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Measurement of Ξ^- Polarization in the $K^- p \to \Xi^- K^+$ Reaction at 1.8 GeV/c

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The polarization of a Ξ^- baryon produced in the p$(K^-, K^+)\Xi^-$ reaction offers critical insights into the double-strangeness exchange mechanism. Since polarization reflects the spin-flip amplitude of the reaction, it helps us describe the reaction mechanism involving high-spin resonances, which are expected to dominate in the forward region. We have measured the cross-section for the $K^- p \to K^+ \Xi^-$ reaction and Ξ^- polarization in the forward angular region at 1.8 GeV/c. We present preliminary results from J-PARC E42.

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1. Introduction

The absence of $S = -2$ meson forbids the t-channel Born-term diagram in the double-strangeness exchange process. As a result, s-channel Λ and Σ resonances contributes most significantly in the forward region. However, a bump structure observed in the forward differential cross-section suggests a more complex reaction mechanism. Contributions from high spin Λ and Σ resonances dominates the reaction amplitude, but the interactions among these resonances remain poorly understood due to the unknown coupling constants at the KNY and $K\Xi Y$ vertices, where Y represents either Λ or Σ including its excited states.

Despite the lack of data, many theoretical models have been proposed to describe the (K^-, K^+) reaction. One approach employs an effective Lagrangian based on a hybrid Regge-plus-resonance model[1], while another takes a phenomenological approach. In the latter model, a noticeable polarization intensity arises from the inclusion of some resonances[2]. Polarization measurements serve as a crucial test for refining and validating these models. Regardless of the model specifics, polarization characterizes the spin-flip and non-flip amplitude of the final state[3], which are essential to understanding the reaction mechanism. However, experimental data on polarization remain limited to bubble chamber experiments conducted in the 1960's and 1970's[4][5][6].

Since the double-strangeness exchange reaction is a strong interaction process, physically observable asymmetry, such as polarization asymmetry along the longitudinal or perpendicular direction, is prohibited. However, the reaction plane, defined as the cross-product of two momentum vectors, is a pseudo-vector and remains invariant under parity transformation. As a result, polarization asymmetry arises along the reaction plane. The decay asymmetry of daughter baryons produces a specific angular decay spectrum, allowing us to estimate the polarization of the produced hyperon.

Unlike the production process, the parity is not conserved in the Ξ weak decay. Since the π carries no spin, the daughter baryons (such as Λ or proton) inherit the corresponding spin component, resulting in a distinct angular distribution. The violation of parity conservation permits change in the angular momentum states, giving rise to decay asymmetry. The decay amplitude consist of two complex numbers: parity violating amplitude and parity conserving amplitude. From the normalization constraint and the freedom of phase selection, the degree of freedom are reduced to two. As a result, the decay asymmetry is represented with two real numbers: the decay asymmetry parameter α and phase shift ϕ. However, for practical purpose in describing decay asymmetry, it is more convenient to use β and γ where the relation $\beta/\gamma = \tan\phi$ holds. Additionally, the constraint $\alpha^2 + \beta^2 + \gamma^2 = 1$ is imposed to ensure proper normalization. Adopting these three parameters, the decay angular distribution of the $\Xi^- \to \Lambda\pi^-$ at the rest frame of Ξ^- can be given by:

$$\frac{dN}{d\cos\theta} = 1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}. \tag{1}$$

where θ is the angle between the reaction plane and $\hat{\Lambda}$, the Λ direction in Ξ^- rest frame. Note that since Ξ^- polarization is only allowed along the reaction plane, $\vec{P}_\Xi$ is identical to the reaction plane vector multiplied by Ξ^- polarization. The Λ polarization vector is given by:

$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \cos\theta)\hat{\Lambda} + \beta_\Xi(\vec{P}_\Xi \times \hat{\Lambda}) + \gamma_\Xi \hat{\Lambda} \times (\vec{P}_\Xi \times \hat{\Lambda})}{1 + \alpha_\Xi \cos\theta}, \tag{2}$$

Since the polarization of Λ from Ξ^- decay is determined, we obtain the proton decay spectrum:

$$I = 1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda} + \alpha_\Lambda \hat{p} \cdot [(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{\Lambda})\hat{\Lambda} + \beta_\Xi(\vec{P}_\Xi \times \hat{\Lambda}) + \gamma_\Xi \hat{\Lambda} \times (\vec{P}_\Xi \times \Lambda)]. \quad (3)$$

By defining three coordinate axes:

$$\hat{z} = \hat{\Lambda}; \quad \hat{x} = \frac{\hat{e} \times \hat{z}}{|\hat{e} \times \hat{z}|}; \quad \hat{y} = \hat{z} \times \hat{x} \quad (4)$$

where $\hat{e} = \frac{\Xi^- \times \hat{K}^-}{|\hat{\Xi}^- \times \hat{K}^-|}$ represents the reaction plane, the intensity follows a liner distribution for for angles (ϕ_α, ϕ_β, ϕ_γ and θ):

$$\begin{cases} I(\theta) = 1 + \alpha_\Xi P_\Xi \cos\theta \\ I(\phi_\alpha) = 1 + \alpha_\Xi \alpha_\Lambda \cos\phi_\alpha \\ I(\phi_\beta) = 1 + \frac{\pi}{4} P_\Xi \beta_\Xi \alpha_\Lambda \cos\phi_\beta \\ I(\phi_\gamma) = 1 + \frac{\pi}{4} P_\Xi \gamma_\Xi \alpha_\Lambda \cos\phi_\gamma \end{cases}, \quad (5)$$

where ϕ_α, ϕ_β and ϕ_γ represent the angles between the proton and the z, x, y axes, respectively, in the Λ rest frame. Fig. 1 provides an intuitive representations of the polarization angles.

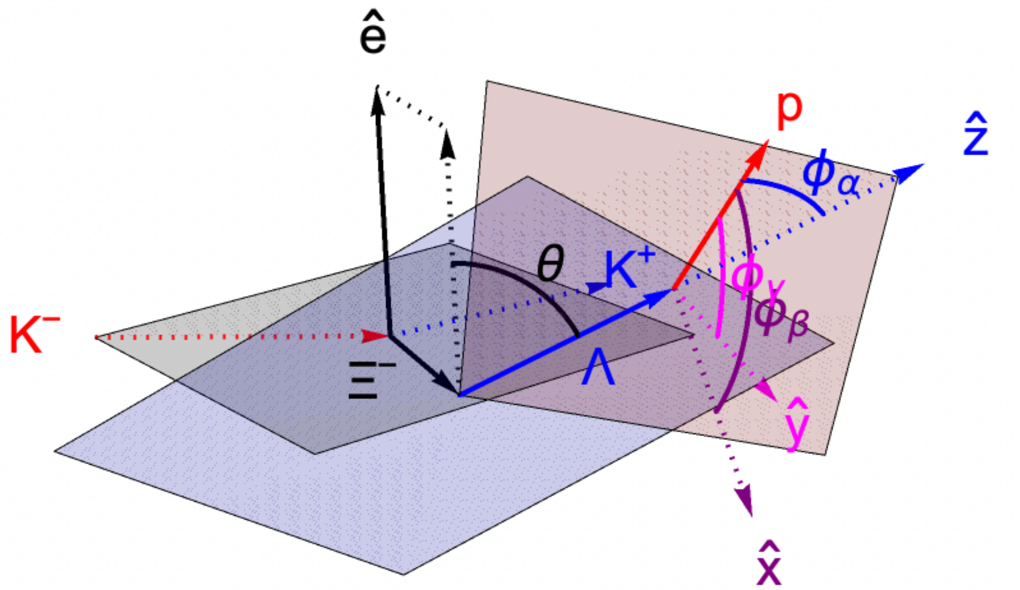

Figure 1: The polarization angles and decay planes.

2. J-PARC E42

We conducted J-PARC E42 at the K1.8 Beamline at J-PARC, as shown in Fig. 2(a). A 1.82 GeV/c K^- beam impinged on a polyethylene target CH_2. An outgoing K^+ particle in the the $(K^-, K^+)\Xi^-$ reaction was tagged using a forward dipole spectrometer.

The $\Xi^- \to \Lambda\pi^-$ decay was detected using a time projection chamber (HypTPC) in a superconducting (HS) magnet. Fig. 2(b) displays typical event of Ξ^- decay. The reconstructed invariant mass of the $p\pi$ and $\Lambda\pi$ systems are displayed in Fig. 3. The incident K^- beam(magenta), the scattered K^+ (dark gray), π from Ξ and Λ, and proton tracks are well reconstructed.

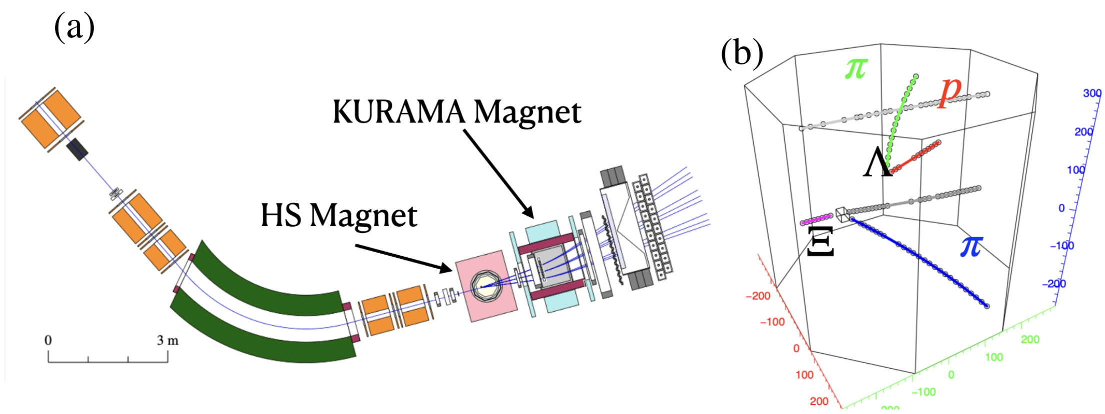

Figure 2: (a) Schematics of the K1.8 Beamline and (b) a typical event display of Ξ decay in HypTPC.

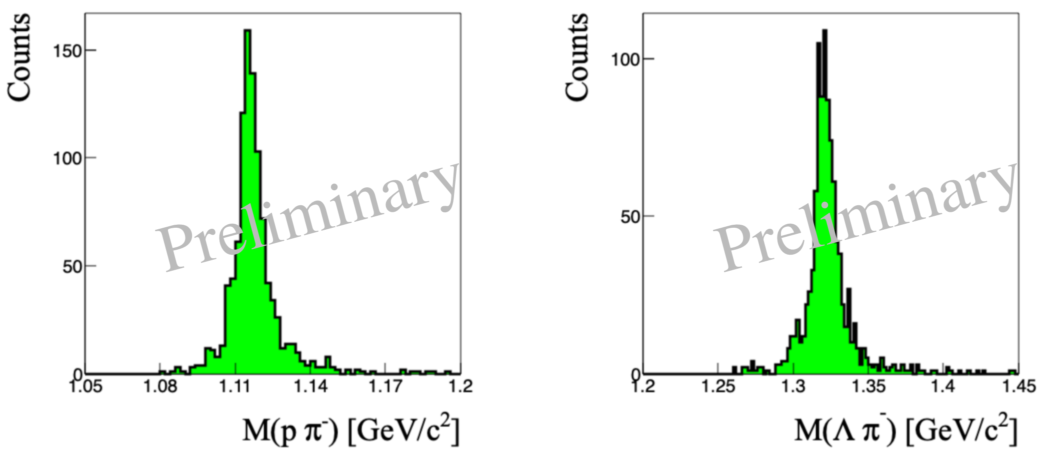

Figure 3: Reconstructed invariant mass spectrum of Λ and Ξ.

3. Polarization analysis with Ξ^- decay

Accurate polarization estimation requires precise measurements of each particle;s momentum. Angles involved in the polarization measurements are defined in the center-of-mass frame, which is highly affected by momentum bias. The reaction plane is not directly related to the bias in momentum magnitude, but can be blurred by Fermi motion in ^{12}C within the CH_2 target. By defining the reaction plane as $\hat{e} = \frac{\hat{\Xi}^- \times \hat{K}^-}{|\hat{\Xi}^- \times \hat{K}^-|}$, this blurring effect can be reduced.

We studied the experimental acceptance using the E42 Geant4 simulation software. The K^- and K^+ were taken from real data to reduce spectrometer acceptance effect in TPC simulation. The Ξ^- momentum was defined as $\vec{K}^- - \vec{K}^+$. We tested the simulation with three different polarization values, $P_\Xi = -1$, 0 and +1. The simulation data passed through the same analysis pipeline as real data. The resulting polarization angle distributions from Geant4 data analysis are shown in Fig. 4. Since three angles, θ, ϕ_β and ϕ_γ, share the same fitting parameter, P_Ξ, we perform a simultaneous unbinned fit to determine the polarization. We nearly recovered the initial polarization, which was set to 1. For datasets where the polarization was set to 0 or -1, we also successfully recovered the initially assigned values.

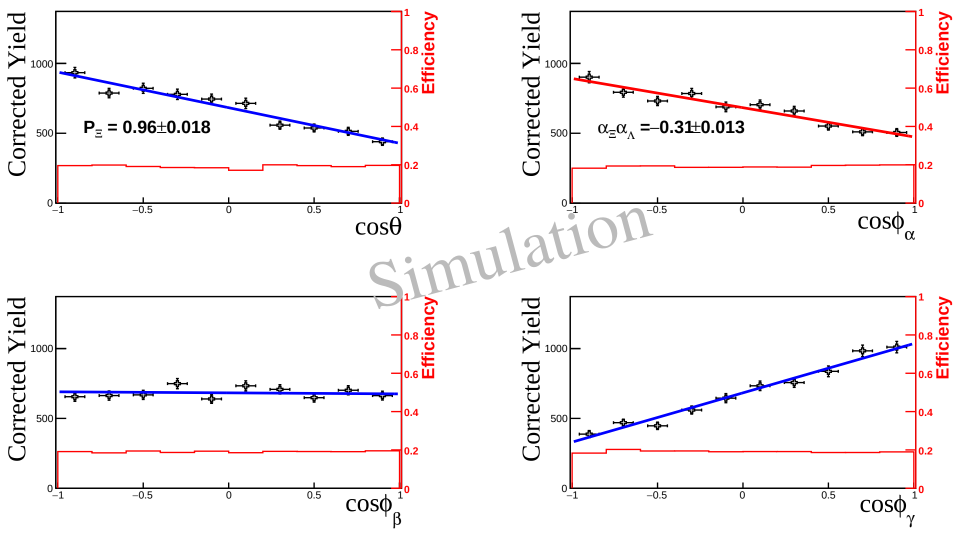

Figure 4: Polarization angle distribution from simulation analysis. The blue line indicates the simultaneous unbinned fit result of θ,ϕ_β and ϕ_γ, while the red line represents the unbinned fit result for ϕ_α

Fig. 5(a) presents the statistical error in E42 with the CH_2 target. Although carbon components are present, the statistical error is significantly lower compared to previous experiments. The E42 data points are shown alongside theoretical expectations from S.H. Kim *et al.* [1]. For the P_Ξ values shown in the figure, α_Ξ parameter used in previous experiments differs slightly from the modern value; this difference has been compensated accordingly.

The angle ϕ_α is independent of polarization but only depends on the product of the decay asymmetry parameters, α_Ξ and α_Λ, which are already well-established. Taking advantage of this, we validate our analysis for real data by properly reconstructing the ϕ_α distribution. We expect a slope parameter of $\alpha_\Xi\alpha_\Lambda = -0.291$[7] for the $\cos\phi_\alpha$ distribution. Fig. 5(b) shows that the reconstructed Λ decay spectrum's slope parameter is within the statistical error, indicating that our analysis is consistent with Particle Data Group values. However, the remaining three angles related to P_Ξ are not shown in this proceeding.

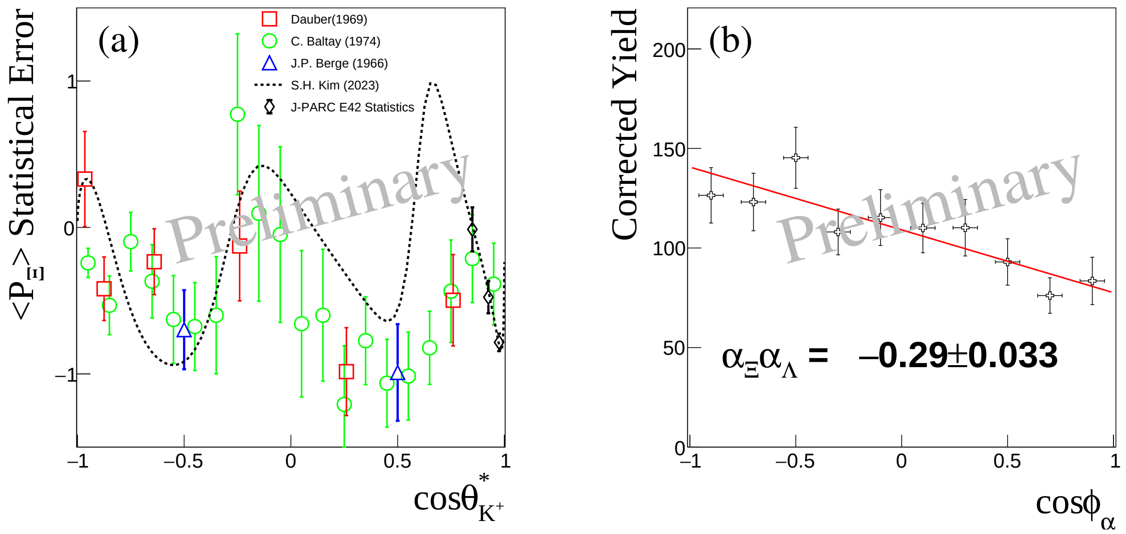

Figure 5: (a) E42 statistics compared to previous experiments, and (b)Λ decay asymmetry measured in E42.

4. Summary

The polarization of the produced Ξ in the (K^-, K^+) reaction provides crucial insights into the underlying spin structure of the reaction. This is particularly important for the double-strangeness reaction, which is dominated by the interaction of high spin Λ and Σ resonances, yet our knowledge of the KYN and $KY\Xi$ vertices remains limited. Measuring the polarization of Ξ^- produced in a KN reaction would provide key insights into the reaction mechanism, but available data have been limited.

J-PARC E42 has measured the Ξ^- polarization in the forward production region, collecting approximately 800 events. This surpasses previous measurements, with had a total of around 200 events. By analyzing the decay asymmetry of $\Lambda \rightarrow p\pi^-$, we confirmed that our preliminary results align with established values. Our new measurement on the Ξ^- polarization will be reported soon.

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