Recent progress and future prospects of hyperon nucleon scattering experiment

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Abstract. A new hyperon-proton scattering experiment, dubbed J-PARC E40, was performed to measure differential cross sections of the $\Sigma^+ p$, $\Sigma^- p$ elastic scatterings and the $\Sigma^- p \to \Lambda n$ scattering by identifying a lot of Σ particles in the momentum ranging from 0.4 to 0.8 GeV/c produced by the $\pi^\pm p \to K^+ \Sigma^\pm$ reactions. We successfully measured the differential cross sections of these three channels with a drastically improved accuracy with a fine angular step. These new data will become important experimental constraints to improve the theories of the two-body baryon-baryon interactions. Following this success, we proposed a new experiment to measure the differential cross sections and

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spin observables by using a highly polarized Λ beam for providing quantitative information on the ΛN interaction. The results of three Σp channels and future prospects of the Λp scattering experiment are described.

1 Introduction

The realistic Nucleon-Nucleon (NN) potentials such as CD Bonn [1] and AV18 [2] NN potentials have been already established. At the stages of updating these theories, a lot of scattering observables of NN scattering were essential inputs. Nowadays, the realistic NN interactions have been making a solid base for nuclear studies. Thanks to these realistic NN interactions, three-nucleon force was confirmed from proton-deuteron scatterings [3]. This three-nucleon force is known as the necessary interaction to reproduce the nuclear binding energies and the equation of state of neutron stars.

The situation is completely different in the Baryon-Baryon (BB) interactions. Theoretical models are developed based on the limited hyperon-nucleon scattering data and the flavor SU(3) symmetry. The Nijmegen model is a representative boson-exchange model [4]. Quark cluster model (QCM) treats the degrees of freedom of the consituent quark [5, 6]. Recently chiral effective field theory, which is widely used in normal nuclear physics, has been extended to the hyperon-nucleon sectors [7, 8]. However, the experimental data for constraining these theories are extremely scarce and not updated from the 1970s. Good quality two-body scattering data are necessary to feed back to and to test the theories including Lattice QCD BB interaction.

In order to change the experimental situation, we started new hyperon-nucleon scattering experiments at J-PARC. We proposed a new hyperon-proton scattering experiment where the scattering events were identified by only the kinematical consistency check without imaging methods. We finally succeeded in measuring the differential cross sections of the $\Sigma^- p$ [9] and $\Sigma^+ p$ [10] elastic scatterings and $\Sigma^- p \to \Lambda n$ reaction [11] with much better accuracy (E40). Then, we proposed a Λp scattering experiment using a polarized Λ beam as a new project at J-PARC (E86) [12]. In this proceedings, We would like to summarize the results of the Σp scattering experiment and mention the future prospects of the Λp scattering experiment.

2 Measurement of the differential cross sections of the Σp reactions at J-PARC E40

Our first step toward precise hyperon-nucleon scattering experiments is the differential cross section measurements of Σp scatterings. One of the biggest motivations in this experiment is to verify the quark Pauli repulsion. In the quark picture, the $\Sigma^+ p$ (spin 1) system contains an up-quark pair having the same spin and color with a high probability. The Pauli effect in the quark level could make the $\Sigma^+ p$ potential quite repulsive. This was firstly predicted by Oka and Yazaki in the quark cluster model [5] and this prediction was confirmed by the Lattice QCD simulation [13, 14]. Another important motivation is to put strong constraints on the BB interaction theories by providing the systematic $d\sigma/d\Omega$ measurements with much better accuracy than past measurements. The theoretical predictions for the Σp differential cross sections are different depending on theories. Therefore, we planned the systematic measurements of the $\Sigma^+ p$ and $\Sigma^- p$ elastic scatterings and the $\Sigma^- p \to \Lambda n$ reaction.

Here we shortly summarize the experimental method. The detailed information can be found in [9]. We detected two successive two-body reactions in a liquid hydrogen (LH_2) target: the first one was the Σ production by the (π, K^+) reaction and the second one was

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the Σp scattering. The Σ production was identified using the K1.8 beam-line and KURAMA spectrometers and the momentum of Σ particle was tagged using the missing momentum. The interaction of this momentum tagged Σ particle was identified by CATCH detector [15], which comprised a cylindrical fiber tracker and BGO calorimeter.

The Σ particles running in the LH_2 target were regarded as Σ beam. To tag these Σ particles, we detected K^+ with the KURAMA spectrometer. Then, we reconstruct Σ from the missing mass. Each momentum was able to be reconstructed from the missing momentum. The typical momentum range was from 0.45 GeV/c to 0.8 GeV/c. These Σ particles sometimes reacted with a proton in LH_2 target and the recoil proton and decay particles from Σ decay were detected by CATCH. The particle identification for proton and π was performed using the dE-E information between CFT and BGO as shown in FIG. 8 in [9].

In order to identify the $\Sigma^- p$ scattering, the kinematical consistency between the energy and scattering angle was checked. We defined two values, that is, $E_{measured}$ as the measured kinetic energy for the recoil proton and E_{calc} as the calculated energy from the scattering angle based on the $\Sigma^- p$ elastic scattering kinematics. We checked the difference between these two values, that is, $\Delta E = E_{measured} - E_{calc}$. The $\Sigma^- p$ scattering events made a peak at $\Delta E = 0$ as shown in FIG. 15 (c) in [9]. If we changed the kinematical assumption, for example, $\Sigma^- p \to \Lambda n$ reaction, we could also identify the $\Sigma^- p \to \Lambda n$ event from this kinematical consistency check as shown in FIG. 1 (d) in [11].

Finally, we have obtained these differential cross sections for $\Sigma^- p$ elastic scattering and $\Sigma^- p \to \Lambda n$ inelastic scattering as shown in FIG. 17 in [9] and FIG.3 in [11], respectively. The black points are our experimental data and the accuracy has been improved to 10% level for a narrow angular step of $d\cos(\theta) = 0.1$. Now, we can identify the clear forward peaking angular dependence in the $\Sigma^- p$ elastic scattering and moderate forward peaking dependence in the $\Sigma^- p \to \Lambda n$ scattering. The fss2 [6] and chial EFT [7, 8] show a reasonable angular dependence for both channels. On the other hand, Nijmegen ESC models [16, 17] clearly underestimate the forward angle.

Next, we summarize the results obtained for the $\Sigma^+ p$ channel. As we mentioned, this channel is very interesting in relation to the quark Pauli effect. The more repulsive the ${}^3S_1$ potential is, the larger the cross section is predicted like fss2. However, we have found that the value is much smaller than the fss2 prediction and the E289 results as shown in Fig. 24 in [10]. The size parameter in fss2, which determines the strength of the quark Pauli repulsion, must be smaller than the present value to explain the present experimental data. In Chiral EFT, the differential cross section gets larger in higher momentum. This momentum dependence does not match the present data. On the other hand, Nijmegen models are rather consistent. However, we should keep in mind that the NSC96f predicts the attractive potential for this channel and this does not agree with the present understanding for the ΣN interaction.

Furthermore, we performed a phase-shift analysis for the derived differential cross sections to determine the strength of the quark Pauli repulsion quantitatively. The detailed description can be found in Section 6.2 in [10]. An important point in this analysis is that the ΣN (I=3/2) channel is simply represented by 27-plet and 10-plet. Here, the channels represented by 27-plet, such as the ${}^1S_0$ channel in the $\Sigma^+ p$ system, are less uncertain because 27-plet is well- estimated from the NN ($I = 1$) interaction based on the flavor SU(3) symmetry. In the phase shift analysis, we set the phase shifts of ${}^3S_1$ ($\delta_{{}^3S_1}$) and ${}^1P_1$ ($\delta_{{}^1P_1}$) as the fitting parameters, because these two phase shifts are theoretically the most uncertain. Other phase shifts up to D wave were fixed at some values from the Nijmegen model or pp scattering based on the explanation for the 27-plet. Finally, we obtained the momentum dependence of the ${}^3S_1$ phase shift as shown in Fig. 28 (a) in [10]. The absolute values of $\delta_{{}^3S_1}$ range from 20 to 35 degrees in the momentum range of 0.44 - 0.80 GeV/c. Because the sign is expected to be negative from the Σ production spectra in nuclei [18], we have concluded that the quark Pauli repulsion is moderately repulsive.

In E40 experiment, the systematic $d\sigma/d\Omega$ measurements of the Σp interaction were performed. Because all channels are related to each other within the framework of flavor SU(3) symmetry, these data must impose strong constraints on the theories of two-body BB interactions. We expect that "realistic" BB interaction will be constructed in the near future with a collaboration between theories and experiments.

3 Future prospects of the Λp scattering (E86)

Next, we would like to move to future prospects toward Λp scattering. The detailed study of the ΣN interaction can only be performed by the scattering experiment, because Σ is merely bound by nuclei. In contrast, the situation is different for the ΛN interaction. Reliable two-body ΛN interaction is a key to deepen the Λ hypernuclear physics. Indeed, such reliable two-body ΛN interaction is indispensable for deriving the ΛNN three-body interaction from Λ hypernuclear binding energies [17, 19]. This is crucially important to solve the so-called hyperon puzzle in neutron stars [20]. Nowadays, new two-body ΛN data are coming from femtoscopies in heavy ion collision experiments [21], new Λp cross section data from Jlab CLAS [22]. We are also planning a new project at J-PARC to measure the Λp scattering with a polarized Λ beam [12]. Here, we describe a feasibility study using the E40 data at first. Then the expected results in the new experiment are also briefly summarized.

3.1 Feasibility study with E40 data

Important experimental issue is how to identify the Λ production via the $\pi^- p \to K^0\Lambda$ reaction. Actually, the (π^-, K^0) spectroscopy method was not established for a long time due to the difficulty of the K^0 detection. In such a situation, we have newly established a new K^0 detection method where the forward emitted π^+ and the transversely emitted π^- from the K^0 decay are measured by the forward KURAMA spectrometer and CATCH surrounding the target, respectively. The detailed analysis for the Λ identification is written in [23]. Then, Λ can be identified in the missing mass spectrum of the $\pi^- p \to K^0 X$ reaction as shown in Fig. 8 in [23].

Based on the past measurement [24], the Λ spin is expected to be highly polarized with respect to the Λ production plane. We also measured the Λ polarization by measuring the angular dependence of protons from the Λ decay with CATCH. In the coordinate system at rest for Λ, the angular distribution of the emitted proton is represented by the following equation,

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

where P_Λ denotes the Λ polarization and α denotes asymmetry parameter. This asymmetry parameter has been measured with a good precision by BES3 collaboration [25] as

$$\alpha = 0.750 \pm 0.009 \pm 0.004. \tag{2}$$

For the polarization measurement, this α value was used. θ_p is the angle of the proton direction from the polarization axis (normal vector of the Λ production plane) in the coordinate system at rest for Λ. The Λ polarizations were obtained by fitting the proton's angular distribution after the CATCH's acceptance correction with the equation (1). We obtained approximately 100% polarization, which was consistent with the past measurements [24]. The details are described in the Sakao's proceedings of HYP2022. Therefore, it is a big advantage that the highly polarized Λ beam can be used for the Λp scattering experiment.

3.2 Next Λp scattering experiment at J-PARC

This high spin polarization of Λ enables us to measure not only the differential cross section but also spin observables such as analyzing power from left-right asymmetry of Λp scattering and depolarization from the up-down asymmetry of protons from scattered Λ's decay. We have proposed a new Λp scattering experiment using the spin polarized Λ beam at the J-PARC K1.1 beam line [12]. This Λp scattering experiment is one of the flagship experiments at the K1.1 beam line of the Hadron experimental facility extension project [26].

Figure 1 shows the sensitivities of analyzing power (A_y) which were obtained from the left-right asymmetry for the Λp scattering for 5×10^7 Λ beam. The expected statistical error is about 10% for the angular step of $d\cos\theta = 0.2$. In this simulation, $A_y = 0$ is assumed to check the experimental validity easily. Figure 2 shows the simulated results for the depolarization (D_y^y) measurement for 10^8 Λ beam. For this measurement, the polarization of the scattered Λ has to be measured from the up-down asymmetry of the decay proton from Λ with respect to the scattering plane. For the spin observables, there is no experimental constraint so far. Therefore, the theoretical prediction is completely different, especially around the ΣN threshold energy [27]. In the middle momentum range, 10% level accuracy can be achieved for both measurements. We believe that these new scattering data become an important constraint to determine spin-dependent ΛN interaction.

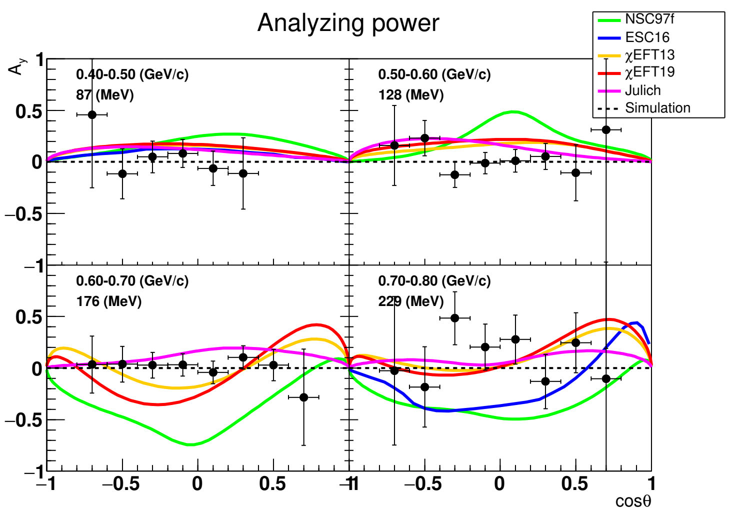

Figure 1. Simulated results for A_y measurement of the Λp scattering in the momentum range from 0.4 to 0.8 GeV/c with 0.1 GeV/c momentum interval for 5×10^7 Λ beam. Two types of Nijmegen models (NSC97f and ESC16 [17]) and Jülich model [28] are presented as the typical example of the boson exchange picture. The two results by chiral EFT (chiral EFT13 and 19) [7, 8] are calculated with the different sets of the LEC parameters both of which reasonably reproduce the YN scattering cross section.

4 Summary

Experimental research on the BB interactions has made great progress in recent years. Femtoscopy has played an important role for studying hadron-hadron interactions between various hadrons produced in high-energy heavy-ion collision experiments. New and accurate

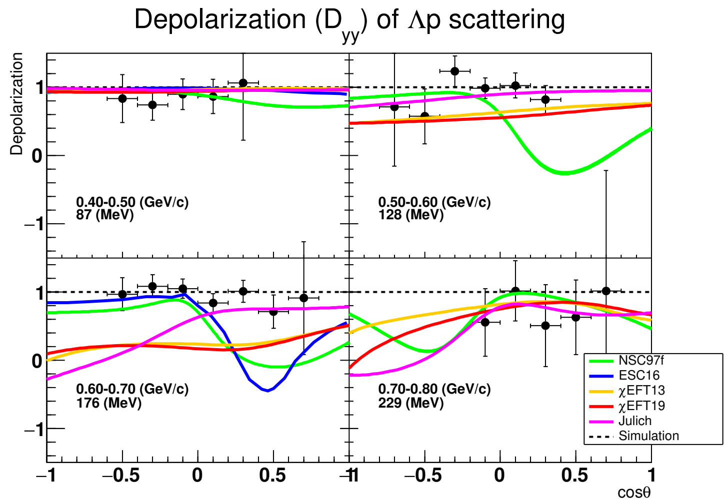

Figure 2. Expected D_y^y accuracy for 10^8 Λ beam. In this simulation, no spin transfer ($D_y^y = 0$) and no induced polarization ($P = 0$) in the Λp scattering are assumed for simplicity. The beam polarization of $P_\Lambda = 1$ is also assumed based on the past measurement. Theoretical calculations are also shown together. Due to the limitation of the statistics, errors in the high momentum region (0.7-0.8 GeV/c) are still large. However, in the middle momentum region (0.5 to 0.7 GeV/c) model difference between the chiral EFT and Nijmegen models can be clearly separated.

hyperon-nucleon scattering data also have become available at J-PARC and Jlab. Especially, we, J-PARC E40 collaboration, succeeded in systematically providing the differential cross sections of the $\Sigma^+ p$, $\Sigma^- p$ and $\Sigma^- p \to \Lambda n$ channels. The accuracy improved to 10% level for a narrow angular step of $d\cos\theta = 0.1$. Any theories cannot reproduce these data consistently. We believe that these data are essential for improving the theories to more realistic ones. In addition, we derived the ${}^3S_1$ phase shift in the $\Sigma^+ p$ channel for the first time by performing a phase-shift analysis for the obtained differential cross section. This phase shift value is directly related to the strength of the quark Pauli repulsion in this channel. We have concluded that the interaction in this channel is moderately repulsive from the obtained phase shift values.

We plan new Λp scattering experiment, J-PARC E86, as a future project. By utilizing a highly polarized Λ beam, we can measure not only the differential cross sections but also spin observables such as analyzing power and depolarization. We believe that these new scattering data become an important constraint to determine the spin-dependent ΛN interaction.

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