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High resolution spectroscopy of the "ΣN cusp" by using the $d(K^-,\pi^-)$ reaction

Yudai Ichikawa[1,*], *Jungkeun* Ahn[2], *Sungwook* Choi[2], *Manami* Fujita[1], *Toshiyuki* Gogami[3], *Shoichi* Hasegawa[1], *Takeshi* Harada[1,3], *Shuhei* Hayakawa[4], *Shigeru* Ishimoto[5], *Wooseung* Jung[2], *Byungmin* Kang[2], *Shinhyung* Kim[1], *Koji* Miwa[4], *Tomofumi* Nagae[3], *Takuya* Nanamura[1,3], *Hiroyuki* Sako[1], *Susumu* Sato[1], *Shoji* Suzuki[5], *Hirokazu* Tamura[1,4], *Kiyoshi* Tanida[1], *Mifuyu* Ukai[1], *Takeshi* Yamamoto[1], and *Seongbae* Yang[3]

[1]ASRC, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
[2]Department of Physics, Korea University, Seoul 02841, Republic of Korea
[3]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[4]Department of Physics, Tohoku University, Sendai 980-8578, Japan
[5]High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan

Abstract. We present a new proposal, J-PARC E90, to measure a missing-mass spectrum near the ΣN threshold for the $d(K^-,\pi^-)$ reactions at 1.4 GeV/c. While many previous experiments support apparent enhancement near the ΣN threshold, the dynamical origin of this so-called "ΣN cusp" remains yet unsolved. The enhancement suggests either a cusp structure or a weakly bound state. One of the keys to making it clear is improving the missing-mass resolution and statistics. Our new experiment can achieve the missing-mass resolution of 0.4 MeV in σ using the K1.8 beam line and S-2S spectrometers at J-PARC. Furthermore, we can suppress quasi-free background processes with the time projection chamber (HypTPC), which operated nicely for the H-dibaryon search experiment (J-PARC E42). The J-PARC E90 aims to extract the scattering length of the ΣN system with isospin T = 1/2 and spin-triplet channels.

1 Introduction

An enhancement near the ΣN threshold (~2.13 GeV/c^2) was clearly observed in the $K^-d \to \pi^-\Lambda p$ reaction at rest more than 50 years ago [1]. This enhancement is called as "ΣN cusp", while whether the "ΣN cusp" is cusp (inelastic virtual state) or an unstable bound state has not been confirmed yet. The "ΣN cusp" was measured by various experiments using $K^-d \to \pi^-\Lambda p$, $\pi^+d \to K^+\Lambda p$, and $pp \to K^+\Lambda p$ reactions [2–8]. Recently, the "ΣN cusp" has also been observed by the Λ-p femtoscopy [9]. At J-PARC, E27 collaboration reported a clear enhancement due to the "ΣN cusp" in the inclusive missing-mass spectrum of the $d(\pi^+,K^+)$ reaction [10]. There exists a lot of experimental observations; however, the dynamical origin of the "ΣN cusp" remains unclear as yet. One of the reasons is the insufficient resolution and statistics of the past experiments.

*e-mail: yudai@post.j-parc.jp

2 "ΣN cusp" for the $K^- d \to \pi^- \Lambda p$ reaction

Theoretical work for the "ΣN cusp" was performed by Dalitz and Deloff [11, 12]. The detail is also described in the J-PARC E90 proposal [13]. In the framework of Ref. [11], the "ΣN cusp" is generated through the following two-step processes,

$$K^- + d \to \pi^- + (\Sigma N)^+ \to \pi^- + \Lambda + p. \tag{1}$$

The reaction amplitude for the net process shown in Eq. (1) can be expressed by three factors as,

$$T(\bar{K}d \to \pi\Lambda N) \sim T(\bar{K}N \to \pi\Sigma)F_d(Q_\Sigma, k_\Sigma)T(\Sigma N \to \Lambda N). \tag{2}$$

The first factor, $T(\bar{K}N \to \pi\Sigma)$, is the T-matrix of the elementary process. The second one is the deuteron factor reflecting deuteron properties. The third factor, the T-matrix of $\Sigma N \to \Lambda p$ process, is an important term to describe the interaction of an intermediate Σ particle with the second nucleon of the deuteron target. $T(\Sigma N \to \Lambda N)$ can be expressed in terms of the ΣN ($T = 1/2$, ${}^3S_1$) scattering length $A_0 = (a + ib)$. Because the measured final state is Λp, the total isospin of ΣN system should be $T = 1/2$. Moreover, the amplitude of the elementary reaction $\bar{K}N \to \pi Y$ has no spin-flip component for the (K^-, π^-) reaction at 0°. Therefore, the YN states also are necessary to be in spin-triplet by reflecting the target-deuteron spin configuration, as ${}^3S_1$.

The third factor of Eq. (2), $T(\Sigma N \to \Lambda N)$, can be expressed as,

$$T(\Sigma N \to \Lambda N) \sim T^t_S(\Sigma N \to \Lambda N) = \frac{\beta^t_{\Sigma\Lambda}}{1 - ik_\Sigma A_0}, \tag{3}$$

where $\beta^t_{\Sigma\Lambda}$ is the $\Sigma N \to \Lambda N$ element of the reaction matrix and b is proportional to $(\beta^t_{\Sigma\Lambda})^2$ (ΛN phase space). The k_Σ denotes the relative momentum of ΣN system in the final ΛN at rest frame. Note that it is clear that the reaction amplitude has a pole at $k_\Sigma = -i/A_0$.

Above the threshold, the reaction rate related to $T(\Sigma N \to \Lambda N)$ term can be expressed as,

$$R^t_S \sim (k_\Sigma \sigma^t_S(\Sigma N \to \Lambda N)) = \frac{4\pi b}{(1 + k_\Sigma b)^2 + (k_\Sigma a)^2}. \tag{4}$$

Below the threshold, k_Σ is replaced by $+i|k_\Sigma|$ due to the analytic continuation, and the corresponding reaction rate is given by

$$R^t_S \sim \frac{4\pi b}{(1 + |k_\Sigma| a)^2 + k_\Sigma^2 b^2}. \tag{5}$$

3 J-PARC E90 experiment

3.1 Experimental setup

The E90 experiment will be performed at the K1.8 beamline by using the S-2S spectrometer [14] and HypTPC [15]. Figure 1 shows the schematic view of the proposed experiment. The beam K^- will be measured by using the existing K1.8 beam-line spectrometer [16]. The design value of the momentum resolution is $\delta p/p = 3.3 \times 10^{-4}$ (FWHM) with the position accuracy of 0.2 mm in rms.

The scattered π^- in the (K^-, π^-) reaction are momentum analyzed by using the S-2S spectrometer [14]. The momentum resolution of S-2S will be $\delta p/p = 6.0 \times 10^{-4}$ in FWHM. Then, the total mass resolution 0.4 MeV in σ will be achieved, which is two times better than the past experiment (HIRES at COSY [7]).

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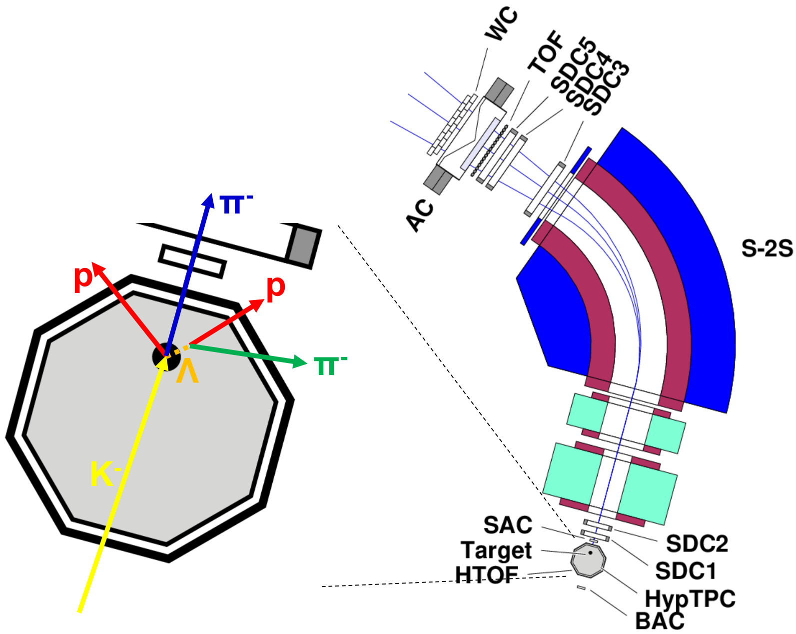

Figure 1. The schematic view of the J-PARC E90 experiment.

In this experiment, we plan to install the Time Projection Chamber (HypTPC) to suppress the quasi-free background and improve the signal-to-noise ratio by requiring the charged multiplicity, $Mt = 3$. The detailed strategy to suppress the background by using HypTPC is described in J-PARC E90 proposal [13]. The liquid deuterium target will be installed inside the TPC volume to achieve the large acceptance. We plan to use the same liquid target system as J-PARC E45 experiment [17], which concerns the baryon spectroscopy using $p(\pi^{\pm}, 2\pi)$ reaction.

3.2 Expected result

The simulated missing-mass distributions are presented in Fig. 2. Here, 3 choices of the scattering length are shown to demonstrate different shapes, namely, the theoretical values of Jülich potential–A [18], ((a), shallow bound), Nijmegen model (D ((b), deeply bound) and F ((c), sharp cusp)) [19]. Note that there is no reason to select these three models by considering theoretical justification. The points with error bars are the smeared spectra with the experimental resolution of ΔM = 0, 0.4, 1, and 2 MeV in σ shown by the different colors. In these plots, 1.4×10^4 events, corresponding to the statistics of the E90 experiment, are generated and the statistical errors are shown.

The mass resolutions of the past bubble-chamber experiments using in-flight $d(K^-, \pi^-)$ reaction were 2 MeV ("Braun" [2]) and 3 MeV ("Eastwood" [3]). As shown in Fig. 2, the original shapes are significantly distorted in the case of ΔM = 2 MeV. The high mass-resolution is really important for the "ΣN cusp". Moreover, the statistics of these past experiments were poor as 603 events ("Braun") and 217 events ("Eastwood"). By improving statics to 1.4×10^4 events and mass resolution to 0.4 MeV, we can deduce the scattering length with the statistical error $\lesssim$ 0.3 fm.

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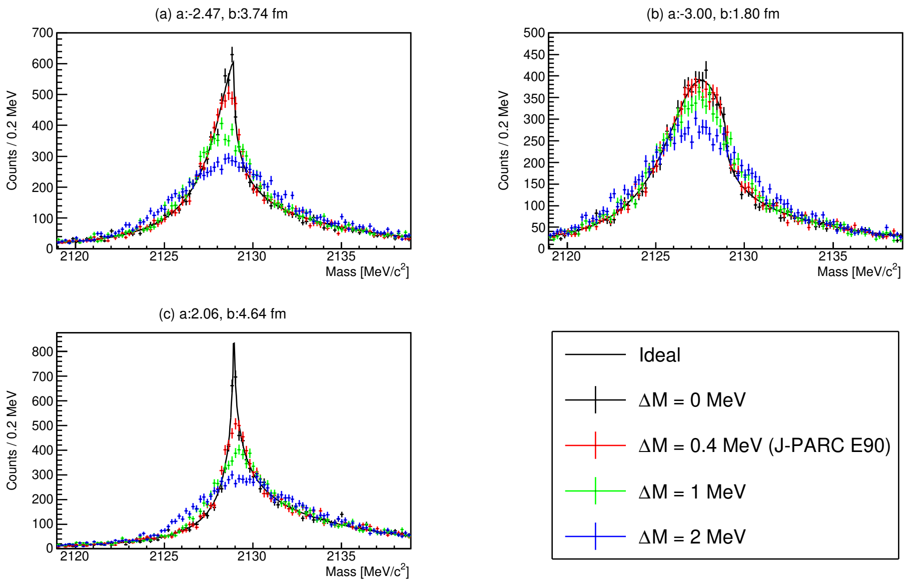

Figure 2. The simulated mass distributions for three choices of the scattering-length, which are shown in the title of the plots. The solid black-lines show the original distribution given by Eqs. (2). The points with error bars show the smeared spectra with the experimental resolution of ΔM = 0, 0.4, 1, and 2 MeV in σ and the statistic errors with 1.4×10^4 events.

4 Summary

We proposed the high resolution missing-mass spectroscopy of the "ΣN cusp" by using the S-2S spectrometer and HypTPC. The mass resolution is a quite important key to investigate the nature of "ΣN cusp". We can achieve 0.4 MeV resolution in σ, which is twice better than the past COSY HIRES experiment [7]. Moreover, the in-flight $d(K^-, \pi^-)$ reaction is unique to derive ${}^3S_1$ spin contribution with low background. By fitting the measured mass spectra, we are able to deduce the $(T = 1/2, S = 1)$ ΣN scattering length with good accuracy, statistical error of $\lesssim 0.3$ fm.

References

[1] O.I. Dahl *et al.*, Phys. Rev. Lett., **6**, 3 (1961)
[2] O. Braun *et al.*, Nucl. Phys. **B124**, 45 (1977)
[3] D. Eastwoood *et al.*, Phys. Rev. D **3**, 2603 (1971)
[4] C. Pigot *et al.*, Nucl. Phys. **B249**, 172 (1985)
[5] T.H. Tan, Phys. Rev. Lett. **23**, 395 (1969)
[6] R. Siebert *et al.*, Nucl. Phys. **A567**, 819 (1994)
[7] A. Budzanowski *et al.*, Phys. Lett. B **692**, 10 (2010)
[8] S. Abd El–Samad *et al.*, Eur. Phys. J. A **49**, 41 (2013)
[9] ALICE Collaboration, Phys. Lett. B **833**, 10 (2022)
[10] Y. Ichikawa *et al.*, Prog. Theor. Exp. Phys. **2014**, 101D03 (2014)
[11] R.H. Dalitz, Nucl. Phys. **A354**, 101, (1981)
[12] R.H. Dalitz and A. Deloff, Czech. J. Phys. **B**, 32, (1982)

[13] Y. Ichikawa *et al.*, *High resolution spectroscopy of the "ΣN cusp" by using the* $d(K^-, \pi^-)$ *reaction*, J-PARC E90 proposal,
https://j-parc.jp/researcher/Hadron/en/pac_2201/pdf/P90_2022-03.pdf
[14] T. Nagae *et al.*, *Proposal for the next E05 run with the S-2S spectrometer*,
http://j-parc.jp/researcher/Hadron/en/pac_1801/pdf/P70_2018-10.pdf
[15] S.H. Kim *et al.*, Nucl. Instrum. Meth. A **940**, 359 (2019)
[16] T. Takahashi (the Hadron Beamline Group and the K1.8 Experimental Group), Nucl. Phys. A **835**, 88 (2010)
[17] Technical Design Report of the J-PARC E45 experiment
[18] J. Haidenbauer and Ulf-G. Meißner, Phys. Rev. C **72**, 044005 (2005)
[19] K. Miyagawa and H. Yamamura, Phys. Rev. C **60**, 024003 (1999)