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A Σp Scattering Experiment at J-PARC and the Analysis Status

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J-PARC E40 aims to measure the differential cross sections of the $\Sigma^{\pm} p$ elastic scatterings and the $\Sigma^- p \to \Lambda n$ conversion. A clear peak of Σ^- was observed in a missing mass spectrum of the $\pi^- p \to K^+ X$ reaction and recoil protons from the πp elastic scattering were successfully observed in the data taken in the summer 2018. The rest of data taking is coming in the spring 2019.

KEYWORDS: J-PARC, strangeness, ΣN scattering, scintillating fiber tracker

1. Introduction

The interactions between spin-$\frac{1}{2}$ baryons in the flavor SU(3) symmetry are expected to show unique features depending on each interaction channel [1–3]. For example, in the spin triplet $\Sigma^+ p$ channel, a strong repulsive force in the short range is predicted. On the other hand, the flavor singlet channel which is included in the spin singlet $\Lambda\Lambda$ channel is predicted to be attractive without any repulsive core by a lattice QCD calculation [4]. However, we have not reached sufficient understanding of the interaction between octet baryons, because there exists very little data about the interaction between baryons including one or more strange quarks. The information of the interaction between hyperon (Y) and nucleon (N) has been studied by investigating hypernuclear structures [5]. However, it is not straightforward to extract two-body interaction from nuclear many-body system. In addition, in the case of the ΣN interaction channel, Σ is hardly bounded in nuclei, and ${}^{4}_{\Sigma}$He is the only observed Σ hypernucleus [6], because the spin-isospin averaged interaction between Σ and nuclei is repulsive [7,8]. Although the direct Σp scattering experiments were carried out at KEK, the statistics were quite poor due to hyperon's short lifetime [9, 10]. Therefore, the information of the ΣN interaction is quite limited.

The short range repulsive force in the spin triplet $\Sigma^+ p$ channel is expected to be quite large due to the Pauli blocking effect among the quarks composing Σ and proton. Theoretical models taking into account the quark effect predict the strong repulsive force in this interaction channel [1]. By measuring differential cross section of the $\Sigma^+ p$ elastic scattering with a good accuracy and by comparing it with the theoretical predictions, we can approach the origin of the repulsive force of the spin triplet $\Sigma^+ p$ interaction as well as the repulsive core of the nuclear force.

2. Experiment

J-PARC E40 aims to measure the differential cross sections of the $\Sigma^- p$ and $\Sigma^+ p$ elastic scatterings and also that of the $\Sigma^- p \to \Lambda n$ inelastic scattering within 10% precision [11]. In order to obtain the sufficient statistical accuracy of the differential cross sections, we use a high intensity secondary π beam of 20 M/spill (1 spill is 2.2 second of beam duration with 5.2 second of beam cycle) at the K1.8 beam line in J-PARC. We expect to detect as many as 10^4 events for each of the $\Sigma^+ p$ and $\Sigma^- p$ elastic scattering channels and also as many as 6×10^3 events of the $\Sigma^- p \to \Lambda n$ inelastic scattering channel. $\Sigma^\pm$ are produced via the $\pi^\pm p \to \Sigma^\pm K^+$ reactions in a liquid hydrogen target (LH_2) with a thickness of 2.6 g/cm^2. The beam momenta of 1.32 GeV/c and 1.40 GeV/c are used for the $\Sigma^- p$ channel and for the $\Sigma^+ p$ channel, respectively. The beam momentum analysis is performed by the K1.8 spectrometer, and the momentum analysis for forward scattered particles is performed by the KURAMA spectrometer. The produced Σ is tagged by the missing mass spectroscopy. The following Σp scattering events after the Σ production are reconstructed by measuring the energy and the angle of the recoil proton with detectors surrounding LH_2, combining the information of the spectrometers.

Since we deal with the high intensity beams, we need to take special cares for the detectors which are not designed to be tolerant to such a high count-rate environment. We made special scintillating bars for the TOF wall with an acrylic part in the beam region to reduce the number of accidental triggers and to protect the readout photon detector from such a high counting rate. We disabled the gas amplification for some wires in the drift chambers by disconnecting the potential wires from the bias voltage to protect them from the over current. To recover the Σ yield in the region of the inefficient wires, we placed a new tracking detector made of scintillating bars. The masses of particles were selected in a trigger level to take data of the (π^+, K^+) reaction effectively. In the first level trigger, events with allowed trajectories were selected by gating the hit pattern combinations of the detectors before and after the spectrometer magnet. In addition, they were judged whether they met the gate of allowed time of flight in the second level trigger.

The energy and the trajectory of recoil protons are measured by a dedicated detector system (CATCH) surrounding the LH_2 target. CATCH consists of a cylindrical fiber tracker (CFT), BGO calorimeter, and PiID counter. CFT has two different configurations of fibers; one has fibers arranged in helical to the beam direction, and the other has fibers arranged in parallel to the beam direction. The information of energy deposits in each fiber is obrained as well as timing information. These two types of the fiber layers are placed one after another, and compose eight cylindrical layers of CFT surrounding the target cell. The BGO calorimeter consists of 22 crystals of $Bi_4Ge_3O_{12}$ placed surrounding CFT. The PiID counter consists of plastic scintillating counters, and surrounds the BGO calorimeter for detecting particles penetrating the BGO calorimeter. The construction work of the experimental setup had started in the summer 2017, and had finished in the end of the year.

We took a part of data for the $\Sigma^- p$ channel in June 2018. The allocated beam time was 87 hours in total. This was about 15% of our full plan for the $\Sigma^- p$ channel. Calibration data for CATCH were also taken with 0.5 GeV/c and 0.6 GeV/c proton beams.

3. Analysis and Results

The analysis efficiencies of the KURAMA spectrometer and the K1.8 spectrometer were obtained to be about 85% and 90% even in the high counting rate environment, respectively. The peak corresponding to Σ^- was clearly observed in the missing mass spectrum of the $\pi^- p \to K^+ X$ reaction after requiring the mass of K^+ as shown in Fig. 1. The KURAMA spectrometer and the K1.8 spectrometer showed the sufficient performance to identify the Σ production events.

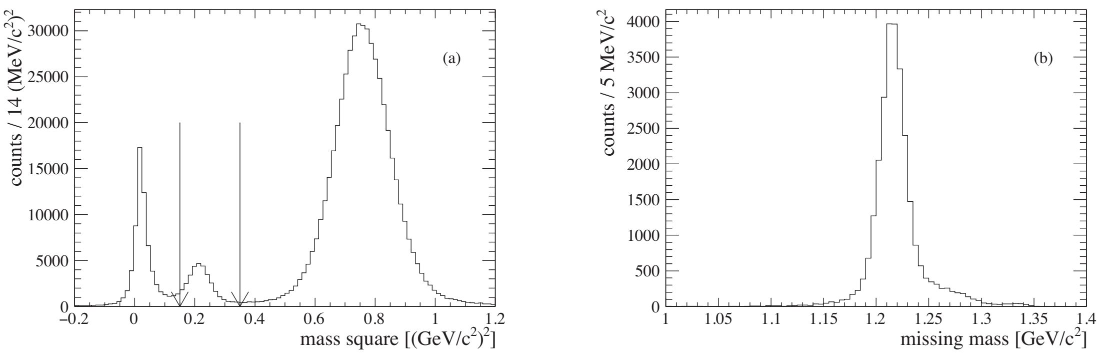

Fig. 1. (a) The mass square spectrum obtained from the KURAMA spectrometer analysis. K^+ was selected in the mass square region of 0.15 - 0.35 (GeV/c^2)^2. (b) The missing mass spectrum with the mass square gate of K^+. A clear peak of Σ^- was observed. The peak shifts to higher mass side because the momentum correction due to energy losses of K^+ in materials is not performed.

The energy informations of the BGO calorimeter and the fibers in CFT were calibrated by comparing the simulation and the proton-proton scattering data with proton beams of 0.50 and 0.60 GeV/c. Since the scattering protons lose its energy and stop in the BGO calorimeter in this momentum region, an event rejection with a hit in the PiID counter, which is placed in the outer side of the BGO calorimeter, is effective for selecting recoil protons. In the Σ^- production data with the 1.32 GeV/c π^- beam, accidental $\pi^- p$ scattering events were clearly observed. A locus of the $\pi^- p$ scattering events was observed in the correlation between particle angle from the beam axis measured by CFT and the energy deposits in the BGO calorimeter as shown in Fig. 2 (a). The calculated correlation between the scattering angle and the energy of the recoil proton supposing the πp elastic scattering is also shown in the figure. The events on the kinematics curve are recognized to be the πp scattering events.

Since the energy loss of proton in a material is much larger than that of π in the energy region of J-PARC E40, we can separate protons from π's by using the information of energy deposits in CFT. Thus, protons and π's are distinguishable in the correlation between the energy deposit in the BGO calorimeter and that in CFT. By selecting the angle range of 60~80 degrees where the πp scattering events are included, the recoil protons can be identified as shown in Fig. 2 (b). CATCH shows a sufficient performance to distinguish proton from π.

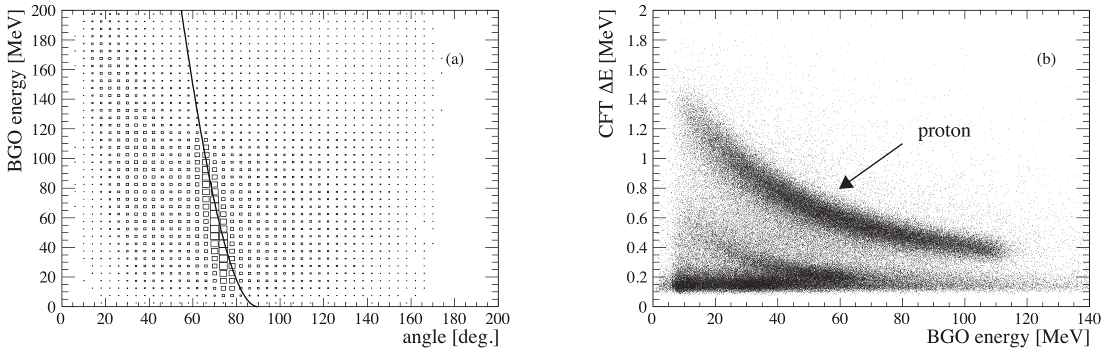

Fig. 2. (a) The correlation between the angle from the beam axis of scattering particles and the energy deposits in the BGO calorimeter. The solid line shows the kinematics curve of the πp elastic scattering without taking the energy loss of particles into account. The clear locus of the πp elastic scattering events was observed. (b) The correlation between energy deposit in the BGO calorimeter and energy deposit ΔE per single fiber thickness (1 mm). The energy deposits in fibers was corrected by the angle from the beam axis of scattering particle. The clear locus of the recoil protons was observed above that of the scattered π's.

4. Summary and Prospects

The interaction between Σ and nucleon is expected to be a key to understand the origin of the repulsive core of the nuclear force. However the information of the ΣN interaction is quite scarce due to the experimental difficulty. J-PARC E40 developed a sophisticated method to reconstruct the $\Sigma^{\pm} p$ scattering events with CATCH and the spectrometers. We confirmed the feasibility of the system of the experiment during the run in 2018. A clear missing mass peak of Σ^- in the $\pi^- p \to K^+ X$ reaction was observed by the spectrometers, and the $\pi^- p$ elastic scattering events and the recoil proton were successfully detected by CATCH. We will accumulate more data for the $\Sigma^- p$ channel, and take data for the $\Sigma^+ p$ channel in the coming beam time in 2019.

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