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Study on the baryon interaction by Ξ hypernuclear spectroscopy with the (K^-, K^+) reaction

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Abstract. We performed Ξ hypernuclear spectroscopy with the (K^-, K^+) reaction at J-PARC to investigate the ΞN interaction (J-PARC E05). A new experiment (J-PARC E70) in which a better energy resolution could be achieved is now being prepared. In this article, an analysis status of J-PARC E05 and a preparation status of J-PARC E70 are described.



1. Introduction

The strong interaction which acts between nucleons is well studied by means of scattering experiments. On the other hand, the interactions of hyperon-nucleon (YN) and hyperon-hyperon (YY) are hard to be studied by the scattering experiment due to short lifetimes of hyperons. Therefore, spectroscopy of hypernuclei have been played important roles in the investigation of the baryon interaction that includes strangeness degrees of freedom ($S < 0$). It is worth to note that a proton- Σ scattering experiment (J-PARC E40 experiment [1]) started at the Hadron Facility of the Japan Proton Accelerator Research Complex (J-PARC), and data taking will be completed in the beginning of 2020. The lightest baryon with the strangeness is the Λ ($S = -1$) hyperon, and about forty species of Λ hypernuclei have been measured [2, 3, 4] with various experimental methods [5] to investigate the ΛN interaction. In the next sector $S = -2$, information on the baryon interaction is limited due to scarce experimental data.

Successful measurements of double hypernuclei in emulsion experiments led to studies of the $\Lambda\Lambda$ and ΞN interactions [6]. However, events which were uniquely identified as specific double hypernuclei are only a few cases such as NAGARA (${}^6_{\Lambda\Lambda}\text{He}$) [7] and KISO ($\Xi^- + {}^{14}\text{N}$) [8]. Recently, a hybrid-emulsion experiment J-PARC E07 was performed at the J-PARC K1.8 beam line, and provided new experimental data of a Be double-hypernucleus (MINO) [9] and a nuclear system of $\Xi^- + {}^{14}\text{N}$ (IBUKI) [10]. Analyses of J-PARC E07 data are ongoing and more results will be provided. The emulsion experiment essentially measures the ground state energy because it analyses particle tracks from weak decay processes which take much longer time than that of deexcitation to the ground state by emitting gamma rays. In addition, the attractive strong interaction between a Ξ and a proton was observed in a two-particle correlation in a heavy-ion collision experiment at the Large Hadron Collider with ALICE [11].

There were attempts to observe a Ξ hypernucleus with a missing mass method through the (K^-, K^+) reaction at KEK, Japan [12] and at BNL, US [13]. However, no peaks were observed due to a lack of either resolution or statistics. The (K^-, K^+) missing mass spectroscopy investigates structures of Ξ hypernuclei from which detailed baryon interactions such as a spin-dependent interaction could be studied [14, 15]. Double Λ hypernuclei may also be investigated by the (K^-, K^+) missing mass spectroscopy if the coupling between ΞN and $\Lambda\Lambda$ is reasonably large [16], although a recent lattice QCD simulation at almost physical quark masses shows that the ΞN - $\Lambda\Lambda$ coupling is small [17]. In 2015, at the J-PARC K1.8 beam line [18], we performed the (K^-, K^+) missing mass spectroscopy with Superconducting Kaon Spectrometer (SKS) to search for a bound system of a Ξ^- and a ${}^{11}\text{B}$ (J-PARC E05) [19, 20]. The missing mass resolution of J-PARC E05 is the best among existing experiments. To further enhance sensitivity to Ξ hypernuclei, we newly designed and constructed a high-resolution magnet spectrometer, $S = -2$ Spectrometer (S-2S) [21]. A new Ξ -hypernuclear spectroscopy (J-PARC E70) in which we are going to use S-2S instead of SKS is now being prepared. In the present article, an analysis status of J-PARC E05 and a preparation status of J-PARC E70 are described.

2. J-PARC E05 Experiment

2.1. Goal of the Experiment

We aimed to observe a Ξ hypernucleus ${}^{12}_{\Xi}\text{Be}$ by means of the (K^-, K^+) reaction spectroscopy in the J-PARC E05 experiment. In addition, we took data of an elementary process $p(K^-, K^+)\Xi^-$ at the small K^+ scattering angle ($\theta_{K^+} \leq 20$ deg) for various incident K^- momenta ranging from 1.5 to 1.9 GeV/c.

2.2. Experimental Conditions and Expected Mass Resolution

The J-PARC E05 experiment was performed at the J-PARC K1.8 beam-line combined with the SKS spectrometer in Oct–Nov, 2015. Momenta of incident K^- s at $p_{K^-} \simeq 1.8$ GeV/c were analyzed event by event by the K1.8 beam-line spectrometer with a precision of $\Delta p/p_{K^-} \simeq$

1×10^{-3} FWHM. The beam intensity was about 6×10^5 K^- per spill with a 2.2 seconds beam-duration in a cycle of 5.52 seconds. The Main Ring (MR) power was 39 kW. The ratio of the number of K^- to that of π^- on a target was about 0.8 thanks to two electrostatic separators. Experimental targets were natural carbon (^{nat}C) and polyethylene (CH_2), and their thicknesses were 9.36 and 9.54 g/cm^2 , respectively. Ξ production from protons in the polyethylene target was used for the energy calibration as well as for the study of the elementary process. Generated K^+ s were momentum-analyzed by SKS with a precision of $\Delta p/p_{K^+} \simeq 3 \times 10^{-3}$ FWHM. Particle angles are needed as well as particle momenta in order to reconstruct the reaction missing mass, and we used drift chambers for the angle measurement. Consequently, resolutions of resulting missing masses were estimated to be about 5.1 and 6.0 MeV/c^2 (FWHM) for Ξ^- and $^{12}_{\Xi}\text{Be}$, respectively. In preliminary missing mass spectrum of Ξ^- , the mass resolution turned out to be 5.4 MeV/c^2 FWHM which is fairly consistent with what we expected. Therefore, the mass resolution for the Ξ hypernucleus production would also be similar to what we estimated.

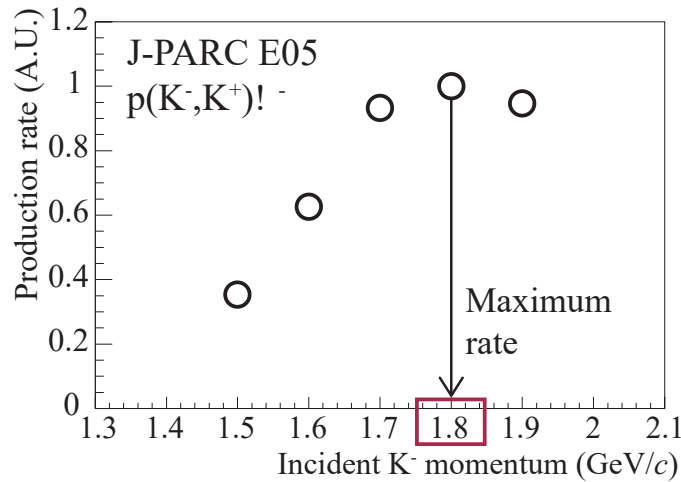


Figure 1. Preliminary result about the production rate of Ξ^- from the proton target as a function of incident K^- momentum. The K^+ scattering angle was averaged over the SKS acceptance ($\theta_{K^+} \leq 20$ deg) for each data point. Statistical errors are within the size of markers.

2.3. Preliminary Results

Figure. 1 shows a preliminary result about the production rate of Ξ^- from the proton target as a function of incident K^- momentum. The angular acceptance of SKS was about $\theta_{K^+} \leq 20$ deg, and each data point was obtained by averaging over the SKS angular acceptance. The statistical error on each data point is within the size of each marker, and the uncertainty is much smaller than that of old bubble chamber experiments [22]. It was found that the production rate is maximum at $p_{K^-} = 1.8$ GeV/c in the range of 1.5–1.9 GeV/c . We briefly analyzed the polyethylene data during the experiment, and we obtained the same conclusion. Therefore, we chose the incident momentum at $p_{K^-} = 1.8$ GeV/c for the production of Ξ hypernuclei in the experiment. It is noted that the angular dependence of the elementary process is under analysis as well.

A preliminary spectrum of $-B_{\Xi}$ ($= M_X - [M(^{11}\text{B}) + M(\Xi^-)]$) for the $^{12}\text{C}(K^-, K^+)^{12}_{\Xi}\text{Be}$ reaction is shown in the Fig. 2. The region of our main interest is a bound region ($-B_{\Xi} \leq 0$) where a few tens of events exist. Statistics in the bound region is similar to that obtained in the previous BNL experiment [13], while the missing mass resolution was improved by a factor of more than two. Not only events in the bound but also the shape of quasi-free Ξ (events in unbound region; $-B_{\Xi} > 0$) would be useful to extract information of the ΞN interaction [23].

Analyses of the bound and the quasi-free regions for the carbon target as well as that of the elementary production are in progress.

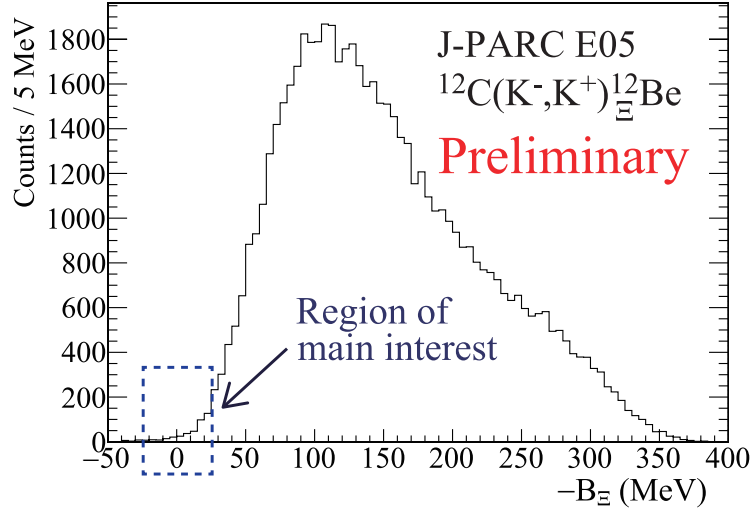


Figure 2. Preliminary spectrum of the $^{12}\text{C}(K^-, K^+)_{\Xi}^{12}\text{Be}$ reaction.

3. J-PARC E70 Experiment

3.1. Goal of the Experiment

The J-PARC E70 experiment aims to observe peak structures of ^{12}Be by the (K^-, K^+) missing mass spectroscopy. A goal energy resolution is $\Delta B_{\Xi} \leq 2$ MeV (FWHM) which is about three times better than that of J-PARC E05.

3.2. Experimental Setup

Incident K^- s at the central momentum of $p_{K^-} = 1.8$ GeV/ c will be transported to an experimental target by the J-PARC K1.8 beam line. By the time of experiment, the MR power is expected to be increased up to about 85 kW which would lead to the K^- intensity of about 9.5×10^5 K^- per spill (spill cycle may be shortened to 4.7 sec). We are going to use S-2S for a K^+ detection instead of SKS which was used for the J-PARC E05 experiment. S-2S that was designed to achieve $\Delta p/p = 6 \times 10^{-4}$ (FWHM) at the central momentum of $p_{K^+} = 1.37$ GeV/ c consists of two quadrupole magnets and one dipole magnet (QQD configuration) [24]. S-2S has smaller R11 (magnification; $\langle x|x \rangle$) and R12 ($\langle x|\theta \rangle$) terms as well as a larger R16 term (dispersion; $\langle x|p \rangle$) compared to those of SKS. Therefore, S-2S could achieve the better momentum resolution than SKS, although the solid angle of S-2S ($\Omega \simeq 55$ msr at the central momentum) is smaller by a factor of about two. A successful example of the QQD spectrometer to achieve a momentum resolution $\Delta p/p$ of an order of 10^{-4} (FWHM) for K^+ s at $p_{K^+} > 1.0$ GeV/ c is High resolution Kaon Spectrometer (HKS) [25, 26]. HKS was used for Λ hypernuclear spectroscopy with the $(e, e'K^+)$ reaction at the Thomas Jefferson National Accelerator Facility, US [27, 28]. Particle detectors between the experimental target and the S-2S magnets will be two layers of drift chambers for a particle tracking. At a downstream of the S-2S magnets, there will be three layers of drift chambers for the particle tracking, one layer of time-of-flight (TOF) detector for a timing measurement, and two types of Cherenkov detectors (radiation media of aerogel and pure water; refraction indices of 1.05 and 1.33, respectively) for a K^+ identification under a huge amount of background hadrons consisting of π^+ s and protons. The condition of S-2S trigger will be: $\text{TOF} \otimes \overline{\text{AC}} \otimes \text{WC}$ where TOF, AC and WC represent hit conditions in the TOF, aerogel and water Cherenkov detectors, respectively [24]. The expected trigger rate is less than a hundred counts per spill.

We will introduce an active fiber target (AFT) [29] as the experimental target in order to increase statistics of Ξ hypernuclei in a given beam time while maintaining the energy resolution of about 2-MeV FWHM. The energy straggling of particles in a target material becomes larger as the target thickness is thicker. For example, the effect of the energy straggling from a 9-g/cm² carbon target is expected to be about 3-MeV FWHM in a resulting missing mass spectrum. The purpose of AFT is to measure the energy loss of each particle event by event. The information of the measured energy loss will be used for a missing mass correction to avoid a resolution deterioration due to the energy straggling effect in the target. AFT consists of about nine-hundreds scintillation fibers (Saint-Gobain BFC-10, ϕ 3 mm, single clad) which are light-coupled to Multi-Pixel Photon Counters (MPPC, Hamamatsu S13360-3075PE) at both edges. VME EASIROC modules [30] are used to supply powers to MPPCs as well as to read MPPC signals. One set consists of $xx'yy'$ layers, and nine sets are combined in total.

3.3. Preparation Status

All of S-2S magnets have been constructed and a magnetic field for each magnet was measured at KEK. A magnetic field map for a whole volume where scattered particles pass through is needed to analyze momenta of particles. However, the field measurement was done for a limited volume with finite steps. Therefore a magnetic field map is generated by a calculation software Opera3D (TOSCA) to be used for the particle-momentum analysis. A TOSCA model of S-2S was optimized to make magnetic field at reference points consistent with that of the field measurement. The S-2S momentum resolution was evaluated with a Monte Carlo simulation taking into account a deviation of the TOSCA field from the measured field. As a result, it was found that S-2S could achieve the goal resolution of $\Delta p/p = 6 \times 10^{-4}$ FWHM [31]. The S-2S magnets are ready to be installed in the experimental area at Hadron Facility of J-PARC.

The TOF detector was tested by cosmic rays, and a time resolution was obtained to be $\sigma = 90$ ps which is good enough to separate K^+ s from background π^+ s and protons. The drift chambers are going to be commissioned by using cosmic rays. We will use the existing aerogel Cherenkov detector that was used as a π^+ veto counter in the SKS experiments. The water Cherenkov detector was newly designed and developed for S-2S [24]. Components of the water Cherenkov detector such as PMTs and water containers are already purchased, and a mass production will be done soon. PMTs (Hamamatsu H11284-100UV) used for the water Cherenkov detector will be installed only about 2.5 m away from an exit of the S-2S dipole magnet. Therefore, there is non-negligible stray magnetic field in parallel to the PMT axis of the water Cherenkov detector, although a field shield was attached right after the dipole exit. It was found that there is about 4.5 G around the PMTs when the S-2S dipole magnet is excited at 2500A ($B_y \simeq 1.5$ T in the gap), and the stray field of 4.5 G in parallel to the PMT axis reduces a gain of the PMT by 60%. In order to avoid the PMT gain reduction, we are going to implement bucking coils on the PMTs [32]. We carried out a test of the PMT gain recovery with the bucking coil in an uniform magnetic field that was generated by a Helmholtz coil. As a result, it was found that a 20-turn bucking coil with a current of 4.5A is able to fully recover the PMT gain against a 5-G magnetic field [19]. A prototype AFT that has three sets of $xx'yy'$ layers (1/3 of channels of the real version) is now being constructed. The prototype AFT will be tested at the GeV- γ Experimental Room of ELPH, Tohoku University, Japan [33] in November 2019 (ELPH experiment No. 2917).

In the 28th J-PARC PAC meeting (2019), the J-PARC E70 experiment has been approved to be on Stage 2 which is the final stage to perform an experiment at J-PARC. We are preparing the experiment aiming to have a beam time in 2021.

4. Summary

The ΞN interaction could be studied through spectroscopy of Ξ hypernuclei. We performed the missing mass spectroscopy of Ξ hypernuclei via the (K^-, K^+) reaction at J-PARC K1.8 beam line in 2015 (J-PARC E05). J-PARC E05 has the best missing mass resolution among the existing experiments, and data analyses are in progress. To enhance a sensitivity to Ξ hypernuclear signals, a new magnetic spectrometer S-2S was designed and constructed. In the experiment with S-2S (J-PARC E70), the energy resolution is expected to be FWHM ≤ 2 MeV which is about three times better than that of J-PARC E05. We are now preparing the experiment aiming to have a beam time in 2021.

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