves show the total fit. The (yellow) shaded area show the MC simulated backgrounds from Λ_c^+ decay.

determined by

$$\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+) = \frac{N^{\rm obs}_{nK_S^0\pi^+}}{N^{\rm tot}_{\bar{\Lambda}_c^-} \times \varepsilon_{nK_S^0\pi^+} \times \mathcal{B}(K_S^0 \to \pi^+\pi^-)}, \quad (1)$$

where $\varepsilon_{nK_S^0\pi^+}$ is the detection efficiency for the $\Lambda_c^+ \to nK_S^0\pi^+$ decay, which does not include the branching fraction for $K_S^0 \to \pi^+\pi^-$. For each ST mode i, the efficiency $\epsilon^i_{nK_S^0\pi^+}$ is obtained by dividing the DT efficiency $\epsilon^i_{{\rm tag},nK_S^0\pi^+}$ by the ST efficiency $\epsilon^i_{\rm tag}$. Weighting $\epsilon^i_{nK_S^0\pi^+}$ by the ST yields in data for each tag mode, we obtain $\varepsilon_{nK_S^0\pi^+} = (45.9 \pm 0.3)\%$. Inserting the values of $N^{\rm obs}_{nK_S^0\pi^+}$, $N^{\rm tot}_{\bar{\Lambda}_c^-}$, $\varepsilon_{nK_S^0\pi^+}$ and $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$ [1] in Eq. (1), we obtain $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82 \pm 0.23)\%$, where the statistical error, including those from $N^{\rm obs}_{nK_S^0\pi^+}$ and $N^{\rm tot}_{\bar{\Lambda}_c^-}$ is presented.

With the DT technique, the systematic uncertainties from the ST side cancel in the branching fraction measurement. The systematic uncertainties for measuring $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+)$ mainly arise from the uncertainties of PID, tracking, K_S^0 reconstruction and the fit procedure. Throughout this paragraph, all quoted systematic uncertainties are relative uncertainties. The uncertainties in the π PID and tracking are both determined to be 1.0% by studying a set of control samples of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, $e^+e^- \to K^+K^-\pi^+\pi^-$ and $e^+e^- \to p\bar{p}\pi^+\pi^-$ based on data taken at energies above 4.0 GeV. The uncertainty in the efficiency of K_S^0 reconstruction is determined to be 1.5% by studying the control samples of $J/\psi \to K^{*\mp}K^\pm$ and $J/\psi \to \phi K_S^0 K^\pm\pi^\mp$.

TABLE II. Summary of the relative systematic uncertainties for $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+)$.

Source	Uncertainty
$\pi^\pm$ PID	1.0%
$\pi^\pm$ tracking	1.0%
K_S^0 reconstruction	1.5%
Fit	5.2%
$\mathcal{B}(K_S^0 \to \pi^+\pi^-)$	0.1%
$N^{\rm tot}_{\bar{\Lambda}_c^-}$	1.0%
MC statistics	0.6%
MC Model	1.3%
Total	5.9%

The uncertainty due to the fit procedure is estimated to be 5.2% by varying the fit range, the shapes of background and signal components, and the choice of sideband regions. Besides these uncertainties mentioned above, there are systematic uncertainties from the quoted branching fraction for $K_S^0 \to \pi^+\pi^-$ (0.1%), the $N^{\rm tot}_{\bar{\Lambda}_c^-}$ (1.0%) evaluated by using alternative signal shapes in fits to the $M_{\rm BC}$ spectra, the MC statistics (0.6%), the signal MC model (1.3%) estimated by taking into account the statistical variations in the $M_{n\pi^+}$, $M_{nK_S^0}$ and $M_{K_S^0\pi^+}$ spectra observed in data. These systematic uncertainties are summarized in Table II, and the total systematic error is estimated to be 5.9% by adding up all the sources in quadrature.

In summary, using 567 pb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 4.599$ GeV with the BESIII detector, we report the observation of the decay $\Lambda_c^+ \to nK_S^0\pi^+$. We measure the absolute branching fraction for $\Lambda_c^+ \to nK_S^0\pi^+$, $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82\pm0.23\pm0.11)\%$, where the first uncertainty is statistical and the second is systematic. This is the first direct measurement of a Λ_c^+ decay involving the neutron in the final state since the discovery of the Λ_c^+ more than 30 years ago. Quoting $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ and $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)$ measured by BESIII [17], it can be found that the amplitudes of the above three decay processes satisfy the triangle relation and validate the isospin symmetry [2]. Besides, we obtain $\mathcal{B}(\Lambda_c^+ \to n\bar{K}^0\pi^+)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.62 \pm 0.09$ and $\mathcal{B}(\Lambda_c^+ \to n\bar{K}^0\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\bar{K}^0\pi^0)) = 0.97 \pm 0.16$ [18], in which the common uncertainties have been cancelled in the calculation. According to Ref. [2], based on these ratios, the strong phase difference of $I^{(0)}$ and $I^{(1)}$ is calculated to be $\cos\delta = -0.24 \pm 0.08$, which is useful to understand the final state interactions in Λ_c^+ decays. Furthermore, the relative size of the two amplitudes $|I^{(1)}|/|I^{(0)}|$ is evaluated to be 1.14 ± 0.11, which indicates that the amplitude $I^{(1)}$ is not small as expected in the factorization scheme. This is consistent with the behaviors in the charmed meson decays [19]. These results will be essential inputs for the study of other Λ_c decays in theory. Hence, the measurement of the neutron mode in this work provides the first complementary data to the previously measured decays involving a proton, which represents significant progress in studying the Λ_c^+. The analysis method used in this work can also be extended to study more decay modes involving a neutron.

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