Production of double-strangeness systems near the threshold in the ^{12}C(K^-, K^+) reaction at 1.8 GeV/c

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This study aims to measure the cross sections of the ^{12}C(K^-, $K^+\Xi^-$) and ^{12}C(K^-, $K^+\Lambda\Lambda$) reactions at 1.8 GeV/c using data from the J-PARC E42 experiment. Here, we present the measurement of the inclusive cross section for the ^{12}C(K^-, K^+) reaction and the reconstruction of Ξ^- and $\Lambda\Lambda$ final states using the Hyperon Spectrometer at J-PARC.

1. Introduction

The S = -2 hyperon–nucleon interaction plays a key role in understanding SU(3) flavor symmetry breaking, but experimental information on this sector remains limited.

An early investigation of the Ξ^-–nucleus interaction was conducted at KEK through a cross section measurement for the elementary process using the (K^-, K^+) reaction. The total cross section of the $\Xi^- p \to \Lambda\Lambda$ conversion was reported, and the width of the Ξ^- state in nuclear matter was estimated to be approximately $\Gamma_{\Xi^-} \sim 3$ MeV [1]. However, due to the very limited number of observed events, only an upper limit on the $\Xi^- p$ elastic scattering cross section was provided, and the $\Xi^- p \to \Lambda\Lambda$ cross section was derived from just three candidate events.

This result highlighted the need for more precise measurements with significantly higher statistics in order to quantitatively determine the ΞN interaction and the $\Xi^- p \to \Lambda\Lambda$ conversion probability in nuclear matter.

To probe the nature of ΞN interactions and $\Xi^- p \to \Lambda\Lambda$ conversions, we have conducted high-statistics measurements of the $^{12}C(K^-, K^+\Xi^-)$ and $^{12}C(K^-, K^+\Lambda\Lambda)$ reactions using a 1.8 GeV/c K^- beam at J-PARC, which is known as the J-PARC E42 experiment. This study aims to quantify the Ξ^- escaping probability, the inelastic scattering cross sections, and the cross section of the $\Xi^- p \to \Lambda\Lambda$ conversion.

The J-PARC E42 experiment is particularly sensitive to such measurements, since it simultaneously measures the $^{12}C(K^-, K^+)$ reaction and reconstructs all charged decay products of the Ξ^- and $\Lambda\Lambda$ systems using a time-projection chamber [2].

## 2. J-PARC E42 experiment

Cross sections for double-strangeness production in the $^{12}C(K^-, K^+)$ reaction were measured using a separated 1.82 GeV/c K^- beam at the K1.8 beam line of the J-PARC Hadron Experimental Facility [3, 4]. The beam was incident on a diamond target with dimensions of 2×3×2 cm^3 and a density of 3.223 g/cm^3, and the outgoing K^+ particles were tagged in the forward direction. A polyethylene target was also used to obtain calibration data.

The J-PARC E42 detector system includes the K1.8 beam-line spectrometer for measuring the incident K^- beam, the Superconducting Hyperon Spectrometer (SHS) for detecting charged particles from the target, and the forward KURAMA spectrometer for tracking outgoing K^+ particles.

The K1.8 beam-line spectrometer consists of a QQDQQ magnet system for analyzing the momentum of incoming particles. Beam hodoscopes BH1 and BH2 are used to measure the time-of-flight, allowing separation of K^- from π^- based on their time-of-flight differences. In addition, an aerogel Cherenkov counter BAC at the downstream of the beamline provides further π^- suppression. The KURAMA spectrometer measures the momentum of forward-going K^+ particles, using a 0.7 T dipole magnet, upstream drift chambers SDC1&2 and downstream drift chambers and SDC3&4, Cherenkov counters LAC and WC, and timing hodoscopes SCH and TOF. It provides angular coverage of $\theta_{K^+}^{\text{lab}} < 25°$ and its 2.7% momentum resolution at 1.3 GeV/c.

The SHS provides wide-angle coverage and consists of a 1 T superconducting magnet [5], a time-projection chamber (HypTPC) [2], and a time-of-flight array (HTOF) [6]. The HypTPC features a 55 cm drift length and a circular pad plane with 5768 readout channels. The beam axis
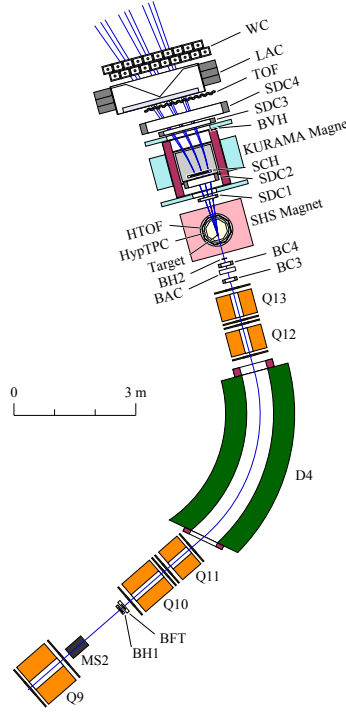
Figure 1: The E42 detector configuration.

is off-axis relative to the electric field direction, and the diamond target is placed inside the TPC, 143 mm upstream of the center.

The trigger logic is based on beam and scattered particle identification using multiple detector signals. The K^- beam and scattered K^+ candidate are defined as:

$$K \text{ Beam} \equiv \texttt{BH1} \otimes \texttt{BH2} \otimes \overline{\texttt{BAC}}, K \text{ Scat} \equiv \texttt{TOF} \otimes \overline{\texttt{LAC}} \otimes \texttt{WC}.$$

The following two main trigger conditions were used in the experiment: TrigA required a coincidence of K Beam and K Scat along with the matrix trigger (Mtx), and was designed to collect K^-, K^+ inclusive events. TrigB had an additional requirement of a hit in the `HTOF-Mp2` detector, corresponding to events with track multiplicity ≥ 2, and was used to collect exclusive reactions.

Here, `Mtx` denotes the matrix trigger composed of `BH2`, `SCH`, `TOF`, and `BVH`, designed to veto beam background. The system includes a total of 14,336 matrix elements, structured as $8 \times 64 \times 28$ ($= 24 + 4$), providing fine granularity in particle selection.

The results presented in this paper are based on the data collected with the prescaled TrigA condition.

3. Cross section Measurement for the ^{12}C(K^-, K^+) Reaction

Inclusive cross sections of the ^{12}C(K^-, K^+) reaction were measured via missing-mass spectroscopy, and, simultaneously, double-strangeness production events were reconstructed using the HypTPC by identifying all charged decay products.

The closest point between the reconstructed K^- and K^+ tracks was defined as the production vertex of the ^{12}C(K^-, K^+) reaction. The missing mass M_X was calculated using the measured four-momenta of the incoming and outgoing particles. The Ξ^- binding energy, B_Ξ, was defined relative to the ground state of the ^{11}B nucleus as:

$$B_\Xi = M_{^{11}\text{B}} + M_{\Xi^-} - M_X, \tag{1}$$

where $M_{^{11}\text{B}}$ is the mass of the ^{11}B nucleus in its ground state, and M_{Ξ^-} is the mass of the Ξ^- hyperon.

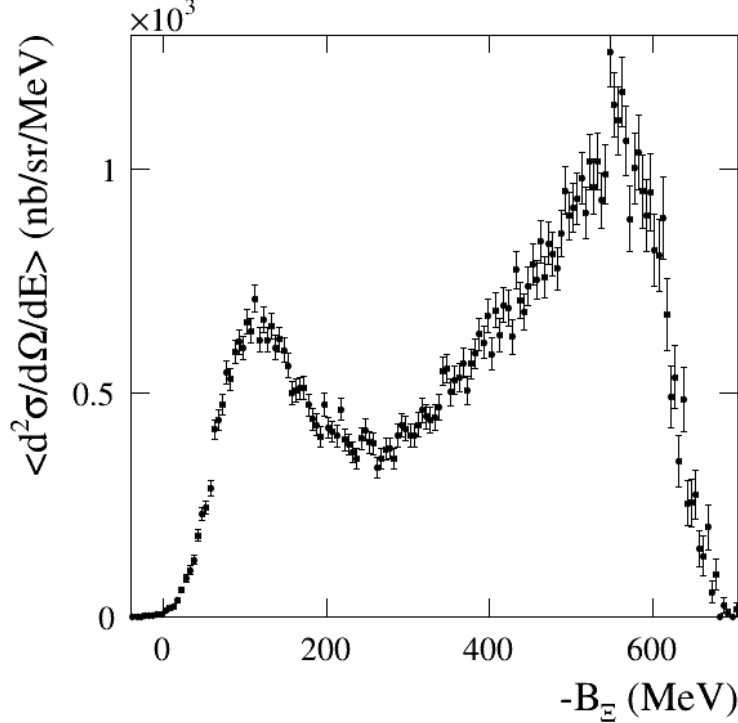The missing mass M_X was calculated as:

$$M_X^2 = (E_{K^-} + M_{^{12}\text{C}} - E_{K^+})^2 - (\vec{p}K^- - \vec{p}K^+)^2, \tag{2}$$

assuming that the ^{12}C target nucleus is initially at rest. Here, E_{K^-} and E_{K^+} denote the energies of the incoming K^- and outgoing K^+, respectively, and $\vec{p}K^-$ and $\vec{p}K^+$ are their corresponding three-momenta.

The double-differential cross section was calculated using the following expression:

$$\left\langle \frac{d^2\sigma}{d\Omega dE} \right\rangle = \frac{A}{\rho x N_A} \frac{N_{KK}}{N_{\text{beam}} \Delta\Omega_{\theta_1 \text{-} \theta_2} \Delta E \varepsilon} \tag{3}$$


Figure 2: Differential cross sections for the ^{12}C(K^-, K^+)X reaction at 1.8 GeV/c, averaged over the region $0° < \theta_{K^+}^{\text{lab}} < 14°$, shown with statistical errors.

Here, N_{KK} is the number of observed (K^-, K^+) events, N_{beam} is the total number of incident K^- particles, and ΔE is the bin width of the Ξ^- binding energy. The solid angle acceptance $\Delta\Omega_{\theta_1-\theta_2}$ was evaluated using a Monte Carlo study of the K^+ acceptance for KURAMA spectrometer.

The experimental efficiency ε includes several components: tracking efficiency of the drift chambers, detection efficiency of the hodoscopes, K^+ track reconstruction efficiency in the HypTPC, data acquisition (DAQ) efficiency, and analysis cut efficiency, including the Z position selection of the (K^-, K^+) production vertex. It also accounts for the survival ratio of K^+ particles reaching the most downstream detectors of the spectrometer. N_A is Avogadro's number, ρx is the areal density of the target, and A is the normalization factor.

A Λ hyperon was identified by reconstructing the decay vertex from a proton and a π^- track using the closest distance of approach (CDA) method, requiring the distance of closest approach (DCA) between the two tracks to be less than 1 cm. The invariant mass of the pair was then calculated, and only events with a reconstructed mass within $0.1\,\text{GeV}/c^2$ of the nominal Λ mass were selected as Λ candidates. A Ξ^- hyperon was subsequently reconstructed from a Λ candidate and an additional π^- track using the same vertex reconstruction approach, with the DCA between the Λ and π^- tracks required to be less than 1.5 cm.
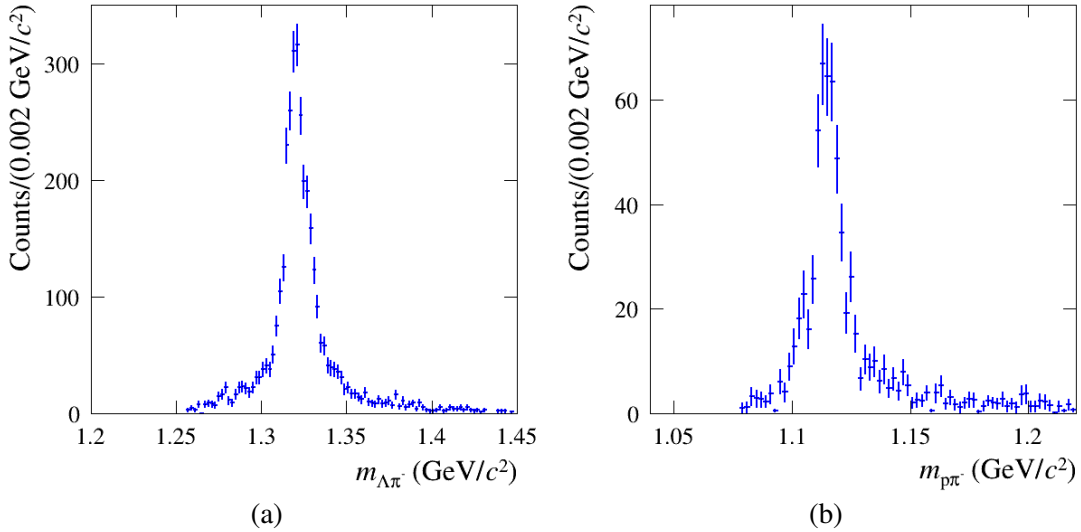
Figure 3: (a) Invariant mass distribution of $\Lambda\pi^-$ for Ξ^- emission, and (b) invariant mass distribution of $p\pi^-$ for $\Lambda\Lambda$ production.

For the exclusive measurements, such as Ξ^- and $\Lambda\Lambda$ reconstruction, the geometrical acceptance of the HypTPC was also taken into account. The acceptance depends on the reaction channel and the momentum of the outgoing K^+, as well as the target orientation condition in the case of Ξ^- emission and $\Lambda\Lambda$ production. The geometrical acceptance for emitted Ξ^- reached up to 70%, while that for $\Lambda\Lambda$ pairs was up to 56%.

4. Summary

We have presented the measurement of inclusive and exclusive cross sections for the ^{12}C(K^-, K^+) reaction at 1.8 GeV/c, performed in the J-PARC E42 experiment. The experiment enables simultaneous reconstruction of Ξ^- and $\Lambda\Lambda$ final states with high statistics, thanks to the large acceptance of the HypTPC.

A detailed analysis of the differential cross sections and kinematic distributions will be presented in a forthcoming publication[7].

Acknowledgment

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