Study of Λn FSI with Λ quasi-free productions on the ^{3}H$(e, e'K^{+})X$ reaction at JLab

K. Itabashi[1*], *K.N.* Suzuki[2], *B.* Pandey[3], *K.* Okuyama[4], *T.* Gogami[2], *S.* Nagao[4], *S.N.* Nakamura[1], *L.* Tang[3,5], *D.* Abrams[6], *T.* Akiyama[4], *D.* Androic[7], *K.* Aniol[8], *C.* Ayerbe Gayoso[9], *J.* Bane[10], *S.* Barcus[9], *J.* Barrow[10], *V.* Bellini[11], *H.* Bhatt[12], *D.* Bhetuwal[12], *D.* Biswas[3], *A.* Camsonne[5], *J.* Castellanos[13], *J-P.* Chen[5], *J.* Chen[9], *S.* Covrig[5], *D.* Chrisman[14,15], *R.* Cruz-Torres[16], *R.* Das[17], *E.* Fuchey[18], *K.* Gnanvo[6], *F.* Garibaldi[11,19], *T.* Gautam[3], *J.* Gomez[5], *P.* Gueye[3], *T.J.* Hague[20], *O.* Hansen[5], *W.* Henry[5], *F.* Hauenstein[21], *D.W.* Higinbotham[5], *C.E.* Hyde[21], *M.* Kaneta[4], *C.* Keppel[5], *T.* Kutz[17], *N.* Lashley-Colthirst[3], *S.* Li[22,23], *H.* Liu[24], *J.* Mammei[25], *P.* Markowitz[13], *R.E.* McClellan[5], *F.* Meddi[11,26], *D.* Meekins[5], *R.* Michaels[5], *M.* Mihovilovic[27,28,29], *A.* Moyer[30], *D.* Nguyen[16,31], *M.* Nycz[20], *V.* Owen[9], *C.* Palatchi[6], *S.* Park[17], *T.* Petkovic[7], *S.* Premathilake[6], *P.E.* Reimer[32], *J.* Reinhold[13], *S.* Riordan[32], *V.* Rodriguez[33], *C.* Samanta[34], *S.N.* Santiesteban[22], *B.* Sawatzky[5], *S.* Širca[27,28], *K.* Slifer[22], *T.* Su[20], *Y.* Tian[35], *Y.* Toyama[4], *K.* Uehara[4], *G.M.* Urciuoli[11], *D.* Votaw[14,15], *J.* Williamson[36], *B.* Wojtsekhowski[5], *S.A.* Wood[5], *B.* Yale[22], *Z.* Ye[32], *J.* Zhang[6], and *X.* Zheng[6]

[1]Department of Physics, Graduate School of Science, the University of Tokyo, Hongo, Tokyo 113-0033 Japan
[2]Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
[3]Department of Physics, Hampton University, Hampton, Virginia 23668, USA
[4]Department of Physics, Graduate School of Science, Tohoku University, Sendai, 980-8578 Japan
[5]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
[6]Department of Physics, University of Virginia, Charlottesville, Virginia 22904, USA
[7]Department of Physics & Department of Applied Physics, University of Zagreb, HR-10000 Zagreb, Croatia
[8]Physics and Astronomy Department, California State University, Los Angeles, California 90032, USA
[9]Department of Physics, The College of William and Mary, Virginia 23185, USA
[10]Department of Physics, University of Tennessee, Knoxville, Tennessee 37996, USA
[11]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 00185, Rome, Italy
[12]Department of Physics, Mississippi State University, Mississippi State, Mississippi 39762, USA
[13]Department of Physics, Florida International University, Miami, Florida 33199, USA
[14]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[15]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[16]Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[17]Department of Physics, State University of New York, Stony Brook, New York 11794, USA
[18]Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA
[19]Instituto Superiore di Sanitá, 00161, Rome, Italy
[20]Department of Physics, Kent State University, Kent, Ohio 44242, USA
[21]Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA
[22]Department of Physics, University of New Hampshire, Durham, New Hampshire 03824, USA
[23]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[24]Department of Physics, Columbia University, New York, New York 10027, USA
[25]Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

*e-mail: kosuke.itabashi@kek.jp

[26] Sapienza University of Rome, I-00185, Rome, Italy

[27] Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana, Slovenia

[28] Jožef Stefan Institute, Ljubljana, Slovenia

[29] Institut für Kernphysik, Johanness Gutenberg-Universität Mainz, DE-55128 Mainz, Germany

[30] Department of Physics, Christopher Newport University, Newport News, Virginia 23606, USA

[31] University of Education, Hue University, Hue City, Vietnam

[32] Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA

[33] División de Ciencias y Tecnologia, Universidad Ana G. Méndez, Recinto de Cupey, San Juan 00926, Puerto Rico

[34] Department of Physics & Astronomy, Virginia military Institute, Lexington, Virginia 24450, USA

[35] Department of Physics, Syracuse University, New York, New York 10016, USA

[36] School of Physics & Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland, UK

Abstract. An $nn\Lambda$ is a neutral baryon system with no charge. The study of the pure Λ-neutron system such as $nn\Lambda$ gives us information on the Λn interaction. The $nn\Lambda$ search experiment (E12-17-003) was performed at JLab Hall A in 2018. In this article, the Λn FSI was investigated by a shape analysis of the ^{3}H$(e, e'K^{+})X$ missing mass spectrum, and a preliminary result for the Λn FSI study is given.

1 Introduction

In the nucleon-nucleon (NN) interaction, realistic nuclear potentials have been constructed based on rich NN scattering data. On the other hand, there are relatively large uncertainties due to limited ΛN scattering data in case of the ΛN interaction. In addition, since there is no Λn scattering data, the Λn interaction have been established from the limited Λp scattering data assuming charge symmetry (CS). However, it has been experimentally observed that charge symmetry is broken between A=4 mirror Λ hypernuclei ($_{\Lambda}^{4}$H, $_{\Lambda}^{4}$He) [1]. Therefore, it is important to derive the Λn interaction experimentally. One of the major experimental investigation methods for the ΛN interaction is the study of the ΛN final state interaction (FSI). The FSI is the reaction between the recoil Λ and a nucleon in a nucleus, and it is known to make an enhanced structure in the missing mass spectrum [2, 3]. Therefore, the spectroscopic study of a pure Λ-neutron system such as $nn\Lambda$ is expected to give us information on the Λn interaction. The ^{3}H$(e, e'K^{+})X$ missing mass spectrum was obtained by using two HRS spectrometers and a tritium target (^{3}H) which is a radioactive material in 2018 at Jefferson Lab (JLab) Hall A [4, 5]. In this study, the Λn FSI interaction was investigated by analyzing the ^{3}H$(e, e'K^{+})X$ missing mass spectrum obtained by this experiment (E12-17-003).

2 ^{3}H$(e, e'K^{+})X$ missing mass spectrum

In this experiment, a cryogenic tritium gas target (40 K) with a thickness of 84.8 mg/cm^{2} was irradiated with an electron with an energy (E_e) of 4.3 GeV, and measured momenta of scattered electrons ($p_{e'}$ = 2.2 GeV/c) and K^{+} mesons (p_K = 1.8 GeV/c) by two high resolution spectrometers (HRS). The missing mass (M_X) was calculated with the momentum vectors ($\vec{p}_{e'}$, $\vec{p}_K$) and energies ($E_{e'}$, E_K) as follows :

$$M_X = \sqrt{(E_e + m_T - E_{e'} - E_K)^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_K)^2}. \tag{1}$$

where m_T and $\vec{p}_e$ are the mass of tritium and momentum vector of the electron beam, respectively. As a function of the measured the ^{3}H$(e, e'K^{+})X$ missing mass, the missing mass

spectrum is shown by black dots with error bars in Fig. 1. This vertical axis represents the differential cross section for the ^{3}H$(e, e'K^+)X$ reaction. Any parameter values such as momentum acceptances ($d\Omega_{e'}$, $d\Omega_K$) used to calculate the cross section are explained in Ref. [6].

2.1 Monte Carlo Simulation (SIMC)

The solid black line in Fig. 1 shows the Λ quasi-free (Λ-QF) distribution calculated by the Monte Carlo Simulation (SIMC); SIMC is a JLab standard Monte Carlo simulation code, which takes into account the effects such as the proton Fermi momentum, kaon decay. Comparing the SIMC spectrum with the missing mass spectrum, the region over 60 MeV is good agreement. However, there is some enhancement around $nn\Lambda$ mass threshold ($-B_\Lambda \sim 0$ MeV) and 20 MeV regions. Around the $nn\Lambda$ mass threshold where a $nn\Lambda$ peak is expected to exist, there are excess events which cannot reproduced by SIMC.

Though the statics is not enough to conclude anything about the existence of the $nn\Lambda$ system [7], the excess events around 20 MeV are expected to be produced by the Λn FSI. In the past Λ-hypernuclear experiment in the ^{3}He$(e, e'K^+)X$ reaction at JLab, a similar enhanced structure was observed within a range of $-B_\Lambda > 0$ MeV. Moreover, this enhanced structure was successfully reproduced by considering the ΛN FSI effect [2]. Therefore, in this study, the Λn FSI effect was investigated by analyzing the structure around 20 MeV.
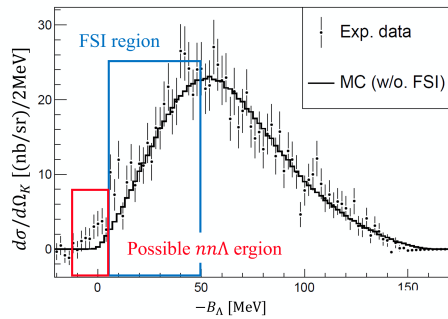
Figure 1. ^{3}H$(e, e'K^+)X$ missing mass spectrum. The horizontal and vertical axes indicate the binding energy of the Λ (MeV) and the differential cross section of the missing mass (nb/sr/2 MeV), respectively. The black points with bar shows the experimental data. The black solid line is the simulation result (SIMC) of the Λ-QF distribution without any final state interaction effects.

3 Calculation of the Λn final state interaction (FSI)

The cross section for Λ-QF productions including FSI is written as follows :

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{FSI}} = \text{I}(\vec{k}_{\Lambda n})\left(\frac{d\sigma}{d\Omega}\right)_{\text{w/oFSI}} , \qquad (2)$$

where I($\vec{k}_{\Lambda n}$) is the influence factor depending on a relative momentum ($\vec{k}_{\Lambda n}$) between a neutron in tritium and a recoil Λ. In the two-body ($\Lambda - n$) scattering model, the influence factor can be written by using the Jost function (J) as I($\vec{k}_{\Lambda n}$) = $1/|J(\vec{k}_{\Lambda n})|^2$ [8]. Moreover, in the effective range approximation ($k_{\Lambda n} \cot \delta = -1/a + r/2k_{\Lambda n}^2$), the Jost function is written as :

$$J(\vec{k}_{\Lambda n}) = \frac{k_{\Lambda n} - i\beta}{k_{\Lambda n} - i\alpha} , \qquad (3)$$

$$\frac{1}{2}r(\alpha - \beta) = 1, \quad \frac{r}{2}\alpha\beta = -\frac{1}{a} , \qquad (4)$$

where a and r are a scattering length and an effective range, respectively. Figure 2 shows the calculation results of the influence factor with various Λn potential models. The weighting ratio of the spin singlet ($^1S_0$) and triplet ($^3S_1$) factors is one to three. From Eq. (2)-(4), the cross section of the Λ-QF productions including Λn FSI can be obtained.
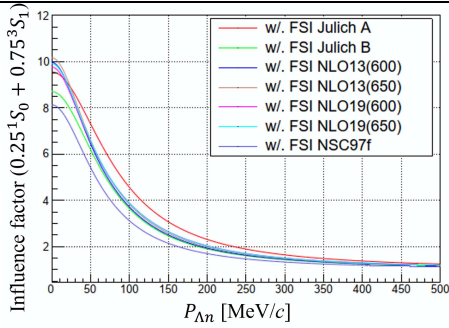
Figure 2. The influence factor depending on a relative Λn momentum in each theoretical model. The influence factor is composed of four spin states, a singlet (I_s) and triplet (I_t) states with a ratio of one to three.
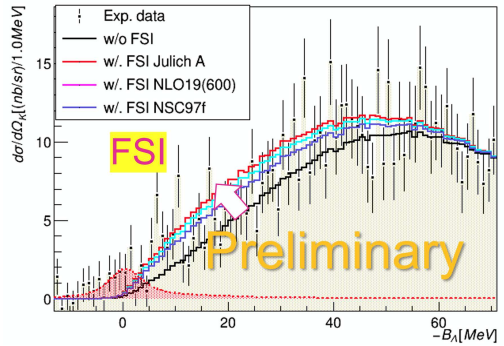
Figure 3. The missing mass spectra with Λn FSI. The black and colored solid lines show the SIMC spectrum without the Λn FSI and with the Λn FSI in each potential model.

## 4 Results

4.1 Λn potential model dependence

The Λn FSI effect was estimated by the χ^2 fitting of the $^3\text{H}(e, e'K^+)X$ missing mass spectrum. The structure around $nn\Lambda$ mass threshold ($-B_\Lambda \sim 0$ MeV) exists, which could not be reproduced by the SIMC spectrum. Therefore, this structure was described as background by using the Breit-Wigner function (f_{WB}) because it was successful to reproduced well by using this function in Ref.[6]. The fitting function of the $^3\text{H}(e, e'K^+)X$ missing mass spectrum was defined as :

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{FSI}} = w_{\text{FSI}} \cdot \text{I}(\vec{k}_{\Lambda n})\left(\frac{d\sigma}{d\Omega}\right)_{\text{SIMC}} + w_{WB} \cdot f_{\text{WB}} \,, \tag{5}$$

where w_{FSI} and w_{WB} are scaling factors for the SIMC spectrum and Breit-Wigner function, respectively. These weighting factors were scaled by the χ^2-fitting with the missing mass spectrum within a range from 0 to 60 MeV. The fitting results of the SIMC spectrum by each Λn FSI model are shown in Fig. 3.

4.2 Search for the best Λn FSI parameters

The scattering length (a) and effective range (r) are parameters that determine the characteristics of the Λn potential. Since these parameters (a, r) were used for calculation of the Λn FSI in Eq.(3)-(4), they can be evaluated by the χ^2-fitting of the experimental spectrum. Figure 4 shows the χ^2-distribution depending on average Λn scattering length ($\bar{a} = (a_s + 3a_t)/4$) and effective range ($\bar{r} = (r_s + 3r_t)/4$). As a result, χ^2 values had the minimum value at $(\bar{a}, \bar{r}) = (-2.6, 5.0)$ fm. Each colored marker in Fig. 4 shows a value of (a, r) in the Λn potential model. Moreover, regions hatched in rad show the experimental results of the singlet and triplet values for Λp FSI [3]. Since the potential values of Λn FSI ($-2.6, 5.0$ fm) took values between these of Λp FSI of the spin singlet and triplet, the potential values at ($-2.6, 5.0$) fm does not conflict with a result of the Λp FSI. On the other hand, the black solid, dashed and dashed-dot lines in Fig. 4 show the contour lines added one, two and three from the chi-square minimum ($\chi^2_{\text{min}} = 59$). Especially, the contour line at $\chi^2_{\text{min}} + 1$ represents the statistics error, so when the scattering length (a) is -2.6 fm, the effective range (r) is successfully limited to be $3.8 < r < 6.3$ fm (preliminary).
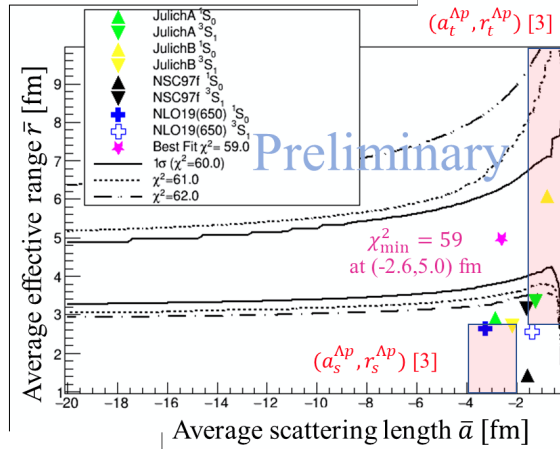
Figure 4. The χ^2 distribution depending on an average scattering length ($\bar{a}$) and effective range ($\bar{r}$). The average values are assumed to be same value of spin singlet and triplet. The χ^2 has minimum value at $(-2.6, 5.0)$ fm (star marker in pink). The colored markers show the potential value in each Λn potential model. The hatched boxes in red show a experimental result of the Λp FSI in the singlet and triplet, respectively [3]. The black lines show the contour lines at $\chi^2 = 60, 61, 62$.

5 Summary

The search for the $nn\Lambda$ experiment (E12-17-003) was performed at JLab Hall A in 2018. By analyzing the ${}^3\text{H}(e, e'K^+)X$ missing mass spectrum by the χ^2-fitting, the Λn FSI was investigated in this study. As a result, the effective range (r) was successfully given a limit for a certain scattering length (a) from Fig. 4 (preliminary).

References

[1] T.O. Yamamoto *et al*., Phys. Rev. Lett. **115**, 222501 (2015)
[2] F. Dohrmann *et al*., Phys. Rev. C **76**, 054004 (2007)
[3] F. Hinterberger *et al*., Eur. Phys. J. A **21**, 313-321 (2004)
[4] S.N. Santiesteban *et al*., Nucl. Inst. And Meth. A 940, 351-358 (2019)
[5] J. Alcorn *et al*., Nucl. Inst. And Meth. A 522, 294-346 (2004)
[6] K.N. Suzuki *et al*., Prog. Theor. Exp. Phys. **2022** 013D01 (2022)
[7] B. Pandey *et al*., Phys. Rev. C **105**, L051001 (2022)
[8] K. Willner *et al*., Phys. Rev. A **74**, 052715 (2006)