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High resolution spectroscopy of Ξ hypernuclei with active fiber target

Takeshi K. Harada[1, 2*], *K.* Ebata[1, 2], *T.* Gogami[1], *S. H.* Hayakawa[3], *R.* Honda[4], *Y.* Ichikawa[2], *K.* Miwa[3, 4], *T.* Nagae[1], *T.* Nanamura[1, 2], *T.* Takahashi[4], *M.* Ukai[4] and *T. O.* Yamamoto[2], for the J-PARC E70 collaboration

[1]Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
[2]Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan
[3]Graduate School of Science, Tohoku University, Sendai, Miyagi 982-0826, Japan
[4]Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

Abstract. We are planning to carry out a high-resolution spectroscopy of Ξ hypernucleus at the J-PARC K1.8 beamline, which provides a high-intensity K^- beam (J-PARC E70 experiment). The high-resolution spectroscopy aims to be realized by introducing a new magnetic spectrometer S-2S and an active fiber target AFT. In this article, the role of the AFT in this experiment and its development status are described.

1 Introduction

Recently, a few Ξ-hypernuclear events have been reported from emulsion experiments [1–4], and they allow us to study the baryon-baryon interaction for the strangeness $(S) = -2$ systems. As a result, the Ξ-nucleus interaction is found to be attractive. The ΞN interaction is studied by various theoretical models such as the mean-field theory [5], based on the observed Ξ hypernuclei from the emulsion experiments. However, there is still a large statistical uncertainty, and further experimental information is desired. A Ξ-hypernuclear production was investigated by missing-mass spectroscopy at KEK [6], BNL [7] and J-PARC [8] in the past. In these experiments, signals were observed in the bound region of the Ξ hypernuclei, but the peak structures were not clarified due to insufficient missing-mass resolution. Therefore, more precise spectroscopic experiments with higher signal sensitivity are needed.

2 J-PARC E70 experiment

We are going to perform a high-resolution spectroscopy of Ξ hypernucleus in a missing-mass method via the (K^-, K^+) reaction (J-PARC E70 experiment). The experiment will be

* e-mail : harada.takeshi.24e@st.kyoto-u.ac.jp

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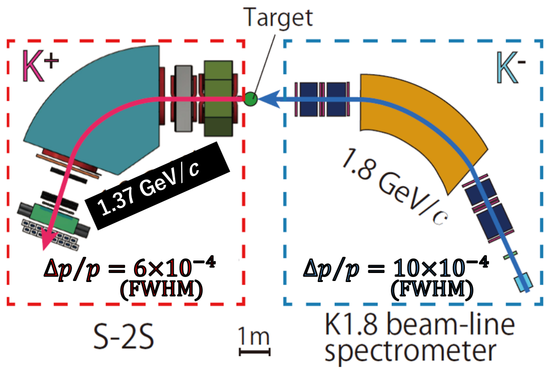

Fig. 1. Experimental setup of the J-PARC E70 experiment.

carried out at the J-PARC K1.8 beamline, which provides a high-intensity K^- beam. The experimental setup is shown in Fig. 1. The momentum of the incident K^- and scattered K^+ particles will be analyzed using the K1.8 beamline spectrometer ($\Delta p/p = 10 \times 10^{-4}$ (FWHM)) and the S-2S spectrometer ($\Delta p/p = 6 \times 10^{-4}$ (FWHM)), respectively. S-2S is a new magnetic spectrometer. An active fiber target (AFT) will be used as an experimental target with a thickness of about 9 g/cm^2. The expected yield and missing-mass resolution are about 100 counts and 2 MeV/c^2 (FWHM), respectively. The resolution of 2 MeV/c^2 (FWHM) is achievable by a correction of the energy losses of particles by AFT as shown in the next section.

3 Active fiber target

K^- and K^+ which are related to the Ξ-hypernuclear production lose their energies in AFT. The energy straggling due to the energy loss deteriorates the missing-mass resolution. AFT directly measures the energy losses event by event. The energy-loss information obtained by AFT is then used to correct the particles' momenta event by event, leading to a large suppression of the missing-mass deterioration. Therefore, AFT is a key detector to achieve the high resolution of 2 MeV/c^2 (FWHM), maintaining the significant statistics from such a thick target (9 g/cm^2) in J-PARC E70.

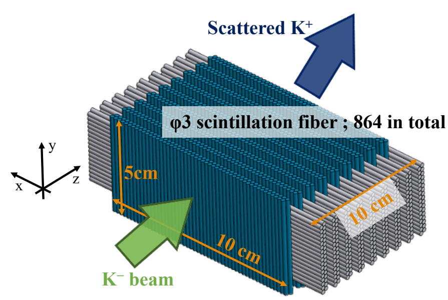

Fig. 2. Schematic drawing of AFT in J-PARC E70. AFT directly measures the energy losses of K^- and K^+ which are related to the Ξ-hypernuclear production event by event.

AFT is composed of about 900 scintillation fibers (Saint-Gobain BCF-10SC, ϕ3 mm), and the carbon nuclei contained in the scintillation fibers are used as the target nuclei to produce $^{12}_{\Xi}$Be hypernuclei. Fig. 2 shows a conceptual drawing of the AFT. The direction of the incident K^- beam is the z-axis and the fibers are arranged orthogonally to it (XX'YY'). The dimension is $5^H \times 10^W \times 10^T$ cm^3, designed to cover the beam area. The energy loss of the charged particles in AFT is converted into a scintillation light. The scintillation light is detected by Multi-Pixel Photon Counters (MPPC, Hamamatsu S13360-3075PE) attached to both ends of each fiber. Therefore, the total number of channels is up to 1800. Electrical signals induced by the MPPC are readout by VME-EASIROC modules. AFT enables us to directly measure the energy loss of $K^{\pm}$ particles in the target event by event because the yield of scintillation light is proportional to the energy loss. The energy loss measured by AFT is used as a correction when the missing mass is calculated in analyses. As a result, the target missing-mass resolution of 2 MeV/c^2 (FWHM) is expected to be achieved.

3.1 Evaluation test of energy resolution at RCNP

We performed an evaluation test of energy resolution at RCNP, Osaka University in 2017 using a detector (AFT-proto1) which consisted of a scintillation fiber, MPPCs, and EASIROC [9]. Proton beams at the energies of E = 64.6 and 295 MeV were irradiated onto the single fiber. The energy loss in the fiber was measured by a high-resolution spectrometer, Grand Raiden. Fig. 3 shows the obtained energy resolution of the detector (AFT-proto1) as a function of the energy loss measured by Grand Raiden. In J-PARC E70, a required energy resolution is $\sigma(\mathrm{E})/\mathrm{E} \leq 10\%$ for the energy loss of 0.6 MeV which is a typical energy loss in a fiber. It was found that the resolution is less than or about 10% for the energy loss of 0.6 MeV as shown in Fig. 3. Fig. 4 shows simulated binding-energy spectra with and without the AFT correction based on the result of the above beam test. The energy resolution gets better from 4.1 to 2 MeV in FWHM thanks to the correction by AFT.

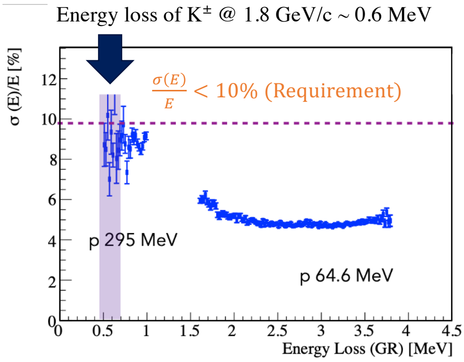

Fig. 3. Obtained energy resolution of detector (AFT-proto1) as a function of the energy loss which was measured by Grand Raiden at RCNP.

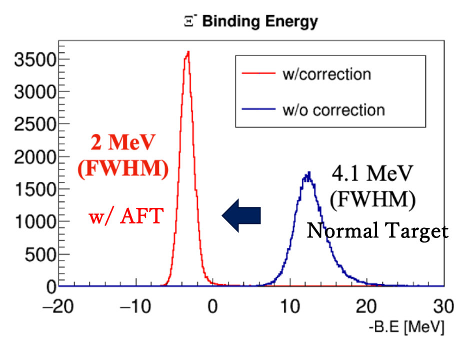

Fig. 4. Simulated spectra for the Ξ-binding energy for the $^{12}\mathrm{C}(K^-,K^+)^{12}_{\Xi}\mathrm{Be}$ reaction. The energy resolution is improved to 2 MeV from 4.1 MeV (FWHM) by the correction using AFT.

3.2 Multi-channel readout test at ELPH

A prototype (AFT-proto2) with a total of about 600 channels, which is 1/3 of the actual AFT, was built (Fig. 5). AFT-proto2 was tested to establish a multi-channel readout system at ELPH, Tohoku University in 2019 [10]. In the beam test, a positron beam at the momentum of 800 MeV/c was impinged on the prototype. AFT-proto2 was sandwiched by fiber trackers (SST) that had a better position resolution than the prototype. The efficiency of AFT-proto2 was analyzed by using a tracking information by the two SSTs. As a result, it was found that the efficiency is more than 95%, which meets our requirement. In addition, the system of multi-channel readout was found to work well.

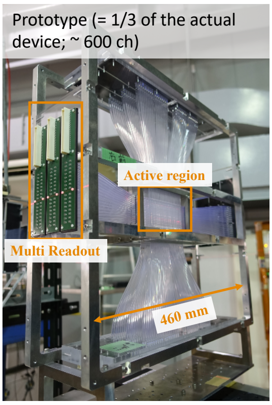

Fig. 5. A photograph of AFT-proto2 tested at ELPH, Tohoku University in 2019.

The successful result allowed us to develop AFT which has three times more channels than AFT-proto2.

3.3 Simulation of pileup effect

Electrical signals output from the MPPC are input to the EASIROC chip in VME-EASIROC for shaping and amplification. The time constant for the signal shaping and amplification is 2 μs. A resolution of ADC, which corresponds to the energy loss information in fibers, could be deteriorated due to pileups of the signals. Particularly, the fibers at the center of AFT may suffer from high rates because the particle density is higher at the beam center. We performed a simulation, in which typical waveforms were taken into account, to evaluate the missing-mass deterioration due to the signal pileup. As a result, the missing-mass resolution may become 3 MeV/c^2 in FWHM which is worse than our goal resolution. Therefore, we also simulated a case of TOT (Time Over Threshold) instead of ADC for the energy-loss analysis. TOT should have a less effect for the signal pileup because it has a short time constant. It was found the TOT analysis allows us to achieve 2.4 MeV/c^2 resolution (FWHM) in a resulting missing-mass spectrum. The simulation result is in a scope of our goal resolution.

4 Summary

We are planning to perform a high-resolution spectroscopy of Ξ hypernucleus at the J-PARC K1.8 beamline with a high intensity K^- beam (J-PARC E70). The missing mass of the Ξ hypernucleus is reconstructed by using the K1.8 beamline spectrometer and the new spectrometer, S-2S. In J-PARC E70, AFT is a key detector to achieve the high resolution of about 2 MeV (FWHM), maintaining a reasonable yield of 100 counts from a thick target material. Prototypes of AFT were tested by using proton and positron beams at RCNP and ELPH, respectively. The successful beam tests for the prototypes allowed us to develop a full scale AFT. AFT is now being constructed and is going to be installed by the end of 2022. A simulation study in which AFT is used for the missing-mass reconstruction was performed. As a result, it is found that a missing-mass resolution of 2.4 MeV/c^2 (FWHM) is reachable by using AFT. The AFT simulations are ongoing to find better ways of analyses.

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