Results of analysis of $\Sigma^+ p$ scattering events in J-PARC E40 experiment: differential cross sections and phase shifts of $^3S_1$ and $^1P_1$ states

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Abstract. We performed a novel $\Sigma^+ p$ scattering experiment at the J-PARC Hadron Experimental Facility. Approximately 2400 $\Sigma^+ p$ scattering events were identified by a kinematical consistency check for the recoil proton. The differential cross sections of the $\Sigma^+ p$ elastic scattering were derived with better precision than in previous experiments. By exploiting high-quality differential cross section data and the simple representation of $\Sigma^+ p$ interaction in the SU(3) flavor symmetry, we performed a phase-shift analysis on hyperon-nucleon scattering data for the first time. The absolute value of the phase shift of the $^3S_1$ channel, where a large repulsive force was predicted due to the Pauli exclusive effect between quarks, was evaluated. These results indicate that the interaction of the $^3S_1$ channel in the $\Sigma^+ p$ channel is moderately repulsive, as the Nijmegen extended-soft-core models predicted.

1 Introduction

By investigating interactions between octet baryons (BB interactions), the role of quarks and gluons in the short-range baryon-baryon interaction can be examined. The BB interactions are labeled by six irreducible multiplets as $8 \otimes 8 = 27 \oplus 8_s \oplus 1 \oplus 10^* \oplus 10 \oplus 8_a$. The nuclear force is represented by the 27-plet and 10*-plet and these multiplets are well-known. The other four multiplets are expected to have different features from the nuclear force. Especially, S-wave interactions of the 8_s-plet and 10-plet are predicted to have a quite large repulsive force due to Pauli exclusion principle at a quark level (quark Pauli effect) [1]. Because the $\Sigma N(I = 3/2)$ channel is simply represented by the 27-plet and 10-plet depending on spin and orbital angular momentum states, the $\Sigma^+ p$ interaction is one of the best channels for studying the repulsive nature of the 10-plet. In particular, the $^3S_1$ state in the $\Sigma^+ p$ system is expected to have a large repulsive force due to the quark Pauli effect. This expectation is supported by

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the experimental information on Σ-nucleus interactions: the spin-isospin-averaged repulsive Σ potential [2, 3] and the isospin dependence in $A = 4$ system [4]. All of recent theoretical models, such as the ESC models [5, 6], fss2 [7], the chiral EFT (χEFT) models [8, 9], and lattice QCD calculation [10], predict repulsive $^3S_1$ interactions in the $\Sigma^+ p$ system. However, the strength of the repulsion, that is, the phase shift value of the $^3S_1$ channel, is different from each other and it should be determined from the $\Sigma^+ p$ scattering experiment.

Hyperon-nucleon scattering experiments have been difficult due to the short lifetime of hyperons. Regarding the $\Sigma^+ p$ scattering for the intermediate energy, two experiments to measure the differential cross section were performed at KEK [11, 12]. In these experiments, however, no conclusions could be reached owing to the insufficient precision stemming from low statistics. We, J-PARC E40 collaboration, have recently succeeded in the systematic measurements of $\Sigma^\pm p$ scatterings with high statistics. $\Sigma^- p$ results have already reported in Ref. [13, 14]. In this paper, we report the $\Sigma^+ p$ results, the differential cross sections and phase shifts. Details of analysis are described in Ref. [15].

2 Experiment and analysis

2.1 Experimental concept

The experiment was performed at the K1.8 beam line [16] in the J-PARC Hadron Experimental Facility with π^+ beams of 1.41 GeV/c. A conceptual drawing of the experiment is shown in Fig. 1. Σ^+ particles were produced in a liquid hydrogen (LH_2) target via the $\pi^+ p \to K^+\Sigma^+$ reaction. Then $\Sigma^+ p$ scattering can occur during the Σ^+ flight in the LH_2 target. In order to identify $\Sigma^+ p$ scattering events, the incident Σ^+' s momentum, the recoil proton's kinetic energy, and recoil angle should be determined. The momentum of each Σ^+ particle can be reconstructed as the missing momentum of the π^+ beam and scattered K^+, analyzed using two magnetic spectrometers. Charged particles involved in the produced Σ^+, such as the recoil proton from $\Sigma^+ p$ scattering and a decay proton from $\Sigma^+ \to p\pi^0$ decay, were detected using the CATCH detector system [17] surrounding the LH_2 target.

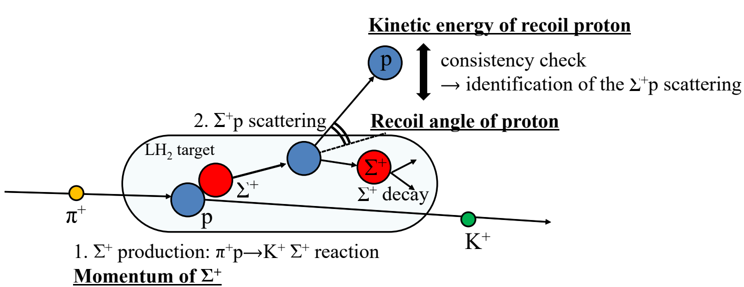

Figure 1. Experimental concept of the $\Sigma^+ p$ scattering experiment. The LH_2 target was used as the target for both Σ^+ production and $\Sigma^+ p$ scattering. $\Sigma^+ p$ scattering events can be kinematically identified by measuring the incident Σ^+'s momentum, the recoil proton's kinetic energy, and recoil angle.

2.2 Identification of $\Sigma^+ p$ scattering events

To identify $\Sigma^+ p$ scattering events, we define the kinematic consistency for the recoil proton as $\Delta E = E_{\mathrm{meas}} - E_{\mathrm{calc}}$, where E_{meas} means the recoil proton's kinetic energy measured using

CATCH and E_{calc} represents the calculated recoil proton's kinetic energy from the incident Σ^+'s momentum and recoil angle. For $\Sigma^+ p$ scattering signal events, ΔE values distribute around 0. Therefore, $\Sigma^+ p$ scattering events could be identified as a peak on backgrounds in the ΔE distribution. Contribution of background reactions, such as the pp scattering following the $\Sigma^+ \rightarrow p\pi^0$ decay and the accidental coincidences were estimated using a Monte Carlo simulation. In total, we identified approximately 2400 $\Sigma^+ p$ scattering events, which is 80 times larger than those achieved in past experiments.

3 Results and discussion

3.1 Differential cross sections

In addition to the numbers of $\Sigma^+ p$ scattering events, we evaluated the total flight length of incident Σ^+s in the LH_2 target and efficiency for the $\Sigma^+ p$ scattering events, including the detection and analysis efficiency, by Monte Carlo simulations. Then, we could calculate differential cross sections. Derived differential cross sections were shown in Fig. 2. The data quality in the present experiment has been improved significantly, with errors of typically less than 20% and a fine angular step ($\Delta \cos \theta = 0.1$). The systematic errors, shown in Fig. 2 as error boxes, came from the background estimation and ambiguity of detection efficiency for low momentum protons. Compared to theoretical calculations, our data is smaller than most theoretical predictions. Especially, FSS and fss2, based on Quark Cluster Model are much larger than the present data. In terms of the differential cross sections, NSC97f[18] agrees well with our data for $p_\Sigma > 0.55$ GeV/c. However, it predicts an attractive $\Sigma^+ p$ interaction, which does not agree with our understanding of the ΣN interaction as mentioned in Sect. 1.

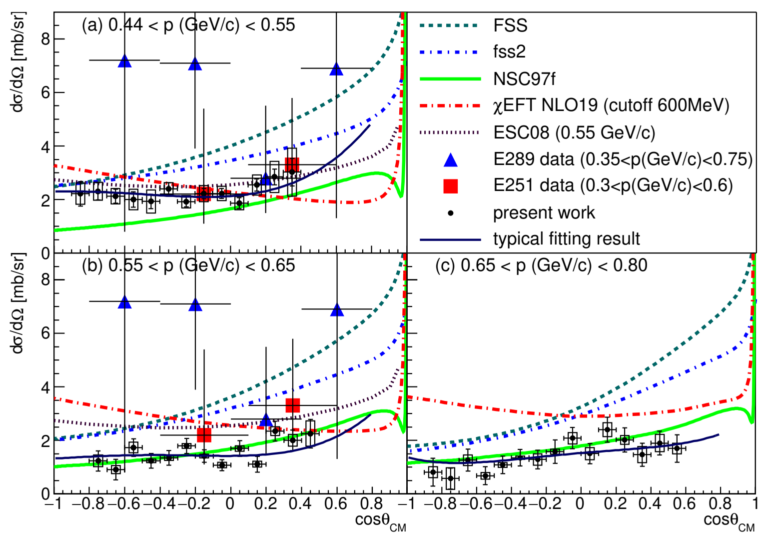

Figure 2. Derived differential cross sections of the $\Sigma^+ p$ scattering for the three momentum regions. The error bars and boxes show the statistical and systematic uncertainties, respectively. The red boxes and blue triangles shows the data of past experiments, KEK E251 and KEK E289. The navy blue lines represents the typical fitting results in the phase shift analysis, described in 3.2. The other lines shows the theoretical calculations.

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3.2 Phase shift analysis

Extracting the contribution of the $^3S_1$ states is important to study the repulsive nature of Σ^+p system due to the quark Pauli effect. For this purpose, we performed a phase-shift analysis. This is the first attempt for hyperon-nucleon scattering data. We represented the differential cross section as a function of eleven phase shifts up to D waves. Nine phase shifts except for the $^3S_1$ and $^1P_1$ states are certain to some extent and can be fixed to reasonable values. Therefore, phase shifts of the remaining two states can be obtained by fitting. The typical fitting results are shown in Fig. 2 and χ^2/ndf are around 1. Obtained phase shifts are shown in Fig. 3. The absolute values of $\delta_{^3S_1}$ are determined within 4 degrees of error. Note that both signs of $\delta_{^3S_1}$ are numerically possible, which can be roughly understood from the fact that differential cross sections would be proportional to $(\sin\delta_0/k)^2$ in the S-wave limit. If the sign is assumed to be negative, the momentum dependence is consistent with ESC16, suggesting that the repulsive force is moderate. In contrast, the obtained $\delta_{^1P_1}$ values deviate considerably in the range of $-5^\circ < \delta_{^1P_1} < 25^\circ$ depending on the set of fixed parameters. Although the results of $\delta_{^1P_1}$ are ambiguous, they may support the predictions of fss2, ESC, and NSC97f, in which the interaction of the $^1P_1$ state in the Σ^+p system is weakly attractive.

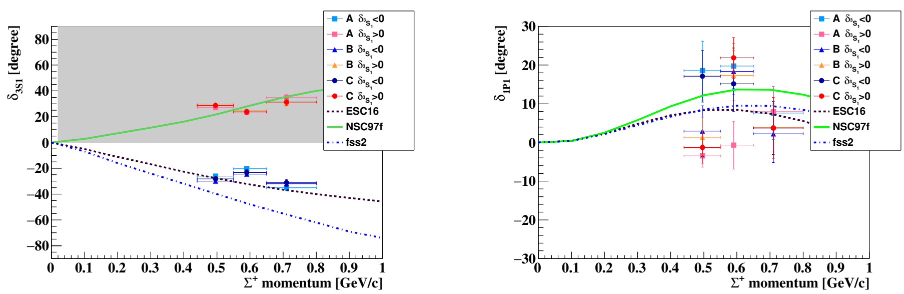

Figure 3. Obtained phase shifts $\delta_{^3S_1}$ and $\delta_{^1P_1}$ as a function of the incident Σ^+ momentum. A, B, and C in the legend correspond to the examined sets of fixed parameters. The black dashed, green solid, and blue dotted lines represent the theoretical calculations of ESC16, NSC97f, and fss2, respectively.

4 Summary

The Σ^+p channel is one of the best channels for investigating 10-plet of the *BB* interaction, which is closely related to the quark Pauli effect. To verify the strong repulsive force due to the quark Pauli effect in the Σ^+p channel, we performed a novel high-statistics Σ^+p scattering experiment at J-PARC. Approximately 2400 Σ^+p scattering events were identified for the incident Σ^+ momentum range 0.44-0.80 GeV/c. The differential cross sections with less than 20 % of errors and a fine angular step were derived. Owing to the precise data points and simple representation of the Σ^+p system, we could derive the phase shifts of the $^3S_1$ and $^1P_1$ states for the first time by performing a phase-shift analysis. Especially, the absolute values of $\delta_{^3S_1}$ range from 20° to 35° in the present momentum range. Comparing these results to theoretical calculations, the Nijmegen ESC models are consistent with present data, which suggests the $^3S_1$ interaction in the Σ^+p system is moderately repulsive. Because theoretical models has been built on little data, our data will be an important input for improving them.

References

[1] M. Oka, K. Shimizu, K. Yazaki, Nucl. Phys. A **464**, 700 (1987)
[2] H. Noumi et al., Phys. Rev. Lett. **89**, 072301 (2002)
[3] P.K. Saha et al., Phys. Rev. C **70**, 044613 (2004)
[4] T. Nagae et al., Phys. Rev. Lett. **80**, 1605 (1998)
[5] T.A. Rijken, M.M. Nagels, Y. Yamamoto, Prog. Theor. Phys. **185**, 14 (2010)
[6] M.M. Nagels, T.A. Rijken, Y. Yamamoto, Phys. Rev. C **99**, 044003 (2019)
[7] Y. Fujiwara, Y. Suzuki, C. Nakamoto, Prog. Part. Nucl. Phys. **58**, 439 (2007)
[8] J. Haidenbauer, S. Petschauer, N. Kaiser, U.G. Meiner, A. Nogga, W. Weise, Nucl. Phys. A **915**, 24 (2013)
[9] J. Haidenbauer, U.G. Meiner, A. Nogga, Eur. Phys. J. A **56**, 91 (2020)
[10] T. Inoue et al., AIP Conf. Proc. **2130**, 020002 (2019)
[11] J.K. Ahn et al., Nucl. Phys. A **648**, 263 (1999)
[12] J.K. Ahn et al., Nucl. Phys. A **761**, 41 (2005)
[13] K. Miwa et al., Phys. Rev. C **104**, 045204 (2021)
[14] K. Miwa et al., Phys. Rev. Lett. **128**, 072501 (2022)
[15] T. Nanamura, K. Miwa et al., PTEP **2022**, 093D01 (2022)
[16] K. Agari et al., PTEP **2012**, 02B009 (2012)
[17] Y. Akazawa et al., Nucl. Inst. Meth. A **1029**, 166430 (2022)
[18] T.A. Rijken, V.G.J. Stoks, Y. Yamamoto, Phys. Rev. C **59**, 21 (1999)