

## Observation of $\Lambda + c \rightarrow nK^0 S^+$ Postprint

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### Abstract

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

### Full Text

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**Abstract**

We report the first direct measurement of decays of the  $\Lambda + c$  baryon involving a neutron. The analysis is performed using 567 pb<sup>-1</sup> of e<sup>+</sup>e<sup>-</sup> collision data collected at  $\sqrt{s} = 4.599$  GeV with the BESIII detector at the BEPCII collider. We observe the decay  $\Lambda + c \rightarrow nK^0 S^+$  and measure the absolute branching fraction to be  $(1.82 \pm 0.23(\text{stat}) \pm 0.11(\text{syst}))\%$ . A comparison to  $B(\Lambda + c \rightarrow pK^-)$  provides an important test of isospin symmetry and final state

interactions.

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## Introduction

The ground-state charmed baryon  $\Lambda^+ c$  decays eventually into a proton or a neutron, each taking about half of the total branching fraction [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 branching fractions of final states with a neutron to those with a proton provides an important observable for testing isospin symmetry in  $\Lambda^+ c$  three-body decays [2].

The decay  $\Lambda^+ c \rightarrow nK^0 \pi^+$  is the most favored decay of the  $\Lambda^+ c$  involving a neutron. Under isospin symmetry, its amplitude is related to those of the most favored proton modes  $\Lambda^+ c \rightarrow pK^0 \pi^+$  and  $\Lambda^+ c \rightarrow pK^0 \pi^0$  through the relation:  $A(\Lambda^+ c \rightarrow pK^0 \pi^+) + \sqrt{2} A(\Lambda^+ c \rightarrow pK^0 \pi^0) + A(\Lambda^+ c \rightarrow nK^0 \pi^+) = 0$ . Hence, precise measurement of the branching fraction for  $\Lambda^+ c \rightarrow nK^0 \pi^+$  provides a stringent test of isospin symmetry in charmed baryon decays by examining this triangle relation.

Furthermore, study of  $\Lambda^+ c \rightarrow nK^0 \pi^+$  is important to explore the decay mechanism of the  $\Lambda^+ c$ , especially the factorization scheme and the involved final state interactions [2, 3]. In the three-body  $\Lambda^+ c$  decay to  $N K \pi$ , the total decay amplitudes can be decomposed into two isospin amplitudes of the  $N K \pi$  system as isosinglet ( $I = 0$ ) and isospin-one ( $I = 1$ ). In the factorization limit, the color-allowed tree diagram, in which the  $\pi^+$  is emitted and the  $N K$  is an isosinglet, dominates  $I = 0$ , and  $I = 1$  is expected to be small compared to  $I = 0$  as it can only proceed through color-suppressed tree diagrams. Though the factorization scheme is spoiled in charmed meson decays, whether this scheme is valid in charmed baryon  $\Lambda^+ c$  decays is of great interest to both theorists and experimentalists and strongly deserves experimental investigation.

The measurement of the branching fraction for  $\Lambda^+ c \rightarrow nK^0 \pi^+$  can validate or falsify this scheme. Together with the previously measured proton modes,  $\Lambda^+ c \rightarrow nK^0 \pi^+$  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, high-statistics data will facilitate understanding the resonant structures [4, 5] in three-body  $\Lambda^+ c$  decays and testing SU(3) flavor symmetry [2]. Throughout the paper, charge conjugate modes are always implied.

## Experimental Method

This Letter reports on the observation of the final states with a neutron  $\Lambda^+ c \rightarrow nK^0 S^+$ . The data analyzed correspond to 566.93 pb<sup>-1</sup> 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  $\Lambda^+ c$   $\Lambda^- c$  pair production, at which  $\Lambda^+ c$  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  $\Lambda^- c$  baryons by reconstructing exclusive hadronic decays, called the single tag (ST) sample. Then, we search for  $\Lambda^+ c \rightarrow nK^0 S^+$  in the system recoiling against the ST  $\Lambda^- c$  baryons, called the double tag (DT) sample. In the final state  $nK^0 S^+$ , the neutron is not detected, and its kinematics is deduced by four-momentum conservation. The absolute branching fraction for  $\Lambda^+ c \rightarrow nK^0 S^+$  is then determined from the probability of detecting the process  $\Lambda^+ c \rightarrow nK^0 S^+$  in the ST sample. This method provides a clean and straightforward branching fraction measurement independent of the total number of  $\Lambda^+ c$  events produced.

## Detector and Simulation

The BESIII detector is a cylindrical detector with a solid-angle coverage of 93% of  $4\pi$  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 the 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  $\Lambda^+ c$  baryon decaying only to  $nK^0 S^+$  and a  $\Lambda^- c$  baryon 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  $\Lambda^+ c \rightarrow nK^0 S^+$  decay is simulated using a phase space model since the two-body invariant mass spectra found in data for  $Mn^+$ ,  $MnK^0 S$ , and  $MK^0 S^+$  show no obvious structure. To study backgrounds, inclusive MC samples consisting of generic  $\Lambda^+ c$   $\Lambda^- c$  production, ISR return to the charmonium(-like) states at lower masses, and QED processes are generated. All decay modes of the  $\Lambda_c$ ,  $\Sigma_c$ , 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  $\Lambda_c$  states are generated with LUNDCHARM [15].

## Event Selection

The ST  $\Lambda^- c$  baryons are reconstructed using eleven hadronic decay modes as listed in the first column of Table I, where the intermediate particles  $K^0 S$ ,  $\Lambda$ ,

$\Sigma^0$ , and  $\Lambda^0$  are reconstructed through their decays of  $K^0_S \rightarrow \pi^+ \pi^-$ ,  $\Lambda \rightarrow \bar{p} \pi^+$ ,  $\Sigma^0 \rightarrow \Lambda \gamma$ , and  $\Lambda^0 \rightarrow \bar{p} \pi^+$ , respectively.

Charged tracks are required to have polar angles with  $|\cos \theta| < 0.93$ , where  $\theta$  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  $K^0_S$  and  $\Lambda$  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 ( $\pi$ ) and kaon (K) hypotheses. Pion and kaon candidates are selected using  $P(\pi) > P(K)$  and  $P(K) > P(\pi)$ , respectively. For proton identification, information from  $dE/dx$ , TOF, and EMC is combined to calculate the PID probability  $P(p)$ . A charged track satisfying  $P(p) > P(\pi)$  and  $P(p) > P(K)$  is identified as a proton candidate.

Photon candidates are reconstructed from isolated clusters in the EMC in the regions  $|\cos \theta| < 0.80$  (barrel) and  $0.86 < |\cos \theta| < 0.92$  (end cap). The deposited energy of a neutral cluster is required to be larger than 25 MeV (50 MeV) in the barrel (end cap) region, and the angle between the photon candidate and the nearest charged track must be larger than  $10^\circ$ . 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  $\Lambda^0$  candidates, the invariant mass of the accepted photon pair is required to be within (0.110, 0.155) GeV/c<sup>2</sup>. A kinematic fit is performed to constrain the invariant mass to the nominal  $\Lambda^0$  mass [1], and the  $\chi^2$  of the kinematic fit is required to be less than 20. The fitted momenta of the  $\Lambda^0$  are used in further analysis.

To reconstruct  $K^0_S$  and  $\Lambda$  candidates, a vertex-constrained fit is applied to  $\pi^+ \pi^-$  and  $\bar{p} \pi^+$  combinations, and the fitted track parameters are used in 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  $\Lambda$  candidate. The invariant masses  $M_{\pi^+ \pi^-}$ ,  $M_{\bar{p} \pi^+}$ ,  $M_{\Lambda^0}$ , and  $M_{\Lambda^0 \gamma}$  are required to be within (0.485, 0.510) GeV/c<sup>2</sup>, (1.179, 1.205) GeV/c<sup>2</sup>, (1.110, 1.121) GeV/c<sup>2</sup>, and (1.173, 1.200) GeV/c<sup>2</sup> to select candidates for  $K^0_S$ ,  $\Lambda$ ,  $\Sigma^0$ , and  $\Sigma^-$  candidates, respectively.

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

The ST signal candidates are identified using the beam-constrained mass variable,  $MBC = \sqrt{(E_{beam}^2 - |\bar{p}\Lambda c|^2)}/c$ , where  $E_{beam}$  is the beam energy and  $\bar{p}\Lambda c$  is the momentum of the  $\Lambda^- c$  candidate. To improve signal purity, the energy difference  $\Delta E = E_{\Lambda c} - E_{beam}$  is required to be within  $\pm 3 \Delta E$  around the  $\Delta E$

peak, where  $\Delta E$  is the  $\Delta E$  resolution and  $E_{\Lambda c}$  is the reconstructed  $\Lambda - c$  energy. The explicit  $\Delta E$  requirements for the different modes are listed in Table I. The yield of each tag mode is obtained from fits to the MBC distributions in data. The errors are statistical only.

## Single Tag Yields

Table I shows the ST modes,  $\Delta E$  requirements, and ST yields  $N_{\Lambda c}$  in data. The signal region is defined as (2.280, 2.296) GeV/c<sup>2</sup>, which is the same as in Ref. [16]. The yields of reconstructed singly tagged  $\Lambda - c$  baryons are listed in Table I. Finally, we obtain the total ST yield summed over all 11 modes to be  $N_{\text{tot}} = 14415 \pm 159$ , where the error is statistical only.

## Double Tag Analysis

Candidates for the decay  $\Lambda + c \rightarrow nK^0 S^+$  are selected from the remaining tracks recoiling against the ST  $\Lambda - c$  candidates. A pion with charge opposite to the ST  $\Lambda - c$  is selected, and a  $K^0 S$  candidate is selected with the same selection criteria as described above but without the  $M^+ -$  mass requirement. If more than one  $K^0 S$  candidate is formed, the one with the largest decay length significance  $L/L$  is retained, where  $L$  is the vertex resolution of  $L$ .

Since the neutron is not detected, we use a kinematic variable  $M^2_{\text{miss}} = E_{\text{miss}}^2/c^2 - |\vec{p}_{\text{miss}}|^2/c^2$  to obtain information on the missing neutron, where  $E_{\text{miss}}$  and  $\vec{p}_{\text{miss}}$  are the missing energy and momentum carried by the neutron, respectively. These are calculated by  $E_{\text{miss}} = E_{\text{beam}} - E^+ - E_{K^0 S}$  and  $\vec{p}_{\text{miss}} = \vec{p}_{\Lambda + c} - \vec{p}^+ - \vec{p}_{K^0 S}$ , where  $\vec{p}_{\Lambda + c}$  is the momentum of the  $\Lambda + c$  baryon, given by  $\vec{p}_{\Lambda + c} = -\vec{p}_{\text{tag}} + E_{\text{beam}} \cdot c^2 \cdot \hat{p}_{\text{tag}}/|\hat{p}_{\text{tag}}|$ , where  $\hat{p}_{\text{tag}}$  is the direction of the momentum of the ST  $\Lambda - c$  and  $m_{\Lambda c}$  is the nominal  $\Lambda - c$  mass [1]. If the  $K^0 S$  and  $+$  from the decay  $\Lambda + c \rightarrow nK^0 S^+$  are correctly identified, the  $M^2_{\text{miss}}$  distribution is expected to peak around the nominal neutron mass squared.

The scatter plot of  $M^+ -$  versus  $M^2_{\text{miss}}$  for  $\Lambda + c \rightarrow nK^0 S^+$  candidates in data is shown in Fig. 1 [Figure 1: see original paper], where a cluster of events in the signal region is clearly visible. According to MC simulations, the dominant backgrounds are from the decays  $\Lambda + c \rightarrow \Sigma^+ + -$  with  $\Sigma^\pm \rightarrow n^\pm$ , which have the same final state as signal. These background events form a peaking background in  $M^2_{\text{miss}}$ , but are distributed flat in  $M^+ -$ . Backgrounds from non- $\Lambda + c$  decays are estimated by examining the ST candidates in the MBC sideband (2.252, 2.272) GeV/c<sup>2</sup> in data, whose area is 1.6 times larger than the background area in the signal region.

To obtain the yield of  $\Lambda + c \rightarrow nK^0 S^+$  events, we perform a two-dimensional unbinned maximum likelihood fit to the  $M^2_{\text{miss}}$  and  $M^+ -$  distributions in both MBC signal and sideband regions simultaneously. As verified with MC simulations, we model the  $M^+ -$  and  $M^2_{\text{miss}}$  distributions with a product of two one-dimensional probability density functions, one for each dimension. The

signal functions for  $M^2_{\text{miss}}$  and  $M + -$  are both described by double Gaussian functions. The peaking background in the  $M^2_{\text{miss}}$  distribution is described by a double Gaussian function with parameters fixed according to MC simulations, and the flat distribution in the  $M + -$  spectrum is described by a constant function. The non- $\Lambda + c$  decay background is modeled by a second-order polynomial function in the  $M^2_{\text{miss}}$  distribution and a Gaussian function plus a second-order polynomial function in the  $M + -$  distribution, in which the parameters and the normalized background yields are constrained by the events in the MBC 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 [Figure 2: see original paper]. From the fit, we obtain  $N_{\text{obs}} = 83.2 \pm 10.6$ , where the error is statistical only.

## Branching Fraction Measurement

The absolute branching fraction for  $\Lambda + c \rightarrow nK^0 S^+$  is determined by:

$$\mathcal{B}(\Lambda_c^+ \rightarrow nK_S^0 \pi^+) = \frac{N_{\text{obs}}}{N_{\text{tot}} \cdot \epsilon_{nK_S^0 \pi^+}}$$

where  $\epsilon_{nK^0 S^+}$  is the detection efficiency for the  $\Lambda + c \rightarrow nK^0 S^+$  decay, which does not include the branching fraction for  $K^0 S^+ \rightarrow + -$ . For each ST mode  $i$ , the efficiency  $\epsilon_{i nK^0 S^+}$  is obtained by dividing the DT efficiency  $\epsilon_{i \text{tag}, nK^0 S^+}$  by the ST efficiency  $\epsilon_{i \text{tag}}$ . Weighting  $\epsilon_{i nK^0 S^+}$  by the ST yields in data for each tag mode, we obtain  $\epsilon_{nK^0 S^+} = (45.9 \pm 0.3)\%$ . Inserting the values of  $N_{\text{obs}}$ ,  $\epsilon_{nK^0 S^+}$ , and  $N_{\text{tot}}$  into Eq. (1), we obtain  $\mathcal{B}(\Lambda + c \rightarrow nK^0 S^+) = (1.82 \pm 0.23)\%$ , where the statistical error includes those from  $N_{\text{obs}}$  and  $N_{\text{tot}}$ .

## Systematic Uncertainties

With the DT technique, the systematic uncertainties from the ST side cancel in the branching fraction measurement. The systematic uncertainties for measuring  $\mathcal{B}(\Lambda + c \rightarrow nK^0 S^+)$  mainly arise from the uncertainties of PID, tracking,  $K^0 S^+$  reconstruction, and the fit procedure. Throughout this paragraph, all quoted systematic uncertainties are relative uncertainties.

The uncertainties in the PID and tracking are both determined to be 1.0% by studying a set of control samples of  $e^+e^- \rightarrow K^+K^- + -$  and  $\bar{p}p + -$  based on data taken at energies above 4.0 GeV. The uncertainty in the efficiency of  $K^0 S^+$  reconstruction is determined to be 1.5% by studying the control samples of  $J/\psi \rightarrow K^0 S K^\pm$ . 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  $K^0 S \rightarrow + -$  (0.1%), the  $N_{\text{tot}}$  measurement (1.0%) evaluated by using alternative signal shapes in fits to the MBC spectra, the MC statistics (0.6%), and the signal MC model (1.3%) estimated by taking into account the statistical variations in the  $M_n +$ ,  $M_n K^0 S$ , and  $M_n K^0 S +$  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.

Table II. Summary of the relative systematic uncertainties for  $B(\Lambda^+ c \rightarrow nK^0 S +)$ .

Source	Uncertainty
$\pm$ PID	1.0%
$\pm$ tracking	1.0%
$K^0 S$ reconstruction	1.5%
Fit procedure	5.2%
$B(K^0 S \rightarrow + -)$	0.1%
$N_{\text{tot}}$	1.0%
MC statistics	0.6%
MC Model	1.3%
<b>Total</b>	<b>5.9%</b>

## Summary

In summary, using 567  $\text{pb}^{-1}$  of  $e^+e^-$  collision data taken at  $\sqrt{s} = 4.599$  GeV with the BESIII detector, we report the observation of the decay  $\Lambda^+ c \rightarrow nK^0 S +$ . We measure the absolute branching fraction for  $\Lambda^+ c \rightarrow nK^0 S +$  to be  $(1.82 \pm 0.23 \pm 0.11)\%$ , where the first uncertainty is statistical and the second is systematic. This is the first direct measurement of a  $\Lambda^+ c$  decay involving a neutron in the final state since the discovery of the  $\Lambda^+ c$  more than 30 years ago.

Quoting  $B(\Lambda^+ c \rightarrow pK^- +)$  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  $B(\Lambda^+ c \rightarrow nK^0 S +)/B(\Lambda^+ c \rightarrow pK^- +) = 0.62 \pm 0.09$  and  $B(\Lambda^+ c \rightarrow nK^0 S +)/B(\Lambda^+ c \rightarrow pK^0 0) = 0.97 \pm 0.16$  [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  $\cos \delta = 0.08$ , which is useful to understand the final state interactions in  $\Lambda^+ c$  decays. Furthermore, the relative size of the two amplitudes indicates that the amplitude  $I = 1$  is not small as expected in the factorization scheme. This is consistent with the behaviors in charmed meson decays [19]. These results will be essential inputs for the study of other  $\Lambda c$  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  $\Lambda + c$  decay mechanism. The analysis method used in this work can also be extended to study more decay modes involving a neutron.

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