Performance Evaluation of Newly Developed Recoil Proton Detection System "CATCH" with pp Scattering at 80 MeV

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A scattering experiment between a Σ hyperon and a proton is planned at J-PARC K1.8 beam line (J-PARC E40 experiment[1)]) in order to investigate the baryon-baryon interaction and to confirm the repulsive force due to the Pauli effect in quark level, which is considered as one of the origins of the repulsive core in the nuclear force. The quark Pauli effect has not been confirmed experimentally. In order to compare the measured cross section with predicted ones from theoretical models with and without this effect, the accuracy of the measured differential cross section of the Σ^+p elastic scattering reaction is required to be better than ±10% at 3 mb/sr. We also derive Σ-nucleon interaction systematically from the cross section of the Σ^+p and Σ^-p elastic scatterings and the $\Sigma^-p \rightarrow \Lambda n$ reaction.

In order to identify the Σp scattering event kinematically, we need to measure the momentum vector of the Σ beam and the scattering angle (trajectory of recoil proton) and the kinetic energy of the recoil proton. We will use two spectrometer systems installed at the upstream and at the downstream of a liquid hydrogen target. The momentum of Σ particle produced in the target by a $\pi p \rightarrow \Sigma K^+$ reaction is reconstructed by the momenta of the incident π beam and scattered K^+ measured by each spectrometer. In addition to the spectrometer system, a detector system for a recoil proton is necessary and required to measure the trajectory and the energy of the recoil proton. Since a high intensity π beam of 20 MHz is used in this experiment for the Σ production, a sufficient time response is also required for the detector. For this reason, we developed a new detector system, so called "CATCH" (Cylindrical Active Tracker and Calorimeter system for Hyperon-proton scattering).

CATCH is designed to have a large acceptance by covering 300 mm thickness of the liquid hydrogen target cylindrically with a long sensitive area of 400 mm in the beam direction. CATCH consists of a Cylindrical Fiber Tracker (CFT) and a bismuth germanate (BGO) calorimeter as shown in Fig. 1.

CFT is a tracking detector with a fast time response made of 5,000 scintillation fibers with a diameter of 0.75 mm. In order to reconstruct trajectories three dimensionally, we fabricated two types of cylindrical layers where fibers are placed with the straight and spiral configurations on the surface of the cylindrical layer, respectively. As for the BGO calorimeter, 24 BGO crystals are placed for surrounding CFT and are used to measure the kinetic energy of the recoil proton. The size of one crystal piece is $30\times25\times400$ mm^3.

After each detector was fabricated, CFT and the BGO calorimeter were combined together as CATCH. We developed such a new detector system by taking a long time. Especially, since CFT uses a large number of scintillation fibers and has a special shape, it required a lot of R&D. In these development periods including the development of the BGO calorimeter, we also performed test experiments at CYRIC to evaluate the performance of the prototype[2)]. Reflecting these feedbacks, we completed the construction of the actual type of CATCH at the end of 2016.

In order to evaluate the performance of CATCH system for the first time, we performed a pp and pC scattering experiment at CYRIC (Tohoku University) in January 2017. A Polyethylene (CH_2) target of 800 μm thickness installed inside CATCH was irradiated by an 80 MeV proton beam, and scattered protons were measured by CATCH. The measurement accuracy of the differential cross section was evaluated by deriving it from the scattered protons measured by CATCH. Also, we examined energy and fiber position calibration methods and aimed to establish analysis method.

The angular resolution of CFT and the energy resolution of BGO calorimeter are required to be better than 2 degrees (σ_θ) and 3 MeV (σ), respectively for the identification of the scattering reactions. The angular resolution was evaluated to be 1.6 degrees (σ_θ) from the opening angle between two protons emitted from pp scattering. The energy calibrations of CFT and the BGO calorimeter were performed by using the relation between the energy of the scattered protons and the scattering angle θ measured by CFT. The energy resolution of the BGO calorimeter was obtained to be 1.5 MeV (σ) for 80 MeV proton, and that of CFT was obtained to be better than 20% for the energy deposit of a proton in CFT (8 MeV ~ 20 MeV). These performances satisfy our requirements for the Σp scattering experiment. As a result of the energy calibration, the correlation between the scattered proton’s energy and the scattering angle θ was consistent with the kinematic calculation as shown in Fig. 2.

The differential cross sections of pp and pC scatterings were derived by the number of the identified event by CATCH system. Data were taken with three different target positions to investigate the position dependence of the CATCH performance which has a long active region. We could only derive the relative cross sections due to a problem in the measurement of the absolute beam intensity. However, we found that the angular distributions of the obtained relative differential cross sections were consistent with the reference results as shown in Fig. 3. The difference between the measured result and the reference data is regarded as a systematic error in the cross section, which was found to be within ±10%. It satisfies the requirement for the Σp scattering experiment of ±10%. The almost same result was obtained for the pC scattering reaction. These results suggested that we have established an analysis method for deriving the cross section for the newly developed CATCH system.

In conclusion we fabricated the CATCH system and performed the test experiment for the first time. As the results of the performance evaluation, the systematic error in the cross section is within ±10%. We have confirmed that the CATCH system has sufficient performances for the Σp scattering experiment at J-PARC. Although we also took a proton-deuteron scattering data with a Deuteron gas target for study of the three-nucleon forces, it is currently under analysis.

References

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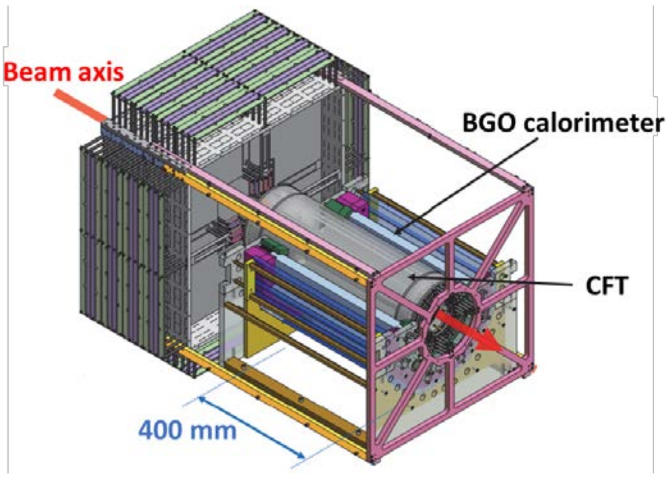

Figure 1. CATCH consists of a Cylindrical Fiber Tracker (CFT) and a BGO calorimeter. It surrounds the target cylindrically in order to measure the recoil proton with a large acceptance.

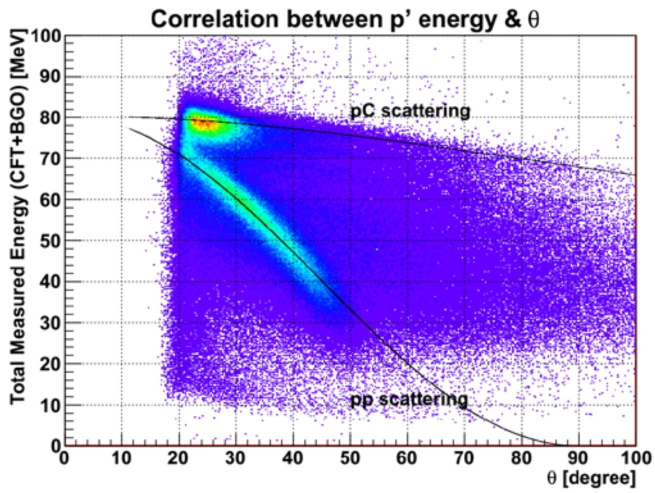

Figure 2. The correlation between the energy and the scattering angle θ of the scattered proton measued by CATCH. It was consistent with the kinematical lines of pp and pC scatterings.

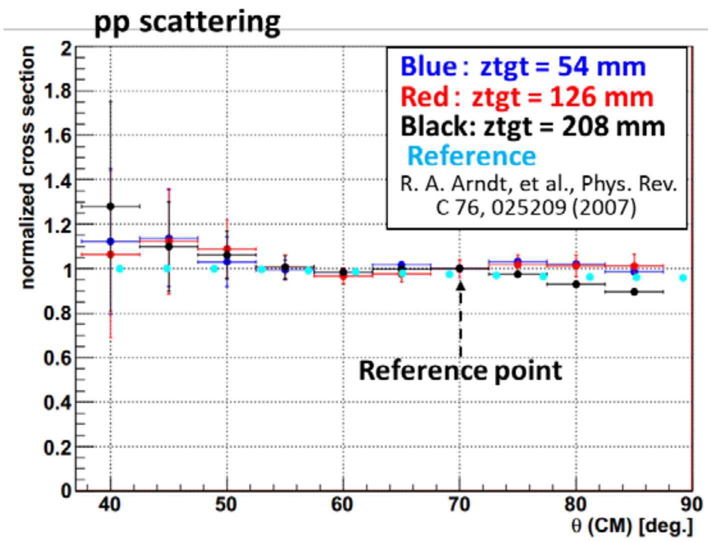

Figure 3. The angular distributions of the obtained relative differential cross sections for three target position. They are consistent with the reference results within ±10% of a systematic error.