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Λ polarization measurement of the $\pi^- p \to K^0\Lambda$ reaction in J-PARC E40 experiment

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Abstract. We performed the J-PARC E40 experiment to measure the Σp scattering cross sections from 2018 to 2020. Together with the $\pi^- p \to K^+\Sigma^-$ data, the $\pi^- p \to K^0\Lambda$ data were accumulated as a byproduct. The analysis confirmed that Λ could be identified with an S/N ratio of ~ 2.67. The polarization of Λ (P_Λ) was preliminarily derived as 1.009 ± 0.049 for the K^0 angular range of $0.7 < \cos\theta_{K^0,\,CM} < 0.8$. It is more accurate than the past data [1]. The high polarization enables us to measure not only the differential cross section but also spin observables of the Λp scattering in the future J-PARC experiment.

1 Introduction

The nucleon-nucleon (NN) interaction is the foundation of nuclear physics. The nuclear force has an attractive potential in the long-range region, which is well described by the one-boson exchange (OBE) model. In contrast, it has a repulsive core in the short-range region. Although the origin of the core is still unknown, it is expected that the quark-gluon dynamics would dominate because the two nucleons overlap in this range. That is why most of us are engaging in hypernuclear physics to expand the nuclear force study by adding strange quarks.

Representative baryon-baryon (BB) interation models are, for example, Nijmegen model [2], quark cluster model [3], and chiral EFT [4] [5]. To update the theories based on experimental results, precise two-body hyperon-nucleon (YN) data are necessary to make the YN interaction models more realistic. Furthermore, accurate binding energy and level scheme of hypernuclei are also important to compare with hypernuclear calculations based on the YN interaction.

Historically, many hypernuclear experiments in KEK, Jefferson Lab, J-PARC, etc., have accumulated many hypernuclear data. In addition, precise two-body YN data should be taken by YN scattering and hypertriton experiments as the fundamental information. The realistic YN interactions would be established by feeding back two-body YN data into theories. Such YN interactions will derive from many-body interactions in the hypernuclear data.

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The J-PARC E40 (Σp scattering) experiment recently pioneered the YN scattering technique in J-PARC [6]. We now plan the next-generation Λp scattering experiment (J-PARC E86) using the same procedure as the E40 experiment. The J-PARC E86 aims to measure many scattering observables such as the differential cross section $(d\sigma/d\Omega)_{\Lambda p}$, analyzing power ($A_y$), and depolarization ($D_y^y$).

2 Λ polarization measurement for the J-PARC E86

2.1 Λp scattering observables and Λ polarization

In the momentum range of 0.4 – 0.8 GeV/c, The J-PARC E86 will measure the Λp scattering observables, such as the differential cross section ($(d\sigma/d\Omega)_{\Lambda p}$), analyzing power ($A_y$), and depolarization ($D_y^y$).

The Λ beam should be polarized in this measurement. Besides, we need to measure the Λ beam polarization (P_Λ) for deriving A_y and D_y^y. It is desirable to confirm the high polarization of Λ produced in the $\pi^- p \to K^0\Lambda$ reaction and to establish the analysis method in advance. Therefore, we analyzed the $\pi^- p \to K^0\Lambda$ data accumulated as a byproduct in the J-PARC E40. Although the past experiment reported P_Λ in the $\pi^- p \to K^0\Lambda$ reaction is $\sim$ 100% for the forward angular range of K^0 [1], its statistic is not enough. Hence, our re-measurement of P_Λ would be valuable.

2.2 Analysis of the reaction $\pi^- p \to K^0\Lambda$ in the J-PARC E40 byproduct data

The J-PARC E40 measured the Σp scattering and pioneered the new hyperon scattering experimental technique. It was performed at the K1.8 beamline of the J-PARC Hadron Experimental Facility. The detector setup is shown in Figure 1. In its byproduct data of the (π^-, K^0) reaction, K^0 was reconstructed from π^+ and π^-. They are detected by the KURAMA spectrometer, and CATCH system [7], respectively. Λ was tagged by calculating the missing mass of the $\pi^- p \to K^0 X$ reaction. The detail of detector configuration and K^0 reconstruction is described in Ref. [9]. The J-PARC E40 byproduct data includes enough Λ beam yield for the P_Λ analysis of 2.80×10^4 with the S/N ratio of $\sim$ 2.67. These values were calculated by requiring the $\Lambda \to p\pi^-$ decay detection with the CATCH system.

2.3 Λ polarization calculation

As we mentioned, the $\Lambda \to p\pi^-$ decay was identified with the CATCH system. Due to the parity violation in the $\Lambda \to p\pi^-$ decay, the emission angle of decay proton (θ_p) distributes asymmetrically. By measuring the θ_p distribution in the rest frame of Λ, we obtain P_Λ from the following equation,

$$\frac{1}{N_0}\frac{dN}{d\cos\theta_p} = \frac{1}{2}(1 + \alpha P_\Lambda \cos\theta_p). \tag{1}$$

Here, N_0 is the yield of the decay proton, and α is the asymmetry parameter (which is recently updated as $0.750 \pm 0.009 \pm 0.004$ [10]). The raw θ_p distribution was corrected by the acceptance of the CATCH system, estimated by a Geant4-based Monte Carlo simulation. Figure 2 shows the θ_p distribution after the acceptance correction in the K^0 angular range of $0.7 < \cos\theta_{K^0,\,CM} < 0.8$. Due to parity violation in the $\Lambda \to p\pi^-$ decay, a clear asymmetry called "Up-Down asymmetry" can be seen.

We calculated the P_Λ for the K^0 angular range of $0.6 < \cos\theta_{K^0,\,CM} < 1.0$ by fitting the $\cos\theta_{K^0,\,CM}$ distribution with Eq. (1). The comparison between the present values of P_Λ

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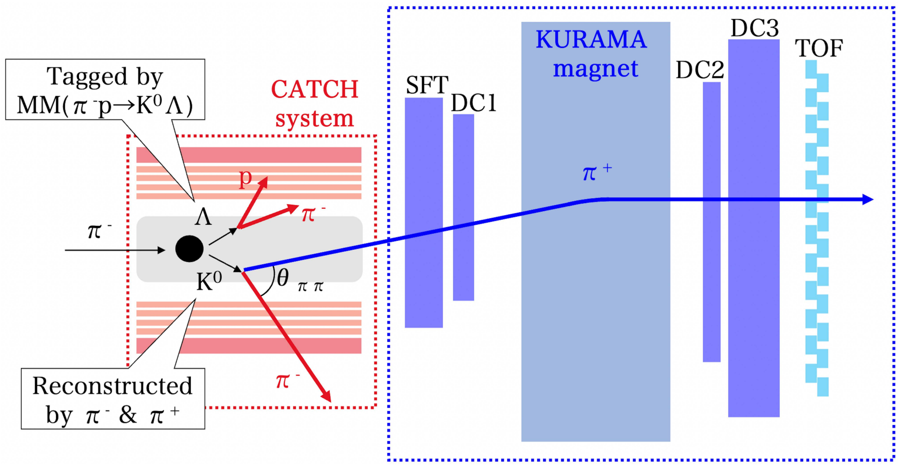

Figure 1. The schematic of K^0 reconstruction and Λ identification in the J-PARC E40 byproduct data of the (π^-, K^0) reaction. The cylindrical detector cluster (CATCH) is represented by pink parts, and the forward magnetic spectrometer (KURAMA), blue ones. The detail of the analysis technique is described in Ref. [9].

and the past experiment is shown in Figure 3. Here, the past data are replotted with the updated asymmetry parameter. The higher statistics of the Λ production in the J-PARC E40 allowed us to get smaller error bars. This result indicates that the Λ produced in the reaction $\pi^- p \to K^0\Lambda$ has high polarization.

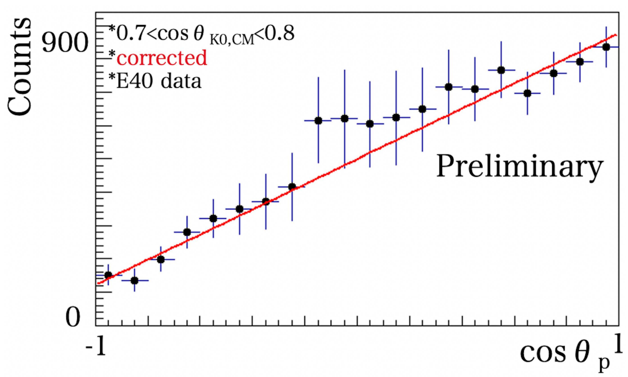

Figure 2. The distribution of the emission angle of decay proton (θ_p) in the K^0 angular range of $0.7 < \cos\theta_{K^0,\,CM} < 0.8$. We measured this in the rest frame of Λ. The Λ polarization (P_Λ) is calculated by fitting this distribution with Eq. (1).

3 Conclusion

To establish the realistic YN interactions, we need feedback on two-body YN data into theories. Such realistic YN interactions are necessary to derive many-body interactions in the

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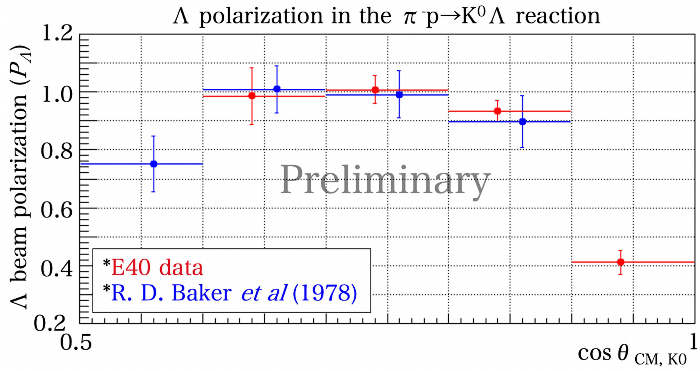

Figure 3. Λ beam polarization (P_Λ) in the reaction $\pi^- p \to K^0\Lambda$. The present value (the J-PARC E40 byproduct data) is marked by red points, and the past data [1], by blue points.

hypernuclear data. J-PARC E40 (Σp scattering) recently pioneered the hyperon scattering experimental technique for the first time. Following this success, we plan the next-generation Λp scattering experiment, J-PARC E86. It aims to measure the spin observables and the differential cross section of the Λp scattering precisely. In the spin observables measurement, we need the highly polarized Λ beam. Although the past experiment reported that the Λ polarization (P_Λ) was $\sim$ 100% for the forward angular region of K^0[1], its accuracy is not enough due to the low statistics. Therefore, we decided to re-measure P_Λ.

In the P_Λ analysis, we used the (π^-, K^0) reaction data accumulated as a byproduct in the J-PARC E40. We have identified the Λ beam yield of 2.80×10^4 with the S/N ratio of $\sim$ 2.67. By measuring the θ_p distribution in the rest frame of Λ, P_Λ was derived from its slope. Now, P_Λ was preliminarily derived as 1.009 ± 0.049 for the K^0 angular range of $0.7 < \cos\theta_{K^0,\,CM} < 0.8$. Using such a highly-polarized Λ beam, Λp spin observables measurement is possible in J-PARC E86.

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