Study of Λ Identification Method by the $\pi^- p \to K^0\Lambda$ Reaction for a Λp Scattering Experiment at J-PARC

T. Sakao[1], J.K. Ahn[2], Y. Akazawa[3], T. Aramaki[1], S. Ashikaga[4], S. Callier[5], S.W. Choi[2], P. Evtoukhovitch[6], N. Fujioka[1], M. Fujita[1], T. Gogami[4], T. Harada[4], S. Hasegawa[7], S.H. Hayakawa[7], R. Honda[1], S. Hoshino[8], K. Hosomi[7], M. Ichikawa[4], Y. Ichikawa[7], M.Ikeda[1], K. Imai[7], Y. Ishikawa[1], S. Ishimoto[3], W.S. Jung[2], S. Kajikawa[1], H. Kanauchi[1], H. Kanda[9], B.M. Kang[2], H. Kawai[10], S.H. Kim[2], K. Kobayashi[8], K. Matsuda[1], Y. Matsumoto[1], K. Miwa[1], S. Nagao[1], R. Nagatomi[8], Y. Nakada[8], M. Nakagawa[11], I. Nakamura[3], T. Nanamura[4/7], M. Naruki[4], S. Ozawa[1], L. Raux[5], T. Rogers[1], A. Sakaguchi[8], H. Sako[7], S. Sato[7], K. Shirotori[9], K.N. Suzuki[4], S. Suzuki[3], M. Tabata[10], C.d.L. Taille[5], H. Takahashi[3], T.N. Takahashi[9], T. Takahashi[3], M. Tanaka[3], K. Tanida[7], H. Tamura[1/7], Z. Tsamalaidze[6/12], M. Ukai[3], H. Umetsu[1], T.O. Yamamoto[7], J. Yoshida[7], K. Yoshimura[13]

[1] *Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan,*
[2] *Department of Physics, Korea University, Seoul 02841, Korea,*
[3] *High Energy Accelerator Research Organization (KEK), Tokai, Ibaraki 319-1106, Japan*
[4] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan,*
[5] *OMEGA Ecole Polytechnique-CNRS/IN2P3, France,*
[6] *Joint Institute for Nuclear Research (JINR), Dubna, Russia,*
[7] *Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan,*
[8] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan,*
[9] *Research Center for Nuclear Physics (RCNP), Osaka University, Japan,*
[10] *Department of Physics, Chiba University, Chiba, Chiba, 263-8522 Japan,*
[11] *RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan,*
[12] *Georgian Technical University (GTU), Tbilisi, Georgia*
[13] *Department of Physics, Okayama University, Okayama, Japan,*

E-mail: sakao@lambda.phys.tohoku.ac.jp

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The $\pi^- p \to K^0\Lambda$ reaction is an important elementary process to produce Λ from a proton target and is a key for a Λp scattering experiment where the momentum of Λ should be tagged from the missing momentum of the (π^-, K^0) reaction. However, the (π^-, K^0) spectroscopy method has not been established yet due to the difficulty of the K^0 detection. Therefore, we have proposed a new K^0 detection method where π^+ and π^- from the K^0 decay are measured by a forward magnetic spectrometer and a detector cluster surrounding the target, respectively. The feasibility of the K^0 detection method was confirmed by analyzing the J-PARC E40 data taken with such a detector system. In the analysis, Λ's were successfully identified in the missing mass spectrum of the $\pi^- p \to K^0 X$ reaction.

KEYWORDS: Strangeness, Hypernuclear Physics, Particle Physics, J-PARC

1. Introduction

The nuclear force has been intensively studied by a lot of pp and pn scattering experiments in the wide-range energy. Meson-exchange models well reproduce the attractive potential in the long-range ($\geq$ 1 fm) region. In the short-range part, however, the nuclear force becomes quite repulsive, and it is represented as a "repulsive core." The origin of the repulsive core is still a riddle. In such a region where two nucleons overlap each other, quarks should play an essential role in forming the repulsive core. Therefore, it is crucial to study the baryon-baryon interaction in the $\mathrm{SU}_f(3)$ space by adding a strange quark [1] [2].

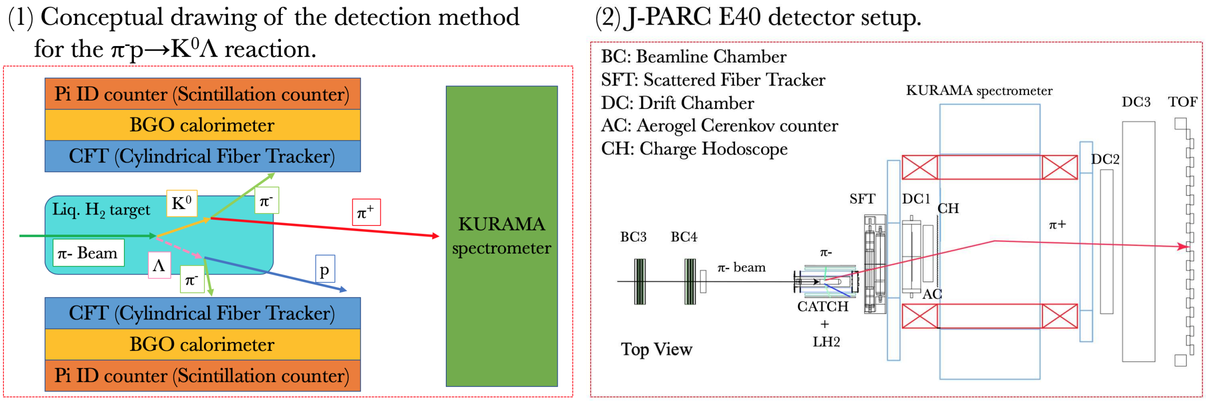
The ΛN interaction has been investigated from the hypernuclear structure by high-resolution spectroscopic studies [3]. Λ feels an attractive potential of 30 MeV in a nuclear matter. Hence, Λ is expected to appear in a deep inside of a neutron star whose density is much larger than the normal nuclear density. The appearance of Λ makes the equation of state of the neutron star quite soft and the maximum mass of the neutron star is considered to be $\sim 1.4M_\odot$ [4]. However, the observation of the specific neutron star, which is two times as massive as solar mass [5], demands the reconsideration of the role of hyperons in the neutron star because the equation of a state can not describe such massive neutron star with hyperons due to its softness. More repulsive forces are essential for the existence of the two-solar-mass neutron stars.

The repulsive force in the ΛNN three-body interaction is a candidate for such interaction [6]. In the high-density matter, the two-body ΛN interaction in the short range becomes dominant while we are short of the knowledge of the ΛN interaction in such a region as the short-range interaction cannot be extracted from the nuclear structure. Considering that, a Λp scattering experiment is necessary to derive the ΛN two-body interaction without any uncertainty originating from the nuclear structure, and to study the range dependence of the ΛN interaction by changing the Λ beam momentum. The ΛNN three-body interaction should be extracted from the precise level structure of heavy Λ hypernuclei using a theoretical calculation with the reliable ΛN interaction information which reproduces the various cross sections of the Λp scattering. One of the things we have to do to realize the Λp scattering experiment is to produce a large amount of Λ in a liquid hydrogen target. Thanks to the large production cross section, the hyperon production with K^- or π^+ beam is one of the most effective methods. In J-PARC, Λ hypernuclei are studied with the $K^- n \to \pi^- \Lambda$ and the $\pi^+ n \to K^+ \Lambda$ reactions by detecting the incoming beam and outgoing particles. In contrast, we need to use the $\pi^- p \to K^0 \Lambda$ reaction to convert p to Λ, whereas the experimental method of this reaction has not been established yet. Thus, we have proposed a new K^0 detection method where π^+ and π^- from the K^0 decay are detected by a forward magnetic spectrometer and a detector cluster surrounding the target, respectively. We report the feasibility study of the Λ identification method by the $\pi^- p \to K^0 \Lambda$ reaction in this proceeding. In the future, we will propose the Λp scattering experiment with this reaction.

2. The $\pi^- p \to K^0 \Lambda$ Reaction for a Λp Scattering Experiment

The (π^-, K^0) reaction spectroscopy, which changes p to Λ, enables us to access the neutron-rich hypernucleus that is difficult to produce by the ordinary (K^-, π^-) or (π^+, K^+) reaction. The (π^-, K^0) reaction spectroscopy also makes it possible to perform a Λp scattering experiment with a liquid hydrogen target, which can be used as the Λ production and the Λp scattering targets.

To identify Λ in the (π^-, K^0) reaction, π^+ and π^- from the K^0 decay should be measured by detectors. However, it is not straightforward to detect these two particles together due to limited spectrometer acceptance. Owing to this, we plan to detect π^+ and π^- separately by different detector systems of the forward spectrometer and the cylindrical detector cluster surrounding the target. The J-PARC E40 experiment, which is designed for Σp scattering, has such a detector setup. It consisted of the KURAMA spectrometer (a forward-magnetic spectrometer) and CATCH (a cylindrical detector for recoil proton), as shown in Fig. 1 [7] [8]. Taking advantage of that, we have analyzed the E40 data to check the feasibility of the experiment we explained above.


(1) Conceptual drawing of the detection method for the π-p→K⁰Λ reaction.

(2) J-PARC E40 detector setup.

Fig. 1. Schematic view of the $\pi^- p \to K^0\Lambda$ reaction and the E40 experimental setup.

3. Analysis of the J-PARC E40 Experimental Data

3.1 *Verification of the New Λ Production Method (Selection of the $\pi^- p \to K^0\Lambda$ Reaction)*

One of the purposes of the J-PARC E40 experiment was to study the ΣN interaction systematically by measuring various isospin channels of the $\Sigma^+ p$, $\Sigma^- p$ elastic scatterings, and the $\Sigma^- p \to \Lambda n$ conversion. Σ^-'s were produced by the $\pi^- p \to K^+\Sigma^-$ reaction with a 1.32 GeV/c π^- beam. To study the $\pi^- p \to K^0\Lambda$ reaction, we used the $\pi^- p \to \pi^+\pi^- X$ reaction events' data which were collected as the background of the Σ^- production. As previously mentioned, the E40 experimental setup consisted of the spectrometer part and the CATCH part. The details on this can be found in reference [7].
The spectrometer system has the beamline spectrometer for the momentum analysis of π^- beam, and the KURAMA spectrometer for outgoing particles, respectively. The particle identification of the outgoing particle was performed by calculating its mass from the momentum and TOF (time of flight) information. The correlation between the square of the mass and the momentum is shown in Fig. 2, where the loci corresponding to π^+, K^+ and p can be identified clearly. We selected the red box region for π^+.
CATCH has a cylindrical fiber tracker (CFT), a BGO calorimeter and a plastic scintillation counter (PiID) from the center to outside. CFT reconstructs the particle trajectory, and the BGO calorimeter measures its kinetic energy. Most of π penetrate the BGO calorimeter due to the small energy deposit. PiID detects such tracks from the hit information. The particle identification in CATCH was performed by the so-called *dE-E* method between the energy deposit in CFT and the total energy deposit in the BGO calorimeter, as shown in Fig. 3. Using this procedure, we selected the π region (the red-colored region in Fig. 3). As already explained, most of π penetrate the BGO calorimeter. In short, what we can measure for π by CATCH is not the momentum vector but the track direction without the momentum magnitude.

3.2 *The Reconstruction of the K^0 Momentum*

In the calculation of the missing mass spectrum of the $\pi^- p \to K^0 X$ reaction, the K^0 assumption for π^+ and π^- was introduced to compensate the missing information of π^- energy. Here, the origin of these two π's were assumed as the K^0 decay. Based on this assumption, the π^- momentum was determined so that the invariant mass of π^+ and π^- became equal to the K^0 mass (Fig. 4). Then, the missing mass of the $\pi^- p \to K^0 X$ reaction was reconstructed from the π^- beam momentum and the calculated K^0 momentum. For the real Λ production events, the missing mass peak corresponding to Λ could be identified, that is, this K^0 assumption is valid for such events. On the contrary, non-K^0 events made background distributions in the missing mass spectrum.

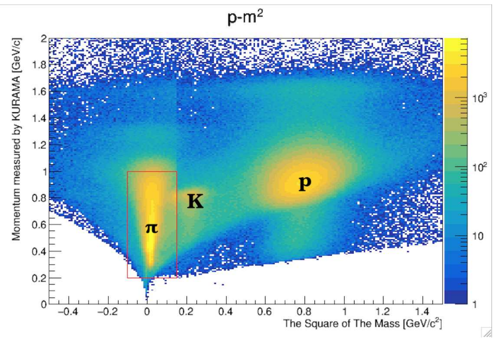


Fig. 2. Scatter plot between the square of the mass and the momentum reconstructed by the KURAMA spectrometer.

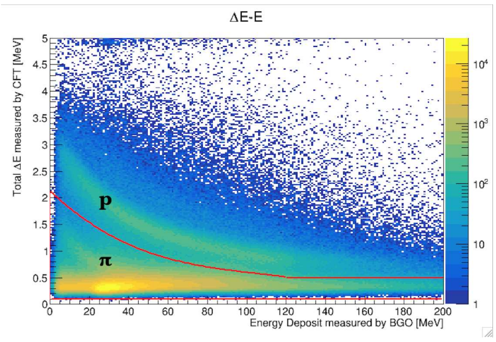


Fig. 3. *dE-E* spectrum between the energy deposit in CFT and the total energy measured by the BGO calorimeter in CATCH.

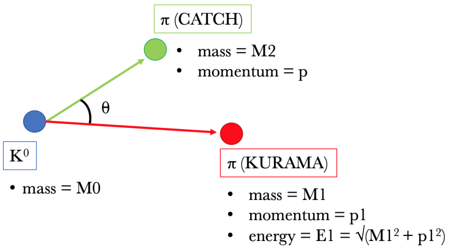


Fig. 4. Schematic view of the K^0 reconstruction with the momentum vector of π detected by KURAMA, and the opening angle θ calculated from kinematics.

3.3 *Separation between the Background and the K^0 Event*

Before checking the missing mass spectrum, we will describe the background rejection method, mainly focusing on the multiple π events without strangeness production as shown in Fig. 5.

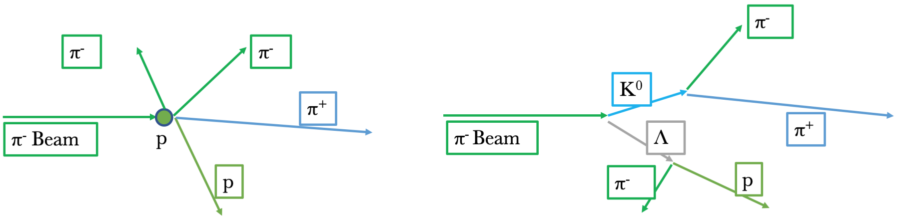


Fig. 5. Left: The main background for the $\pi^- p \to K^0\Lambda$ reaction (a multiple π production).
Right: The K^0 event we plan to measure.

What we focused on is the difference between the K^0 production point and the K^0 decay point resulting from the relatively long lifetime of K^0. In the K^0 event, the closest distance between the π^- beam and the π^+ track becomes larger depending on the K^0 flight length while the closest distance of the non-strangeness multiple π events must be zero in principle. Hence, we required that the closest distance between the π^- beam and the π^+ detected by the KURAMA spectrometer was larger than 8 mm, as shown in Fig. 6. Although this cut improved the S/N ratio (signal to noise ratio) in the missing mass spectrum, we have to keep in mind that it would have killed the short-flight-length K^0.

We adopted the same analysis method for π^- detected by CATCH. Here, the K^0 decay tracks were required not to intersect with the π^- beam. However, the reconstructed K^0 track itself has to intersect with the π^- beam at the production point. Accordingly, we required that the closest distance between K^0 and the π^- beam was less than 8 mm.

Finally, we applied a cut for the relative position between the K^0 decay point and the production point. Fig. 7 shows the simulated spectrum of the position difference of them, taking into account the detector resolution. The spectrum shows the typical K^0 flight length based on its lifetime. In the data analysis, the position difference was required to be from -20 mm to 200 mm, as shown by the red lines in Fig. 7 based on this simulation study.

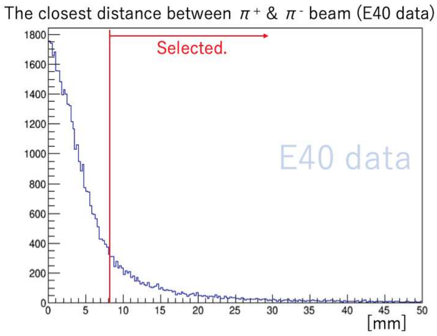


Fig. 6. The closest distance between π^+ and the π^- beam (E40 data).

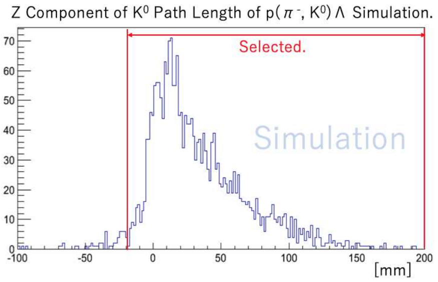


Fig. 7. The z component of the K^0 path length in the $p(\pi^-, K^0)\Lambda$ simulation.

4. The Missing Mass to Identify Λ in E40 Experimental Data

After applying these cuts stated in the last section, we obtained the missing mass spectrum of the $\pi^- p \to K^0 X$ reaction, as shown in Fig. 8. The clear peaks corresponding to Λ and Σ^0 can be found in this spectrum. The background structure under the Λ and Σ^0 peaks is attributed to the unremoved multiple π production events. From the simulation, we roughly estimated the cut efficiency is 62%. Now we are going to perform a more realistic simulation with the E40 setup to estimate the Λ yield and to understand the background structure and so on.

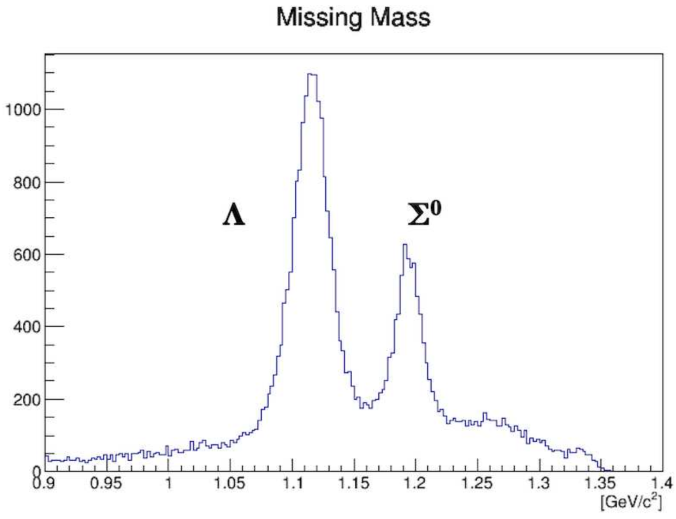


Fig. 8. The missing mass of the $\pi^- p \to K^0 X$ reaction with the proper cuts (E40 data).

5. Summary

The repulsive core in the nuclear force has not been completely understood yet in spite of its importance in forming a stable matter in the world. In such a short-range region where two nucleons overlap each other, it is necessary to study the baryon-baryon interaction with the $\mathrm{SU}_f(3)$ space, including strange quarks. Notably, the precise information on the ΛN interaction derived from the direct scattering experiment is indispensable to solve the so-called ”hyperon puzzle” of the two solar-mass neutron stars. Therefore, we need to establish a new Λ production method via the $\pi^- p \to K^0\Lambda$ reaction, which would enable us to approach a Λp scattering experiment using the produced Λ.

In this experiment, we are going to detect π^+ by the forward spectrometer and π^- by the cylindrical detector cluster surrounding the target, separately. Taking advantage of the same configuration of the J-PARC E40 setup, we checked the feasibility of the (π^-, K^0) reaction by analyzing the missing mass of the $\pi^- p \to K^0 X$ reaction.

After introducing the K^0 selection cuts, we successfully identified the Λ peak in the missing mass spectrum, which means that our K^0 reconstruction and selection methods are working correctly. On the other hand, the Λ yield decreased due to such many analytical filters. Although a realistic Λ yield should be estimated with the optimal trigger, the reconsideration of our selection and cuts is required. Besides, E40 experimental data include the large background structure lying below the Λ peak, so we are going to study this structure with the corresponding simulations.

6. Acknowledgement

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