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Spectroscopic study of Kaonic nuclei using inclusive and exclusive $^{12}\mathrm{C}(K^-, p)$ reaction at J-PARC

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The J-PARC E05 experiment investigated the interaction between $\overline{K}$ and the residual nucleus via an inclusive $^{12}\mathrm{C}(K^-, p)$ spectrum, revealing real and imaginary $\overline{K}$-nucleus optical potential depths of $(-80, -40)$ MeV. Moreover, an event excess near 100 MeV in the $\overline{K}$ binding energy suggests a bound state involving an excited hyperon (Y^*). A subsequent experiment, J-PARC E42, utilized the same reaction with a GEM-based HypTPC around the target. The exclusive measurement with HypTPC enhances the signal-to-noise ratio and enables the detection of the Y^* nuclear state. The inclusive spectrum obtained in the E05 was reproduced also through the E42 analysis, and the analysis of particle identification and momentum measurement with HypTPC is in progress for the coming exclusive analysis.

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1. Introduction

1.1 $\Lambda(1405)$ and $\overline{K}NN$ bound system

Recently, interactions between $\overline{K}$ and nucleons have been actively investigated from both theoretical and experimental perspectives. Theoretically, it has been suggested that the formation of a molecular-like quasi-bound state, $\Lambda(1405)$, arises from the strong $\overline{K}\,N$ attraction in the isospin singlet channel. Experimentally, the lightest Kaonic nucleus called K^-pp was observed at J-PARC [1], indicating a significantly attractive interaction between K^- and N. It is also significant to investigate binding energy and decay width of heavier Kaonic nuclei across a wide range of mass numbers for understanding of many-body system of $\overline{K}$ and nucleons and also of the potential presence of $\overline{K}$ within the inner core region of neutron stars [2].

1.2 Many-body bound system of $\overline{K}$ and nucleons

A heavier Kaonic nucleus was also studied using ^{12}C(K^-, p) reaction in the J-PARC E05 experiment. This experiment studied the interaction between $\overline{K}$ and the core nucleus by measuring an inclusive ^{12}C(K^-, p) spectrum as shown in Fig. 1 (a) [3]. This figure shows the double differential cross section as a function of the K^- binding energy, B_K, with the forward scattering angle selection in the laboratory frame as $3.5° < \theta_{Kp} < 4.5°$. The inclusive spectrum is compared with the calculated spectrum of the optical potential between K^- and the core nucleus shown in green dotted line in this figure. The spectrum shape near the threshold, $B_K \sim 0$ MeV, was best reproduced with the potential depths $V_0 = -80$ MeV (real part) and $W_0 = -40$ MeV (imaginary part). In addition, a significant event excess was observed in the deeply bound region around $B_K \sim 100$ MeV as shown in Fig. 1 (b). The excess fits well with a Breit-Wigner function whose binding energy is 90 MeV and width is 100 MeV, which suggests a possible contribution from a bound state between an excited hyperon (Y^*) and a nucleus.

It is possible to measure the excess region as a clear bump structure using the dataset of an experiment called E42 which was recently conducted at J-PARC, which aims to access various topics including the Kaonic nucleus search. The E42 experiment used the same reaction as the E05, ^{12}C(K^-, p). We used a GEM-based Time Projection Chamber, HypTPC, installed around the target to measure the decay particles. The exclusive measurement helped improve the signal-to-noise ratio and allowed us to detect the Y^* nuclear state as a clear bump structure.

2. Kaonic nucleus search via exclusive ^{12}C(K^-, p) reaction (J-PARC E42)

2.1 J-PARC K1.8 beamline

We performed the E42 experiment using the HypTPC at the J-PARC K1.8 beamline. J-PARC, or Japan Proton Accelerator Research Complex, provides a high-power ($\sim$ 55 kW) and high-energy ($\sim$ 30 GeV) primary proton beam. The secondary K^- beam is produced on the primary target T1 (66 mm thick Au) by the primary proton beam and delivered to the K1.8 experimental area in the Hadron Experimental Facility, where we can use high-intensity ($\sim 10^7$ Hz), high-momentum (1.8 GeV/c), and high-purity ($K/\pi \sim 1$) Kaon beam.

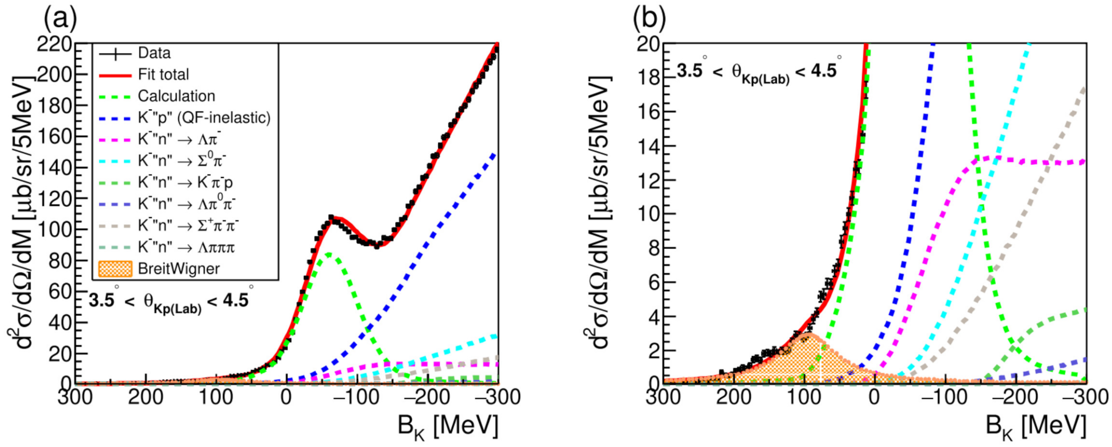

Figure 1: (a) Double differential cross section as a function of the K^- binding energy, B_K with the range of the forward scattering angle in the laboratory frame selected to be $3.5° < \theta_{Kp} < 4.5°$. The inclusive spectrum (black points with error bars) is drawn with some colored lines of template-fit results, where green dotted line shows the $K^- p \longrightarrow K^- p$ quasi-elastic process calculated with the optical potential between K^- and the core nucleus, and the other colors show the other processes. (b) Enlarged view of (a) for around 0 MeV. The figure is taken from Ref. [3].

2.2 J-PARC E42 experiment

Figure 2 shows the experimental setup at the K1.8 beamline of J-PARC. The incident K^- beam is analyzed using a magnetic spectrometer, the K1.8 beam line spectrometer. Outgoing particles are analyzed using the downstream spectrometer (KURAMA spectrometer). We used 6.5 g/cm^2 of diamond as the experimental target. The Hyperon Spectrometer is composed of the HypTPC and the Superconducting Hyperon Magnet installed around the target. The HypTPC is a GEM-based time projection chamber shown in Fig. 2, that has large acceptance ($\sim 4\pi$), high-rate capability ($\sim 10^6$ Hz), and high momentum resolution ($\sigma \sim 1$ MeV$/c$), which enables exclusive measurement of decay particles at the same time as the inclusive measurement. The inclusive spectrum observed in the previous E05 experiment can be measured in the E42 experiment. Note that the K^- beam momentum of E42 experiment is the same as in the E05 experiment, 1.8 GeV$/c$. Additionally, we can also measure decay particles using the HypTPC system to suppress the background reaction.

2.3 Analysis

2.3.1 KURAMA spectrometer for the forward scattered particles

Figure 3 shows a correlation between momentum (P) and charge × squared mass (qM^2) of the scattered particles measured in the KURAMA spectrometer. The momentum P was calculated using the Runge-Kutta method for scattered particles, while the charge q was determined by the bending angle of particle tracks. The squared mass M^2 was calculated using the information of P and Time-of-Flight. The figure shows the correlation in ^{12}C(K^-, p) reaction, and we can confirm

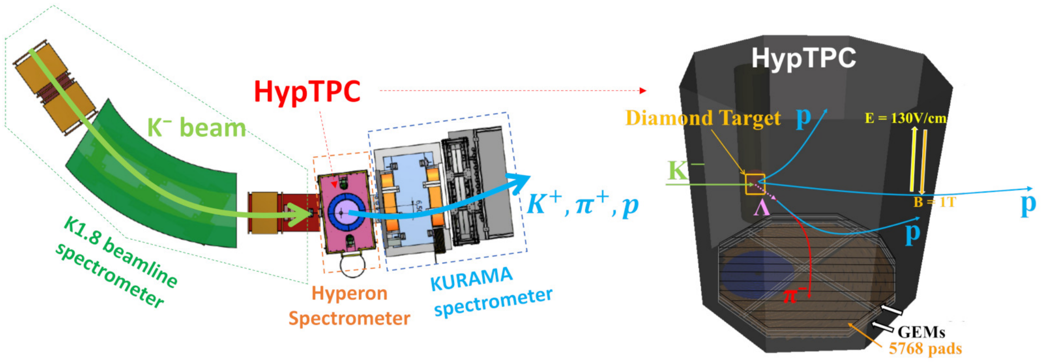

Figure 2: (Left) Experimental setup at the K1.8 beamline of J-PARC. (Right) Detailed view of HypTPC.

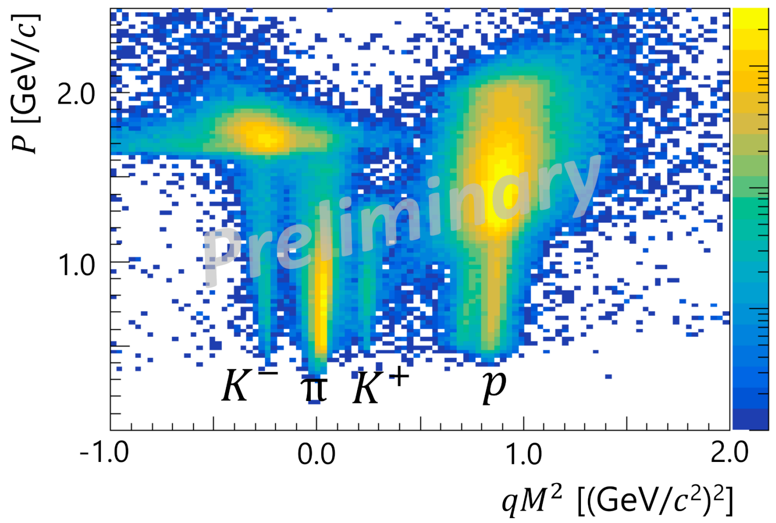

Figure 3: The correlation between momentum and charge times squared mass for the scattered particles detected with KURAMA spectrometer.

the structure of $p, \pi^\pm, K^\pm$. We used the mass square for selecting the scattered protons in the following missing mass analysis.

2.3.2 Missing mass and K^- binding energy

The missing mass, M_X, of the ^{12}C$(K^-, p)X$ reaction is reconstructed as

$$M_X = \left\{ (E_K + M(^{12}\mathrm{C}) - E_p)^2 - \left(P_K^2 + P_p^2 - 2P_K P_p \cos\theta_{Kp} \right) \right\}^{1/2}, \tag{1}$$

where $E_{K(p)}$ and $P_{K(p)}$ are the energy and momentum of the beam K^- (the scattered proton) in the laboratory frame, $M(^{12}\mathrm{C})$ is the mass of the target ^{12}C, and θ_{Kp} is the scattering angle of the

(K^-, p) reaction. The K^--binding energy, B_K, is written as

$$B_K = M(^{11}\text{B}) + M_K - M_X, \tag{2}$$

where $M(^{11}\text{B})$ and M_K are the masses of the core nucleus and K^- respectively.

The inclusive spectrum shape obtained from the E42 experiment is compared with that of the E05 experiment as shown in Fig. 4 (a). Here, the E05 spectrum is scaled because the E42 spectrum is a count-based histogram. The same scattering angle range , $3.5° < \theta_{Kp} < 4.5°$, was selected for the comparison. Here the E42 spectrum represents approximately 10% of the entire dataset. The E42 spectrum looks inconsistent with the E05 spectrum because the energy resolution in E05 and E42 experiments is different. Figure 4 (b) compares the E42 spectrum with the E05 spectrum which is further smeared with the energy resolution of E42. We found that the two spectra appear to be consistent with each other for the most part, while the slight differences in the spectra in the large region of $-B_K$ are attributed to comparing the count-based spectrum and cross-section-based spectrum and momentum dependence of the energy resolution.

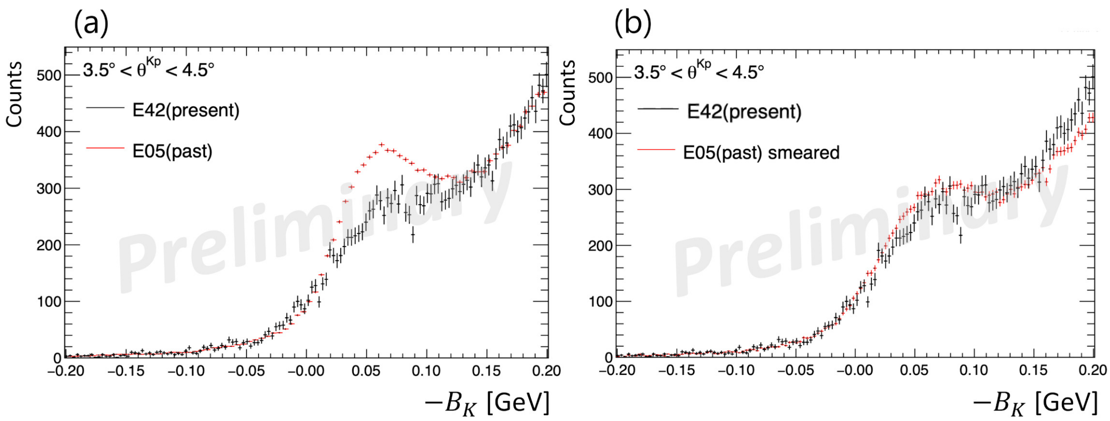

Figure 4: The comparison of inclusive spectra via the ^{12}C(K^-, p) reaction between of E42 (black) and E05 (red). In (a), the E05 spectrum is just scaled to be matched with that of E42 but in (b) the spectrum is scaled and smeared with the energy resolution of E42.

2.3.3 Hyperon spectrometer for decay particles

Further exclusive analysis requiring decay particles in the HypTPC is currently in progress. Figure 5 shows the correlation between momentum and energy deposit of decay particles measured in the HypTPC. This information on the decay particles makes it possible to reconstruct produced hyperons such as Ξ and Λ. We will study the event excess observed in the E05 experiment by reconstructing the exclusive spectra through specific decay channels.

3. Summary

The event excess observed via the ^{12}C(K^-, p) reaction can be accessed as a clear bump structure using the dataset of the the E42 experiment. The exclusive measurement with HypTPC

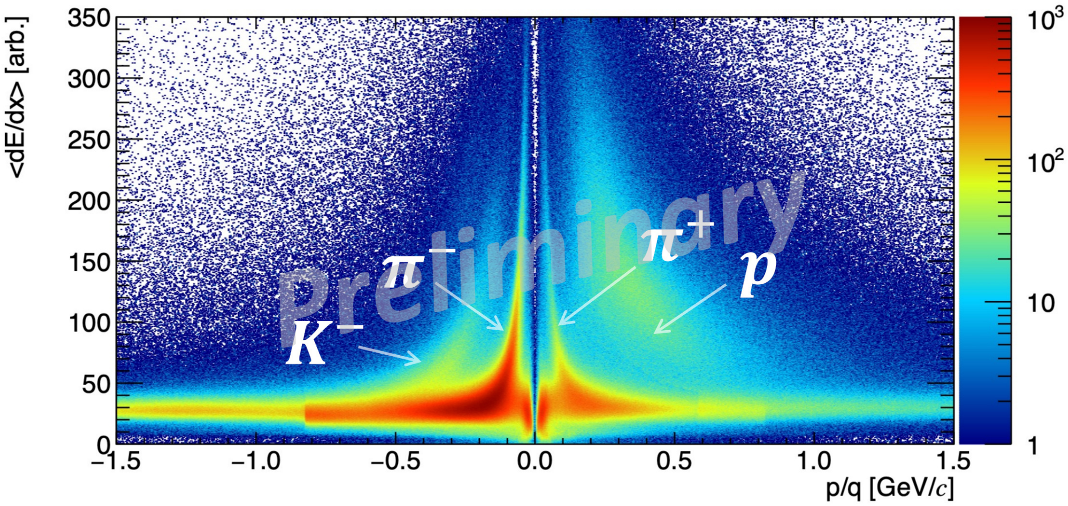

Figure 5: The correlation between energy deposit and momentum over charge of decay particles measured in the HypTPC.

helped to improve the signal-to-noise ratio and allowed us to detect the Y^* nuclear state as a clear bump structure. We have checked the consistency of the inclusive spectra obtained in the E05 and E42 experiments. Further analysis of decay particles in the HypTPC is underway, and it was confirmed that decay particles can be identified with the HypTPC. The information on the particle identification and momentum makes it possible to reconstruct produced hyperons and approach the event excess through specific decay channels.

References

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