Few-Body Syst (2022) 63:16
https://doi.org/10.1007/s00601-021-01717-x

K. Itabashi · T. Akiyama · Y. Fujii · T. Fujiwara · F. Garibaldi · T. Gogami · M. Kaneta · K. Katayama · P. E. C. Markowitz · K. Maeda · M. Mizuno · S. Nagao · S. N. Nakamura · Y. R. Nakamura · K. Okuyama · B. Pandey · J. Reinhold · K. N. Suzuki · L. Tang · Y. Toyama · T. Toyoda · K. Uehara · E. Umezaki · G. M. Urciuoli · for the JLab Hypernuclear Collaboration

Study of the $nn\Lambda$ State and Λn Interaction at Jefferson Lab

Received: 6 June 2021 / Accepted: 22 November 2021 / Published online: 6 January 2022

Abstract An $nn\Lambda$, which consists of two neutrons and a Lambda hyperon, is a multi-baryon system with no charge. Studying the $nn\Lambda$ state would provide information about the Λn interaction which has not been directly measured by a scattering experiment. The experiment (E12-17-003) was performed in order to search for the $nn\Lambda$ state at Jefferson Lab. The $nn\Lambda$ is expected to be produced by the $(e, e'K^+)$ reaction, which has sensitivity to both bound and resonance states if the natural width of the $nn\Lambda$ is narrow enough to be observed as a peak. The experiment used gas targets of hydrogen and tritium for mass calibration and the $nn\Lambda$ production, respectively. The mass calibration with $\mathrm{H}(e, e'K^+)\Lambda/\Sigma^0$ reactions gave the mass resolution of the Λ and Σ^0 each 3.5 MeV/c^2 FWHM, for the elementary reaction. A spectrum of $^3\mathrm{H}(e, e'K^+)X$ was obtained, and a simple model with a Λn final state interaction was applied to reproduce the spectrum.

1 Introduction

The baryon–baryon interaction is studied by scattering experiments. However, the scattering experiment is not easy to be applied for hyperons because of their short lifetimes. There are scattering data for the $p\Lambda$ [1] reaction although the statistics are very limited, and no data exists for the Λn reaction. The Λn interaction has instead been estimated from the Λp interaction as measured by scattering experiments. The HypHI collaboration at GSI reported a peak structure that may be interpreted as a bound state of the $nn\Lambda$ system in 2013 [2]. The HypHI collaboration measured the lifetime and an invariant mass for a final state of the $\pi^- + t$. There is an

K. Itabashi (✉) · T. Akiyama · T. Fujiwara · M. Kaneta · K. Maeda · M. Mizuno · S. Nagao · S. N. Nakamura · Y. R. Nakamura · K. Okuyama · Y. Toyama · K. Uehara
Graduate School of Science Tohoku University, 6-3 Aoba-ku, Sendai, Miyagi 9820-8578, Japan
E-mail: itabashi@lambda.phys.tohoku.ac.jp

Y. Fujii
Tohoku Medical and Pharmaceutical University, Sendai, Miyagi 981-8558, Japan

F. Garibaldi · G. M. Urciuoli
I.N.F.N. Sezione di Roma, Gr. Coll. Santita', Viale Regina Elena 299, Rome, Italy

T. Gogami · K. Katayama · K. N. Suzuki · T. Toyoda · E. Umezaki
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

P. E. C. Markowitz · J. Reinhold
Department of Physics, Florida International University, Miami, FL 27411, USA

B. Pandey · L. Tang
Department of Physics, Hampton University, Hampton, VA 23668, USA

enhancement on the $\pi^- + t$ invariant mass around the $nn\Lambda$ threshold. Moreover, events from the enhancement have a long lifetime ($\tau = 190^{+47}_{-35} \pm 36$ ps) which indicates the decay occurred via the weak interaction process. The HypHI group also finds a similar structure in the invariant mass of the $d + \pi^-$ system and measured its finite lifetime. They observed structure in the $d + \pi^-$ invariant mass distribution which was interpreted as events originating from the reconstruction with missing one neutron of the $d + \pi^- + n$ events from the $nn\Lambda$ three-body decay. A theoretical calculation that reproduces the Λ binding energies of light hypernuclei does not support the existence of a bound $nn\Lambda$ state [3]. On the other hand, a resonance state of $nn\Lambda$ may exist as is suggested by Ref. [4] in which the Λn interaction is strengthened by about 5% in order to produce the resonance state. We performed the experimental search for the $nn\Lambda$ with the $(e, e'K^+)$ reaction at Jefferson Lab's (JLab) Hall A in 2018 (JLab E12-17-003 Experiment). The missing mass is measured in the experiment. Therefore, any existence of both bound and resonance states could be observed if the decay width of the $nn\Lambda$ is narrow enough.

2 Experimental Setup

2.1 Continuous Electron Beam Accelerator Facility (CEBAF)

Electron beams which impinged on an experimental target were provided by the Continuous Electron Beam Accelerator Facility (CEBAF) at JLab. The beam energy was well controlled with a spread in the centeral energy of the beam of $\Delta E/E \leq 1.8 \times 10^{-4}$ (FWHM) which is sufficient for our measurement. We used a beam energy of 4.3 GeV aand a beam current of 22.5 μA together with a beam raster size of 1.8×2.9 mm^2.

2.2 High Resolution Spectrometers (HRSs)

The measurement was performed in Hall A with two high resolution spectrometers (HRSs) comprised of superconducting magnets to measure momenta of charged particles with momentum resolution of ($\Delta p/p \sim 10^{-4}$). Figure 1a shows the HRSs in Hall A. Detectors were installed for particle identification and detection of tracks in the HRSs. Two aerogel Cherenkov detectors, the refractive indexes of which are 1.015 and 1.055, were used for a K^+ identification in the right-arm HRS. The tracking of scattered electrons and K^+ were detected with two vertical drift chambers (VDC1, VDC2) in each HRS which had two layers in each drift chamber.

The experiment measured the K^+ and scattered electrons with central momenta of $p_K = 1.8$ GeV/c and $p_{e'} = 2.2$ GeV/c. The $nn\Lambda$ mass was then obtained with a missing mass method.

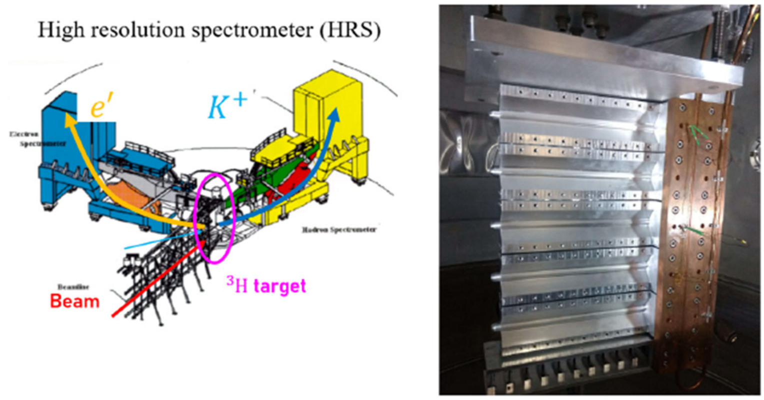
2.3 Gas Target Systems

There were five gas-filled aluminum cells (^{3}H, ^{3}He, ^{2}H, ^{1}H and empty), as well as solid targets (BeO, Al, and multi-carbon foils) in the target ladder (Fig. 1b). Cryogenic gas targets (40 K) with 25-cm lengths were irradiated with an electron beam within the current range of 2.5 to 22.5 μA [5]. The ^{3}H gas target with ρ =86.4 mg/cm^2 was used for $nn\Lambda$ production via the ^{3}H$(e, e'K^+)nn\Lambda$ reaction. The H target with ρ =70.8 mg/cm^2 was used for mass calibration. A few percent of ^{3}He nuclei were present in the tritium target due to the weak decay ($^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_e$) which has a half-life of 12.3 years. The ^{3}He gas target with 53.4 mg/cm^2 was used for an estimation of the ^{3}He shape of the ^{3}He$(e, e'K^+)X$ missing mass spectrum due to this contamination of the tritium target. Multi-carbon foils with 0.25 mm lengths were used for a z-vertex (beam direction) calibration.

3 Results

3.1 H$(e, e'K^+)\Lambda$, Σ^0 Missing Mass

The experiment measured missing masses of Λ and Σ^0 final states with the hydrogen target. Backward matrices of the spectrometers from a detected point to the reaction point were optimized by comparing measured masses



(a) High Resolution Spectrometers(HRS) in Hall A [6] **(b)** Target system in the experiment [7]

Fig. 1 **a** Two HRSs were used for detection of K^+ and scattered electrons (e'). A target system was installed at the cross point of two HRSs. **b** There were five target cells (^{3}H, ^{3}He, ^{2}H, ^{1}H and empty) with 25-cm lengths. The cryogenic gas targets in the experiment were kept at 40 K

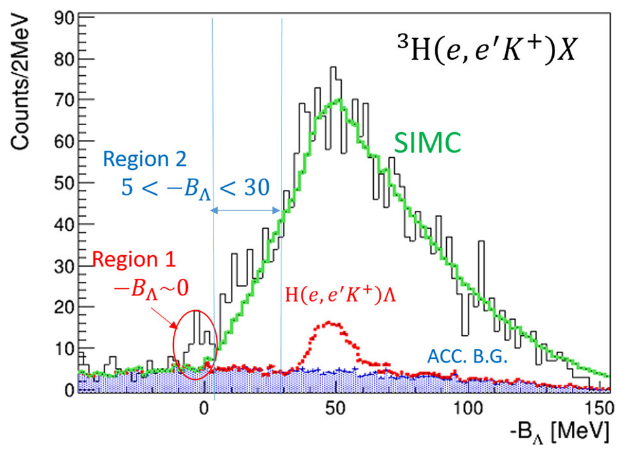


Fig. 2 A $^3\mathrm{H}(e, e'K^+)X$ missing mass distribution: The black line shows experimental data. The blue hashed area shows an accidental background which is estimated by mixing events. The red dotted line is a distribution of Λ productions from hydrogen contamination. The green line shows a Λ quasi-free distribution with the Monte Carlo simulation (SIMC) which is JLab standard simulation code including all backgrounds

of Λ and Σ^0 baryons with their PDG values ($m_\Lambda = 1115.68(3)$, $m_{\Sigma^0} = 1192.6(4)$ MeV/c^2). The Λ mass resolution in past experiments achieved 1.6 MeV/c^2 FWHM by using a mass calibration method with thin solid targets (thickness < 1 mm) [7]. On the other hand, this experiment used long length targets (25 cm), so it was necessary to develop a new mass calibration method with a z-vertex (beam direction) correction. As the result of applying the new mass calibration to the Λ and Σ^0 missing masses, both the Λ and Σ^0 resolution achieved 3.5 MeV/c^2 FWHM. The cross section of the Λ is 0.37 μb/sr at $\theta_{\gamma K}^{C.M.} \sim 8°$, $Q^2 \sim 0.5$ (GeV/c)^2.

3.2 $^3\mathrm{H}(e, e'K^+)X$ Missing Mass

A $^3\mathrm{H}(e, e'K^+)X$ missing mass distribution is shown in Fig. 2. The horizontal axis shows the Λ-binding energy. The green line is a simulation result of Λ quasi-free distribution with SIMC. SIMC is a JLab standard simulation code for coincidence reactions which includes radiative effects, multiple scattering, ionization energy loss, and particle decay. The green line, which includes physics like the Fermi momentum of a proton and the spectral function of tritium, is in good agreement with the experimental data over the 40 MeV region. On the other hand, there are two excess structures in the region less than 30 MeV which cannot be explained by SIMC (Fig. 2).

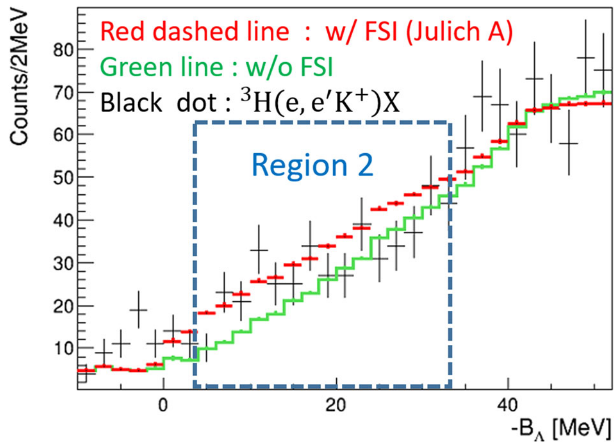


Fig. 3 The Λ quasi-free distribution with SIMC including Λn FSI effect: The error bars are for experimental data. The green line shows the Λ quasi-free distribution with SIMC without a Λn FSI effect. The red dashed line shows the Λ quasi-free distribution with SIMC including the Λn FSI effect with the Jülich A potential [10]

3.2.1 $nn\Lambda$ Threshold Region ($B_\Lambda \sim 0$ MeV)

There are excess events at $-B_\Lambda \simeq 0$ MeV. The peak significance of this excess is about 2σ if the expected mass resolution of 1.6 MeV/c^2 is assumed, though SIMC cannot reproduce the excess. Since clear evidence of the $nn\Lambda$ state is not observed, an upper limit for the cross section is estimated by using the spectrometer acceptance from Geant4 and measured detection efficiencies. The upper limit of this excess is a few tens of nb/sr (C.L. 90 %).

3.2.2 QF Λ-Production Region ($B_\Lambda \sim 20$ MeV)

There is a structure between 5 and 30 MeV in Fig. 2. An enhancement of the $^{3}_{\Lambda}$H missing mass was explained by a final state interaction (FSI) in the study [9]. The Λn FSI hasthe recoil Λ reacting on the remaining neutron within the target. Other FSIs like ΛK^+ can be ignored because these effects are two orders of magnitude smaller than the Λn FSI [8]. The number of events including a Λn FSI effect (N_{FSI}) is described with a Jost function (J_l) and number of events without any FSI effects ($N_{w/oFSI}$) as:

$$N_{FSI} = I N_{w/oFSI} = \frac{1}{|J_l(k_{rel})|^2} N_{w/oFSI}, \tag{1}$$

where k_{rel} is the relative momentum between a Λ and neutron in the center of mass system, and I is an enhancement factor. The Jost function is calculated by:

$$J(k_{rel}) = \frac{k_{rel} - i\beta}{k_{rel} - i\alpha}, \tag{2}$$

where α and β are given by using parameters of scattering length(a) and effective range (r_e) in the Λn potential [10],

$$\frac{1}{2} r_e(\alpha - \beta) = 1, \qquad \frac{1}{2} r_e \alpha\beta = -\frac{1}{a}. \tag{3}$$

As the result of Eqs. 1–3, the Λ quasi-free distribution by SIMC including the Λn FSI effect with the Jülich A potential [10] is shown by the red dashed line in Fig. 3. The red dashed line (with FSI) better reproduces the experimental data within region 2 than the green line (without FSI).

4 Summary

The $(e, e'K^+)$ reaction spectroscopy experiment was performed in order to search for the $nn\Lambda$ state at JLab Hall A in 2018. The Λ mass resolution was found to be 3.5 MeV/c^2 FWHM with the new mass calibration method. However, no clear peak structures were observed in the missing mass distribution of the $nn\Lambda$.

The Λ quasi-free distribution with the SIMC calculation reproduced the experimental data (>40 MeV region). There is an enhancement in the region 2 (Fig. 3) which cannot be reproduced by the SIMC calculation without the Λn FSI effect. However, this structure is in good agreement with the SIMC calculation including the Λn FSI effect using the Jülich A potential.

Acknowledgements This work was supported in part by Aid for Graduate Program on Physics for the Universe. Also, the work was partially supported by JSPS KAKENHI Grants Nos. JP18H05459, 18H01219, 17H01121, 120002001, 15684005, 16GS0201, GP-PU Tohoku Univ., US Department of Energy Contracts Nos. DE-AC05-84ER40150, DE-AC05-06OR23177, DE-FG02-99ER41065, DE-FG02-97ER41047, DE-AC02-06CH11357, DEFG02-00ER41110, DE-AC02-98CH10886, and US NSF Contracts No. 013815 and 0758095

References

1. J.A. Kadyk et al., Nucl. Phys. B **27**, 13 (1971)
2. C. Rappold et al., Phys. Rev. C **88**, 041001 (2013)
3. E. Hiyama et al., Phys. Rev. C **89**, 061302 (2014)
4. I.R. Afnan et al., Phys. Rev. C **92**, 053608 (2015)
5. S.N. Santiesteban *et al.,* Nucl. Inst. and Meth. A **940** (2019)
6. https://hallaweb.jlab.org/equipment/high_resol.html (2018)
7. T. Gogami et al., Phys. Rev. C **93**, 034314 (2016)
8. X. Li, L.E. Wright, J. Phys. G **17**, 1127 (1991)
9. F. Dohrmann et al., Phys. Rev. C **76**, 054004 (2007)
10. https://pdg.lbl.gov/2006/hadronic-xsections/hadron.html