*Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)*
JPS Conf. Proc. **26**, 023005 (2019)
https://doi.org/10.7566/JPSCP.26.023005

# Search for Excited State of $^{4}_{\Sigma}$He Hypernucleus in the J-PARC E13 Experiment

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(Received February 28, 2019)

The $\Sigma N$ interaction is not much studied than the $\Lambda N$ interaction. To understand the $\Sigma N$ interaction, we study $\Sigma$ hypernuclei. As for the $\Sigma$ hypernucleus, only the ground state of $^{4}_{\Sigma}$He has been observed. To obtain more information about the $\Sigma N$ interaction, the excited state should be studied. Therefore, we measure the missing-mass of the $^{4}$He$(K^-, \pi^-)X$ reaction at $p_{K^-}$ = 1.5 GeV/$c$ and $\theta_{\mathrm{Lab}}$ = 2-14° at the J-PARC K1.8 beam line. The ground state of $^{4}_{\Sigma}$He is observed whereas a peak of the excited states is not observed. We also observe suppression of the $\Sigma$ quasi-free process at smaller angles.

**KEYWORDS:** Strangeness, $\Sigma$ hypernuclei, $\Sigma N$ interaction, missing-mass spectroscopy

## 1. Introduction

The nucleon-nucleon interaction has been studied well. The nucleon is the lightest baryon. The next lightest baryon is a $\Lambda$ hyperon which has a strangeness quantum number $S = -1$. The $\Lambda$-nucleon interaction also has been studied. A $\Sigma$ hyperon has $S = -1$ and isospin $I = 1$ (the $\Lambda$ hyperon has $I = 0$). However, the $\Sigma$-nucleon ($\Sigma N$) interaction has not been well studied. To investigate the $\Sigma N$ interaction, there are three types of experiments. First, $X-$rays from various $\Sigma^-$ atoms have been measured [1]. Next, in $\Sigma N$ scattering experiments, it wabbs difficult to measure $\Sigma$ trajectories due to the short lifetime of $\Sigma$ ($\tau \sim 10^{-10} s$). Although it has been measured several times in the past, statistics were limited [2]. Finally, in $\Sigma$ hypernuclei production experiments, there is a possibility of systematic study with many species, however, no bound state has been observed except for ${}^4_\Sigma$He [3].

First observation of ${}^4_\Sigma$He via the ${}^4$He(stopped $K^-, \pi^-)X$ reaction was made by the KEK-PS E167 collaboration in 1989 [4]. However, a 3N+$\Sigma$ threshold cusp state could not be excluded [5]. After that, the bound state of ${}^4_\Sigma$He was confirmed via the ${}^4$He(in-flight $K^-, \pi^-)X$ reaction at $p_{K^-} = 0.6$ GeV/$c$ and $\theta_{\mathrm{Lab}} = 4°$ by the BNL-AGS E905 collaboration in 1998 [6]. Although the low beam momenta (0 and 0.6 GeV/$c$) have been used in the past experiments, we should investigate the excited state of ${}^4_\Sigma$He using higher beam momentum to understand the $\Sigma N$ interaction.

## 2. Experiment

We use liquid ${}^4$He target with a thickness of 2.7 g/cm$^2$. To measure momenta of beam kaons and emitted pions, we use the K1.8 beam line spectrometer and the SKS spectrometer system, respectively. The K1.8 beam line spectrometer consists of $QQDQQ$ magnets, two drift chambers, and a scintillating fiber tracker and has a momentum resolution of $\Delta p/p \sim 10^{-3}$. Kaons are distinguished from pions by using an aerogel Čerenkov counter in front of the ${}^4$He target. The momenta of scattering pions are measured by using the SKS spectrometer system which is composed of a superconducting dipole magnet and four drift chambers. The SKS spectrometer system has wide angle ($\theta_{\mathrm{Lab}}$ = 2-14°) and momentum ($p_{K^-} = 1.0 - 1.5$ GeV/$c$) acceptance. Emitted particles are pions, muons, and kaons. Muons come from the $K^- \to \mu\nu$ decay and vetoed by an iron block and lucite-acrylic counters. Kaons can be rejected by the beam momentum. Pions come from the $K^- \to \pi^-\pi^0$ decay and are the main component of the background events. The shape of this background distribution depends on a scattering angle. The shape will be distorted in the case of an offline-analytic rejection. To avoid distorting the spectrum, we estimate the background distrbution by Monte-Carlo simulation using the Geant4 package and subtracted the distribution from the missing-mass spectrum.

We took data in April and May 2015. The total beam time is 138 hours (corresponding to 23 G kaons). A $K/\pi$ ratio of beams is about 2. For the momentum calibration, a $\Sigma^+$ production run (the $p(K^-, \pi^-)\Sigma^+$ reaction) and beam-through runs are taken. For the $\Sigma^+$ production run, a $CH_2$ target is used. For the beam-through runs, beam momenta of 1.2, 1.37, 1.5, and 1.8 GeV/$c$ are used with or without the ${}^4$He target.

## 3. Analysis

To obtain the missing-mass spectrum of the ${}^4$He($K^-, \pi^-)X$ reaction, momenta of $K^-$ and $\pi^-$ are analyzed. For $K^-$, the momentum is analyzed using a transport matrix. For $\pi^-$, a motion of a charged particle is calculated in a magnetic field of the SKS magnet using the Runge-Kutta method. Using the four-momenta of the ${}^4$He target, $K^-$, and $\pi^-$, we calculate the missing-mass with a mass resolution of 4.5 MeV/$c^2$ (FWHM). We calibrate the relative momentum between the K1.8 beam line spectrometer and the SKS system. We also calibrate the absolute momentum using the mean value of missing-mass peaks of the $\Sigma^+$ hyperon and the ground state of ${}^4_\Lambda$He.

To evaluate our spectrometer, we obtain the $\Sigma^+$ hyperon production cross section.The cross section is 0.59 ± 0.01 $\mu$b/sr in the angular range of $\theta_{\rm Lab}$ = 2-14°. This result is in good agreement with the result of a past emulsion experiment [7].

## 4. Results and Discussion

We obtain the missing-mass spectrum of the $^4$He$(K^-,\pi^-)X$ reaction in the angular range of $\theta_{\rm Lab}$ = 2-14°. We observe a clear peak of the ground state of $^4_\Sigma$He. However, we observe no structure of the excited state. We also obtain the missing-mass spectra of the $^4$He$(K^-,\pi^-)X$ reaction every 2 degrees. At angles smaller than 10 deg, the peak of the ground state is observed and the peak of the excited state is not observed.

Our measurement shows that the ratio between the heights of the distributions of the ground state and the Σ quasi-free is about 1/2 in the range larger than 4 degrees. On the other hand, in the range of 2-4 degrees, the ratio is about 1. Suppression of the Σ quasi-free process at smaller angles (2-4 degrees) can be interpreted as follows. An elementary cross section of the Σ hyperon in the smaller angle drastically changes depending on the center-of-mass energy of kaon and nucleon in 1.5 GeV/$c$ [8]. With theoretical understanding of the Σ quasi-free process, the excited states in detail can be studied [9].

## 5. Summary

We study Σ hypernuclei to understand the $\Sigma N$ interaction. Only the ground state of $^4_\Sigma$He has been observed in the past experiments. At that time, the low beam momenta (0 and 0.6 GeV/$c$) have been used to produce the ground state. For the next step, the excited states should be studied. Thus we measure the missing-mass of the $^4$He$(K^-,\pi^-)X$ reaction using higher beam momentum (1.5 GeV/$c$) in the J-PARC K1.8 beam line. From the experimental results, the ground state of $^4_\Sigma$He is observed. However, the peak of the excited state is not observed. In addition, suppression of the Σ quasi-free process at smaller angles (2-4 degrees range) is observed. With the understanding of the Σ quasi-free process, we can extract information of the excited states in detail.

### References

[1] C. J. Batty *et al.*, Phys. Lett. B **74**, 27 (1978).
[2] J. K. Ahn *et al.*, Nucl. Phys. A **761**, 41 (2005).
[3] C. B. Dover, D. J. Millener and A. Gal, Phys. Repo. **184**, 1 (1989).
[4] R. S. Hayano *et al.*, Phys. Lett. B **231**, 355 (1989).
[5] R. H. Dalitz, D. H. Davis and A. Deloff, Phys. Lett. B **236**, 76 (1990).
[6] T. Nagae *et al.*, Phys. Rev. Lett. **80**, 1605 (1998).
[7] D. F. Kane, Phys. Rev. D **5**, 583 (1972).
[8] G. Gopal, *et al.*, Nucl. Phys. B **119**, 362 (1977).
[9] T. Harada and Y. Hirabayashi, Phys. Lett. B **740**, 312 (2015).