Letter of Intent
for an experiment at the 50-GeV PS

A Hyperon-Nucleon Scattering Experiment using a SCIFI-MPPC System

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Abstract

A hyperon-nucleon (YN) scattering experiment gives unique information in order to understand YN interactions. It is important to understand the nuclear force from the quark level by introducing a new degree of freedom, “strangeness”. A YN scattering experiment is difficult due to the short life of hyperons. Therefore the realistic way to investigate YN interactions has been to measure the structure of hypernuclei using a high resolution spectrometer or germanium detectors. However there could be uncertainties to derive a two body YN interaction from the many body system. Therefore, the YN scattering experiment is the most fundamental way to investigate the YN interactions.

At KEK-PS E289 and E456 experiments, a scintillation fiber (Scifi) active target was used to detect both a production of hyperon and a scattering of hyperon and nucleon as an image. The feasibility of Scifi target was shown. However the statistics of the YN scattering data was still poor, because Image Intensifier Tube, the readout system of Scifi, was slow and could not operate at the high beam intensity.

Here we would like to propose a new YN scattering experiment using Multi Pixel Photon Counters (MPPC) for the readout system of the Scifi. The MPPC is a new Si photo-diode consisted of many pixels of Avalanche Photo Diode, each of that operates in a Geiger mode. The characteristics are following.

- The time response is fast ($<$ 10ns) and MPPC can operate at a high intensity beam.
- The Gain is large ($10^5 \sim 10^6$) and MPPC can detect 1 photon.
- MPPC can operate in a magnetic field.

Because MPPC can operate in a magnetic field, it is possible to surround the Scifi by a tracking chamber and a solenoid magnet. Using the tracking chamber, we can measure the momenta of particles which do not stop in the Scifi. This leads an increase of the acceptance for the charged particles in the final state. In this experiment, Scifi detector is focused to detect the scattered proton and hyperon as an image. The first target of YN scattering experiment is $\Sigma^+ p$ scattering. The Σ^+ hyperons are produced via the (K^-, π^-) reactions. **We need a 1.1 GeV/c K^- beam because the production cross section of Σ^+ becomes maximum. Moreover, in order to fix the production point of the hyperon, a pencil beam whose size is small is desirable.**

In this experiment, with the advantages of both using a high intensity beam and a large acceptance for charged particle, we aim a high statistics YN scattering experiment. By using a 1.1 GeV/c K^- beam whose intensity is more than 1MHz, about 1000 $\Sigma^+ p$ scattering events can be detected within one month beam time.

1 Introduction

It is one of the most important subjects of strangeness nuclear physics to extend the nuclear force to the baryon-baryon (BB) interaction including hyperon-nucleon (YN) interactions and understand its features. The nucleon-nucleon (NN) force is well described by one-meson exchange model. By introducing a new freedom "strangeness", we want to understand the BB interaction from the level of quark and gluon which are the fundamental degrees of freedom of the strong interaction.

Theoretically there are two groups working on this subject vigorously. The Nijmegen group extended one-boson exchange (OBE) model to the YN sector to understand the NN interaction as the strong interaction between the baryon octet[1]. The quark-cluster model takes into account the freedom of quarks and gluons and tried to explain the short-range repulsive force of the strong interaction[2, 3].

From the experimental viewpoints, the YN scattering experiment is the most fundamental way in order to understand its interaction, like the nuclear force has been understood based on the abundant data of the NN scattering. However the YN scattering is difficult due to the short life time of hyperons and data of the YN scatterings are quite poor compared with the NN scattering [4]. As the realistic way to investigate the YN interactions, it becomes popular to derive the two body ΛN interaction from the structure of Λ hypernuclei. A high resolution spectroscopy using a magnetic spectrometer and γ-ray spectroscopy using a germanium detector have revealed the ΛN interaction [5]. However there could be uncertainties in deriving the two-body interaction from the complex many-body system. Moreover it is not clear whether the ΣN and ΞN interactions could be obtained from the structure of the hypernuclei. Therefore it is quite important to investigate the YN interactions from the YN scattering experiment.

We are thinking that the first target of the YN scattering experiment is the $\Sigma^+ p$ scattering. In the ΣN interaction, there are four isospin(I)-spin(S) components;(I, S)=(3/2, 1), (3/2, 0), (1/2, 1), (1/2, 0). By measuring the $\Sigma^+ p$ interaction, the component of $I = 3/2$ can be studied. The component of $(I, S) = (3/2, 1)$, which accounts for 75% of the $I = 3/2$ component, is predicted by the quark-cluster model to have an extremely repulsive hard-core due to the Pauli effect between quarks. The potential which the Σ particle feels in a nucleus is suggested to be quite repulsive from the continuous spectrum of the Σ production via the $^{28}Si(\pi^-, K^+)$ reaction measured at the KEK-PS [6]. This repulsive force can not be explained by any OBE models. There is a possibility that this repulsive potential is attributed to the repulsive force due to the quark Pauli effect in the (I, S)=(3/2, 1) component. Therefore it is quite important to measure the $\Sigma^+ p$ scattering to study the (I, S)=(3/2, 1) component directly.

In the KEK-PS, the YN scattering experiments (KEK-PS E289, E452) have been carried out with active targets using a Scintillation Fiber (Scifi) and a bulk Scintillator (SCITIC) [7, 8]. In the E289 experiment, the trajectories of the hyperon and scattered proton were detected as an image using a Scifi and Image Intensifier Tube (IIT) as its readout. The cross sections of ΛN, $\Sigma^+ N$ and $\Sigma^- N$ elastic scatterings were measured. While the feasibility of using the active target was shown, the observed event number was ∼30, not sufficient. The reason of this poor statistics was slow operation of IIT. IIT can not operate in the beam intensity of more than 10^5. Moreover it is difficult to detect all particles in the final state within the Scifi.

In this proposed experiment, we would like to propose a new YN scattering experiment using a fast photon detector, Multi Pixel Photon Counter (MPPC) for the readout of the Scifi.

2 The Readout System of Scifi using MPPC's and its Characteristics and Problems to be Solved

Multi Pixel Photon Counter (MPPC) is a new type of photon counting device. The MPPC has a sensitive surface of 1mm × 1mm, which consists of multiple Avalanche Photo Diode (APD) pixels operating in Geiger mode. Each APD pixel of the MPPC outputs a pulse signal when it detects one photon. The signal output from the MPPC is the total sum of the outputs from all APD pixels. The following are the features of the MPPC.

- The time response is fast and better than 10ns. This enables the operation in the high beam intensity.
- The gain is as high as $10^5 \sim 10^6$. The detection of one photon is possible.
- The MPPC is insensitive to magnetic field. It is possible to place a Scifi system using MPPC readouts in the magnetic field being surrounded by a tracking chamber.

However,when MPPC is used for the readout of Scifi, each fiber should be read by one MPPC. Huge amounts of MPPC are necessary. For example, in order to read a Scifi of 10cm×10cm×20cm consisted of fibers of 1mm×1mm, 20,000 channels of MPPC are necessary. Therefore the size of Scifi must be as small as possible in order to avoid this problem. In this experiment, the role of Scifi is concentrated on detecting the image of the Σ^+p scattering event. The detection of the particles at the final state is entrusted to the tracking chamber surrounding the Scifi. By separating the role of Scifi and the chamber, we make the size of Scifi as small as possible.

2.1 Size of Scifi

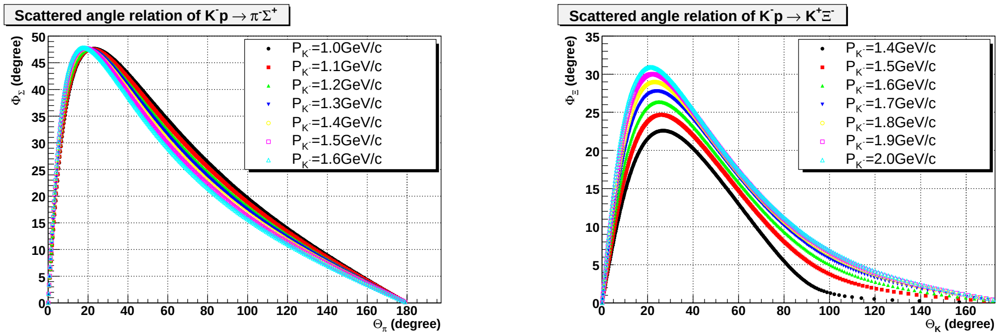

Figure 1: Relation between the scattered angles of hyperon and meson produced by the $K^-p \to \pi^-\Sigma^+$ and $K^-p \to K^+\Xi^-$ reactions.

The size and installation location of the Scifi should be determined by considering the kinematics of the production of hyperons. The $K^-p \to \pi^-\Sigma^+$ and $K^-p \to K^+\Xi^-$ reactions are considered as production reactions of hyperons. The relations of the scattered angles of the produced hyperons and mesons are shown in Figure 1. While the meson is produced in all angles, the hyperon is produced in forward angle less than 50°. If the hyperon-production target and the Scifi are separated, all hyperons can be detected with the Scifi by covering the forward region of the production target with the Scifi as show in Figure 5. Now the size of the Scifi is determined by the flight length of hyperons because the production position is fixed at the production target. Figure 2 shows the flight length of Σ^+ and the relation between the flight length and the momentum. From this study the size of the Scifi is estimated to be enough for 3cm×3cm×3cm. This size is much smaller than that used in the E289 experiment where a Scifi of 10cm×10cm×20cm(beam direction) was used.

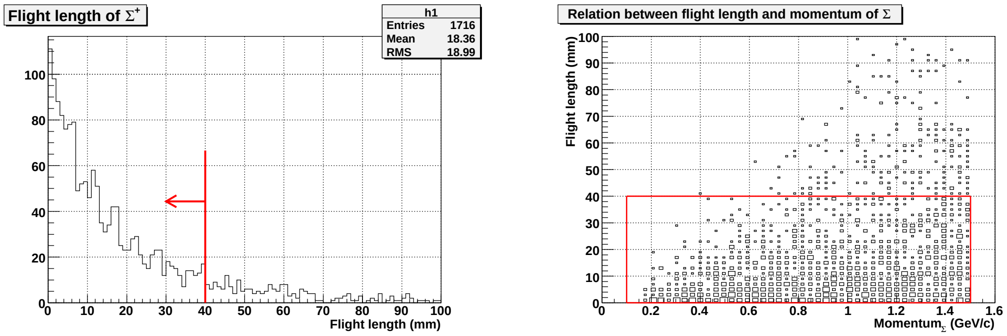

Figure 2: Flight length of Σ^+ and the relation between the flight length and momentum.

2.2 Detection of Scattered particles and decay products from hyperons

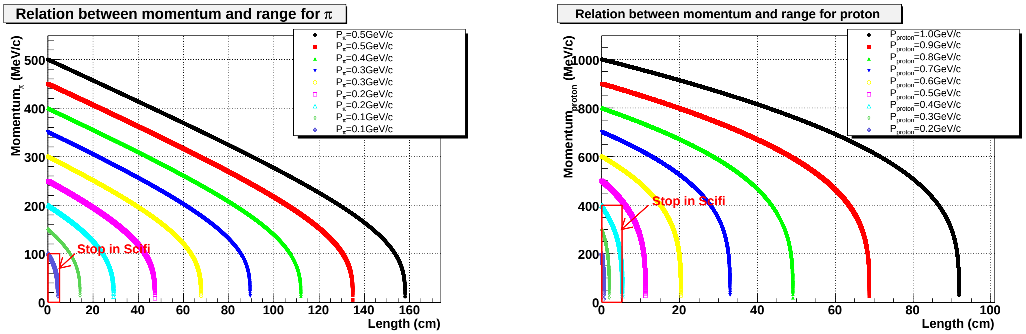

Figure 3: Relation between the range and the momentum for π and proton in the Scifi. Particles inside the box stop in the Scifi.

In the E289 experiment, the charged particles such as scattered proton and decay products from hyperon were made stop in the large Scifi detector. The momentum was determined from the range. In this experiment, because the size of the Scifi is small, many of produced charged particles go to outside of the Scifi. In order to detect the particles and determine these momenta, we use two different ways. At first, for charged particles of low energy which stop in the Scifi, the momentum is determined from the range. The other way is for particles which go to outside of the Scifi. In order to detect such particles, we will place a tracking chamber such as a Cylindrical Drift Chamber (CDC) or a Time Projection Chamber (TPC) around the Scifi, which determines momenta of particles from the trajectories in a magnetic field. Figure 3 shows the relations between the range and momentum for π and proton in the Scifi for several initial momenta. Protons and π's whose momenta are less than 0.4 GeV/c and 0.1 GeV/c, respectively, stop inside the Scifi. The particles with more than the threshold momentum go to the outside and are detected by the tracking chamber. This setup is enabled by the MPPC which can operate in a magnetic field.

3 General Concept of the Experiment

3.1 Hyperon production reaction

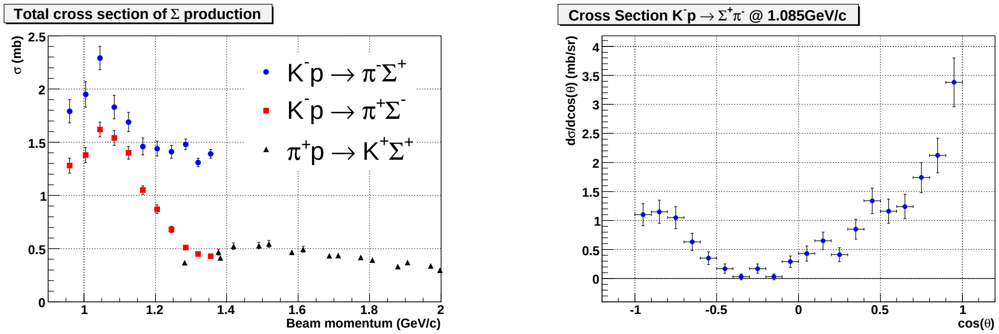

Figure 4: Left : Total cross section of Σ production for K^- and π^+ beams and its relation with the beam momentum [9, 10]. Right: Differential cross section of the $K^-p \to \pi^-\Sigma^+$ reaction at beam momentum of 1.085 GeV/c [9].

We are thinking that the first target of the experiment is the Σ^+p scattering. The left figure of Figure. 4 shows the beam momentum dependence of the production cross sections for the $K^-p \to \pi^\mp\Sigma^\pm$ and $\pi^+p \to K^+\Sigma^+$ reactions [9, 10]. In the (K^-, π^-) reaction, the cross section reaches its maximum of ~2mb around 1.1 GeV/c. On the other hand, in the (π^+, K^+) reaction, the cross section reaches its maximum of 0.5mb at 1.5 GeV/c. Taking into account the cross section of the elementary process and the life time of produced meson for each reaction, the (K^-, π^-) reaction is more suitable for the experiment. Therefore we request a 1.1 GeV/c K^- beam in order to produce Σ^+'s via the $K^-p \to \pi^-\Sigma^+$ reaction. The beam intensity is requested to be more than 10^6 K^-/spill. Moreover, in order to restrict the position of the produced hyperon, the beam size is desired to be quite small.

3.2 Experimental setup

Figure 5 shows the schematic drawing of the experimental setup. The Σ^+ particles are produced via the (K^-, π^-) reaction using a 1.1 GeV/c K^- beam. The Σ^+ production target is put in front of the Scifi. For the production target, a CH_2 of 2cm thickness is used. The forward magnetic spectrometer is located in the left side from the beam direction in order to detect π^-'s produced via the (K^-, π^-) reaction. In the other side, the Scifi is placed to detect the produced Σ^+. The Scifi is located in the magnetic field of ~1T. The CDC is placed around the Scifi in order to detect charged particles which do not stop in the Scifi. By the forward magnetic spectrometer, the (K^-, π^-) reaction is identified for the π^-'s emitted to the forward region from $0^\circ \sim 30^\circ$. For π^-'s emitted to more than 30°, the π^- is detected by the CDC spectrometer around the target. The acceptance for the (K^-, π^-) reaction becomes 1.5 times larger by installing the CDC spectrometer. The momentum range for Σ^+'s also becomes wider up to 1.5 GeV/c. Figure 6 shows a typical event display of the Scifi and CDC. One can understand how the combination of the Scifi and CDC system works.

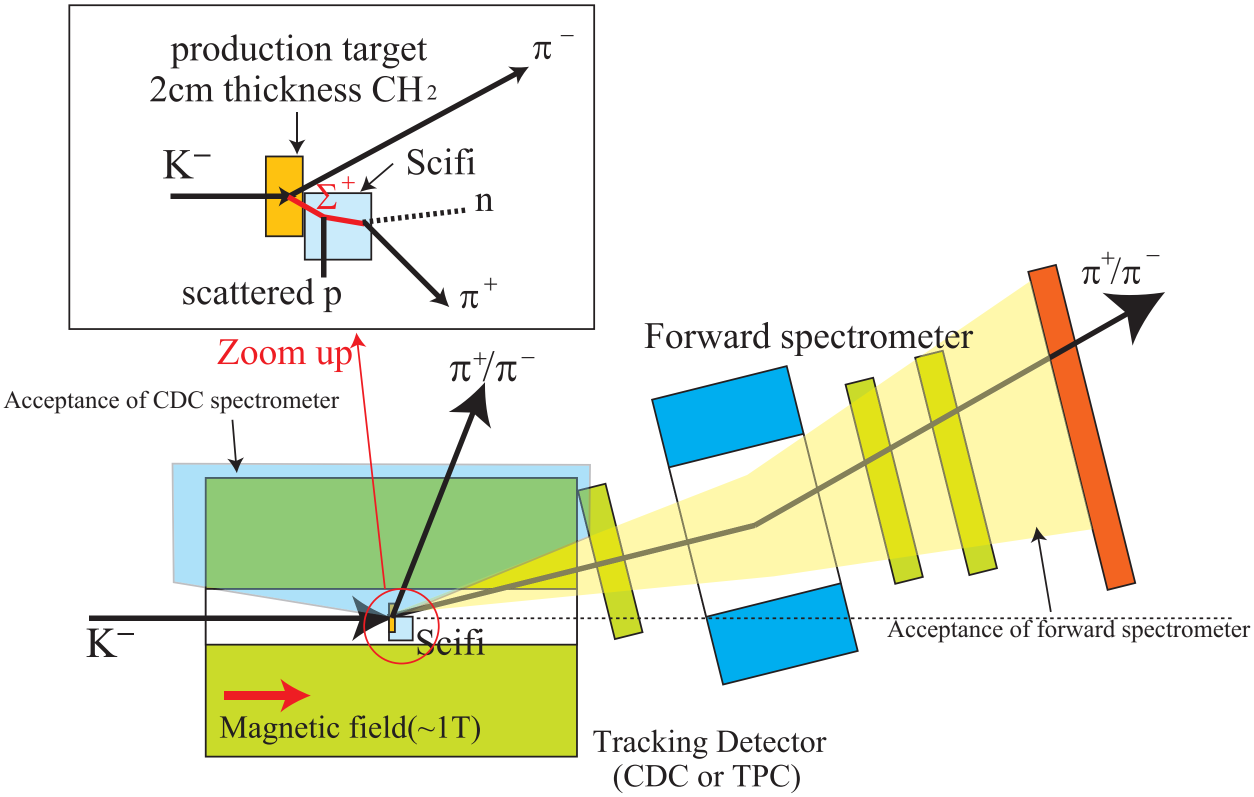

Figure 5: The schematic drawing of the experimental setup. The upper figure is the enlarged figure around the Scifi. The Σ^+ production target of a CH_2 of 2cm thickness is placed in front of the Scifi. The Σ^+ produced in the target is guided to the Scifi. The size of the Scifi is 3cm×3cm×3cm. Many of the charged particles such as scattered proton and decay products from Σ^+ do not stop inside the Scifi and go to the outside. In order to detect such particles, a tracking chamber such as a CDC is placed around the Scifi. The forward magnetic spectrometer is placed in order to identify the (K^-, π^-) reaction and covers the forward region of scattered angles between $0^\circ \sim 30^\circ$. The π^-'s emitted to more than 30° are detected by the CDC spectrometer. For all scattered angles of π^-'s, the produced Σ^+ goes to the Scifi. When the π^- is detected by the forward spectrometer, one or two charged particles are detected by the CDC. When the π^- is detected by the CDC, two or three charged particles including the π^- are detected by the CDC.

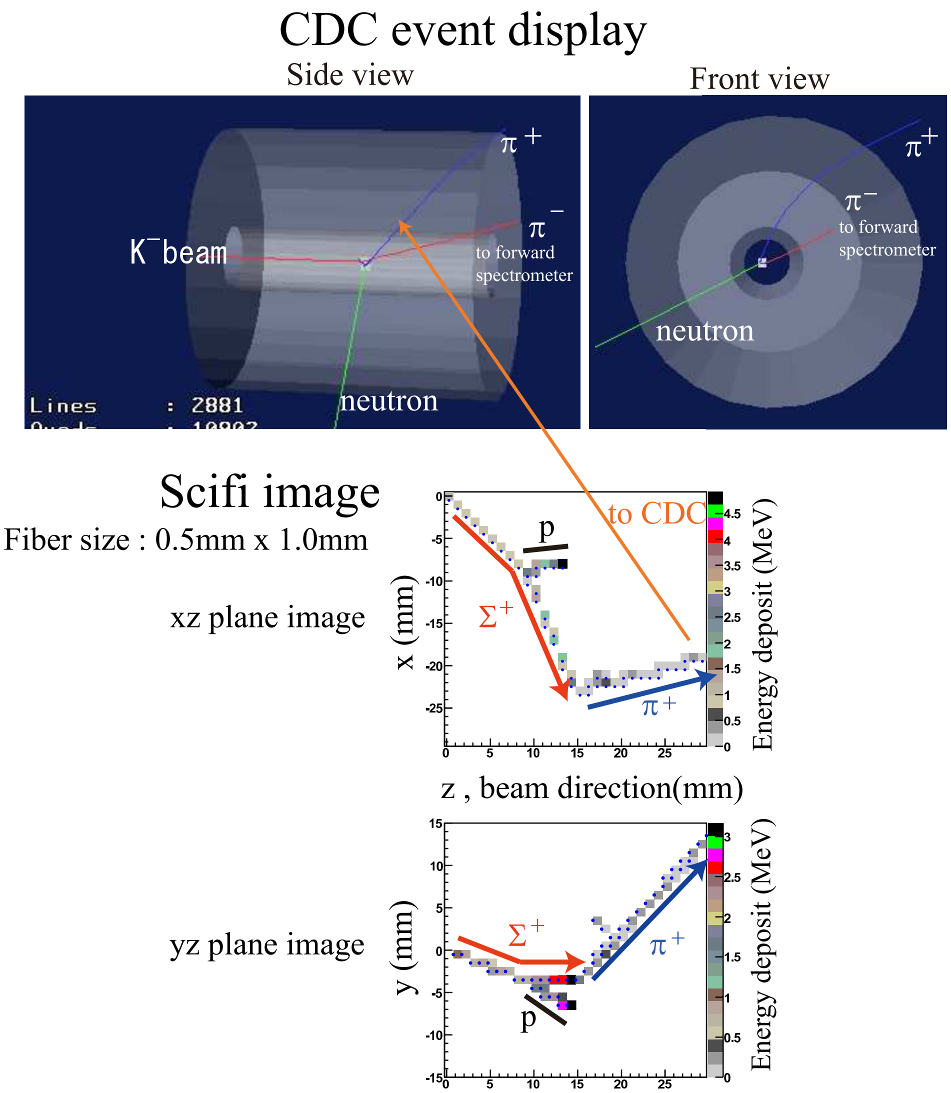

Figure 6: Typical event display of the CDC and Scifi for a $\Sigma^+ p$ scattering event. In this event, the π^- produced via the $K^- p \to \pi^- \Sigma^+$ reaction is detected by the forward spectrometer. The bottom two histograms show the images detected by the Scifi in the XZ and YZ planes. The Σ^+ particle is scattered by a proton. The scattered proton stops in the Scifi. The scattered Σ^+ decays into neutron and π^+ which goes to the outside of the Scifi. The π^+ is detected by the CDC and its momentum is analyzed.

3.3 Requirement for the Scifi-MPPC System

The following are the requirements for the Scifi-MPPC system.

1. Because the Scifi consists of $(\mathrm{CH})_n$, Σ^+ is scattered by both of a free proton ($\Sigma^+ p$ scattering) and protons in the carbon nuclei (quasi-free $\Sigma^+ p$ scattering). The $\Sigma^+ p$ scattering event has to be distinguished from the quasi-free $\Sigma^+ p$ scattering event. For this purpose, the scattering is required to occur on the same plane defined by the Σ^+ beam and the scattered Σ^+. The Scifi-MPPC system is required to have a sufficient angular resolution to distinguish these two kinds of scatterings.

2. The Scifi-MPPC needs a wide dynamic range of energy measurement to measure the energy deposits for minimum ionization particle (MIP) and low momentum proton. Typical energy deposits for MIP and such proton are a few hundred keV and a several MeV, respectively.

3. The Scifi-MPPC system has to measure the momentum from the range.

We discuss the most important topic, angular resolution. The angular resolution of a track depends on both size of the fiber and a flight length of hyperon. If fibers with a fine size are used, the angular resolution is improved. However channel number of the readout MPPC increases and the cost also increases. The realistic sizes of the fiber are 1mm×0.5mm(beam direction) or 1mm×1mm that correspond to 1800 channels and 900 channels for the readout of 3cm×3cm×3cm Scifi, respectively. Figure 7 shows the relation between simulated angular resolution and the flight length of hyperon for each fiber size. As a reference, the resolution obtained in E289 is also shown. The same angular resolution with E289 can be achieved by using the 1mm× 0.5mm fiber.

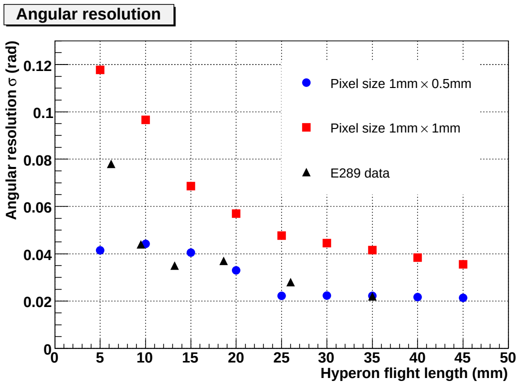

Figure 7: Relation between simulated angular resolution and a flight length of hyperon for 1mm×0.5mm and 1mm×1mm fibers. As a reference, the resolution obtained at E289 is also shown.

3.4 Acceptance of CDC

Charged particles in the final state of Σ^+p scattering such as scattered proton and decay products from Σ^+ are detected by CDC which surrounds the Scifi. The emitted angle distribution (polar angle from the beam direction) and momentum distribution for each particle are estimated. Figure 8 shows the results. For the angular dependence of the $K^- p \rightarrow \pi^- \Sigma^+$ reaction, the differential cross section of Figure 4 is taken into account. The $\Sigma^+ p$ scattering is assumed to be isotropic in the center-of-mass system. The almost all scattered protons are emitted to 90 degree direction from the beam. Therefore they are almost within the acceptance of CDC. On the other hand, π^+ and protons, the decay products from Σ^+, show wide angular distributions. If CDC can cover from 30°

to 150°, the acceptance of CDC for such particles is ∼80%. The momentum distributions for each particle are also shown in Figure 8. The momentum ranges from 0 GeV/c to 1.2 GeV/c.

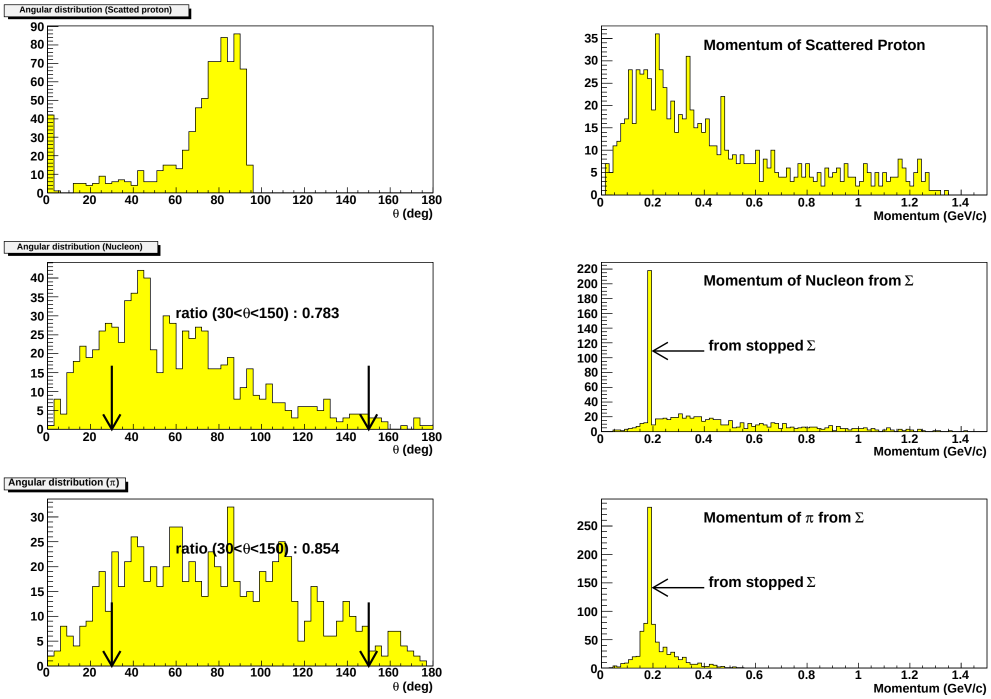

Figure 8: Left figure: Angular distribution for the charged particles in the final state. Right figure:momentum distribution for each particle

3.5 Advantages obtained by detecting all charged particles in the final state

In this experiment all charged particles in the final state can be detected by both of the Scifi and CDC located around the Scifi. Figure 9 shows the typical event display of the Scifi and CDC. In the event display of the Scifi, the tracks reconstructed from CDC are extrapolated onto the image of the Scifi. The following are the advantages obtained by detecting all charged particles in the final state.

1. Quasi-free scattering with proton in carbon nuclei can be rejected using the kinematical condition.
2. By measuring the charged particle from decay of Σ^+, momentum of the Σ^+ can be reconstructed.
3. The extrapolated tracks from CDC help to understand the complex image of the Scifi where two tracks overlap like the bottom figure in Figure 9.

By measuring the momentum and emitted angle of the decay product (proton or π) from Σ^+, the momentum of the Σ^+ after the scattering can be reconstructed. When the momentum and the scattered angle of the Σ^+ are known, if elastic scattering is assumed, the momentum and the scattered angle of the scattered proton can be expected. The Σ^+p scattering with a free proton and quasi-free Σ^+p scattering can be distinguished by checking whether the real measurement of the momentum and the emitted angle of the scattered proton is consistent with the expectation or not. When the momentum and scattered angle of Σ^+ after the scattering are known, the momentum of the Σ^+ before the scattering can be obtained. For the production target of Σ^+, CH_2 is used. When the Σ^+ is produced from a free proton in the CH_2, the momentum of the Σ^+ (we call "Σ^+ beam") can be measured by detecting K^- and π^- using spectrometers. However, when the Σ^+ is produced from quasi-free proton, the momentum of the Σ^+ beam can not be obtained by the same way. In the E289 experiment, such Σ^+ beam was not analyzed because the momentum of the Σ^+ beam was unknown. In this experiment, the momentum of the Σ^+ beam can be reconstructed from the kinematics. Therefore the Σ^+ beam produced from quasi-free proton can be used for analysis, that leads two times larger statistics of $\Sigma^+ p$ scattering event.

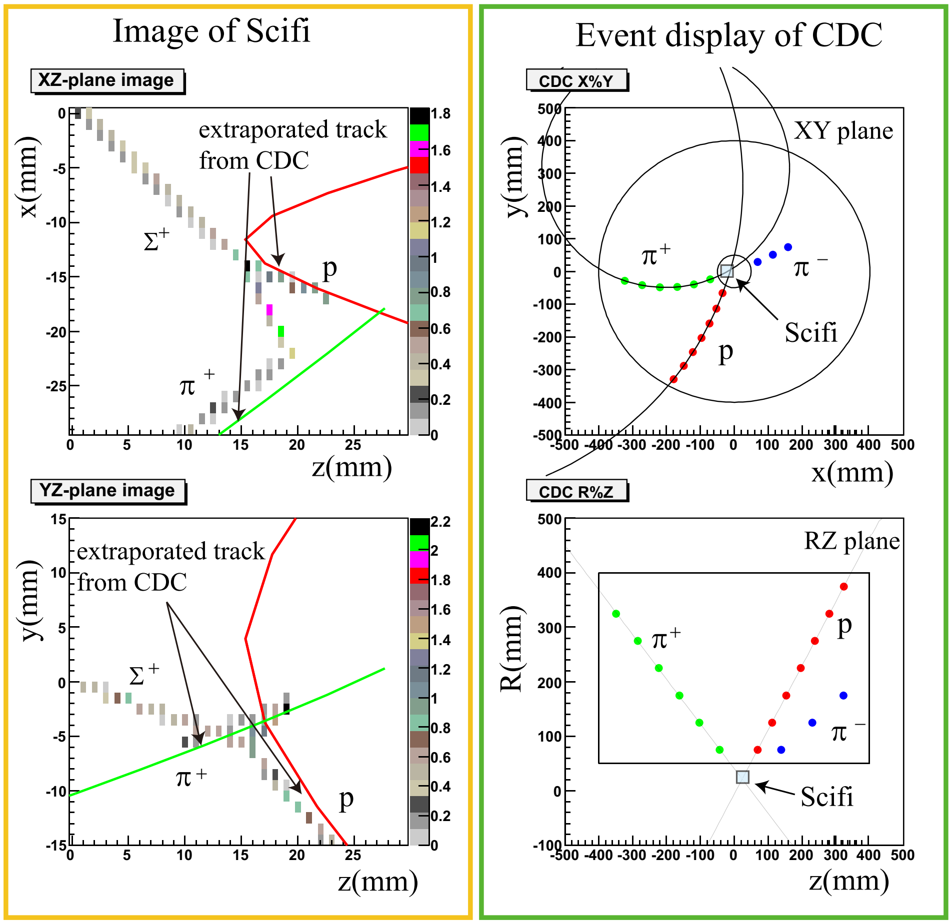

Figure 9: Typical event display of the Scifi (left figure) and CDC (right figure). In the CDC, the tracks are reconstructed using hit points by circular fitting. The tracks on the image of the Scifi are extrapolated ones from the reconstructed tracks by CDC.

4 Yield estimation

4.1 Σ^+ beam

The yield of Σ^+ beam is estimated in the following condition.

- K^- beam momentum : 1.1GeV/c
- K^- beam intensity : 10^6 K^-/spill
- Cross section of the $K^-p \to \pi^-\Sigma^+$ reaction: 1.8mb
- Σ^+ production target : CH_2 (2cm thickness)

The yields of the Σ^+ per one spill are shown in Table 1 for both of a free proton and quasi-free proton as a reaction target. These yields are the numbers of Σ^+ which goes to the Scifi.

	free proton	quasi-free proton in carbon nuclei
Σ^+ / 1spill	42	69
Σ^+ / 1day	9.1×10^5	15×10^5

Table 1: Expected yield of Σ^+ beam

4.2 Σ^+p scattering event

The yield of the observed Σ^+p scattering is represented by the following equation.

$$N_{\Sigma^+p\ scat} = \sigma \times L_{\Sigma^+\ beam} \times \rho_{target} \times f_{\Sigma^+\ decay} \times \epsilon_{ana} \tag{1}$$

Here, σ represents the cross section of the Σ^+p elastic scattering which is assumed to be 10 mb from past experiment [7]. The $L_{\Sigma^+\ beam}$ represents the flight length of the Σ^+ in the Scifi. The mean value of the flight length of the Σ^+ is 1.3 cm and the $L_{\Sigma^+\ beam}$ is the product of this mean value and the number of the Σ^+ beam. The ρ_{target} is the number density of free protons in the Scifi and is 4.78×10^{22} (1/cm^3). The Σ^+ tracks before and after the scattering must be recognized as trajectories. Therefore the trajectory of the Σ^+ is required to be larger than 1cm. The coefficient $f_{\Sigma^+\ decay}$ represents the correction factor due to this requirement. The survival rate of the Σ^+ is 44% in such condition. Because the track length is required for both before and after the scattering, the $f_{\Sigma^+\ decay}$ is 0.44 × 0.44. Finally the ϵ_{ana} shows the correction factor considering the loss in the analysis or acceptance of CDC. Now the ϵ_{ana} is assumed to be a low value of 0.1. This value should be estimated more correctly by the simulation. Using these values, the number of the Σ^+p scattering event is estimated to be 850 events in one month beam time. This number is 30 times larger statistics than that in E289. We would like to provide data of cross section which is much improved statistically.

5 Development Status of Scifi-MPPC System

Basic characteristics of the Scifi-MPPC system required in this experiment are (1) to detect a MIP and (2) MPPC can operate in the magnetic field. In order to evaluate these topics, we performed a test experiment where 600 MeV/c e^+ beam was irradiate to a Scifi-MPPC system. We made a Scifi of 5 segment and 4 layer configuration using 20 scintillation fibers whose cross section was 1mm × 1mm. The Scifi and MPPC were located in a gap of a magnet. The magnetic field was changed from 0T to 1.06T and the operation of MPPC was tested.

Figure 10 shows the photon number detected by Scifi-MPPC system for 600 MeV/c e^+ beam (Magnetic field was 0T). The mean photon number was ~ 7.8, which was sufficient value. When more than 2 photon are required, the system can detect MIP with an efficiency of 95%. Figure 11 shows the photon number when the magnetic field was changed from 0T to 1.06T. We confirmed that the photon number and the gain of the MPPC do not change in the magnetic field. From these studies, the single fiber and MPPC system satisfies the requirement of this experiment. Figure 12 shows the images of 5 segment and 4 layer Scifi when e^+ beam passed through the Scifi. The trajectory of the e^+ beam is recognized.

From now, we plan to increase the channel number of fiber and MPPC and evaluate whether the required angular resolution and position resolution are obtained or not.

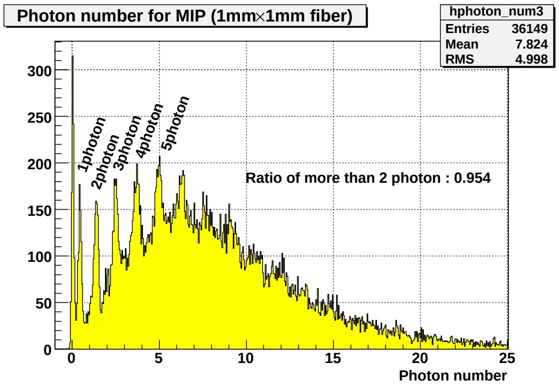

Figure 10: Photon number detected a scintillation fiber and MPPC system when a e^+ beam passed through the fiber (Magnetic field was 0T). Each peak corresponds the photon numbers detected by MPPC.

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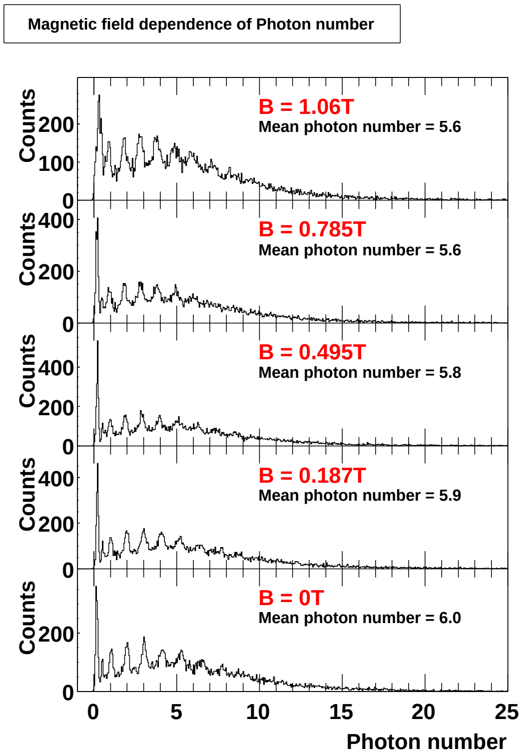

Figure 11: Photon number detected by MPPC when a magnetic field was applied from 0T to 1.06T

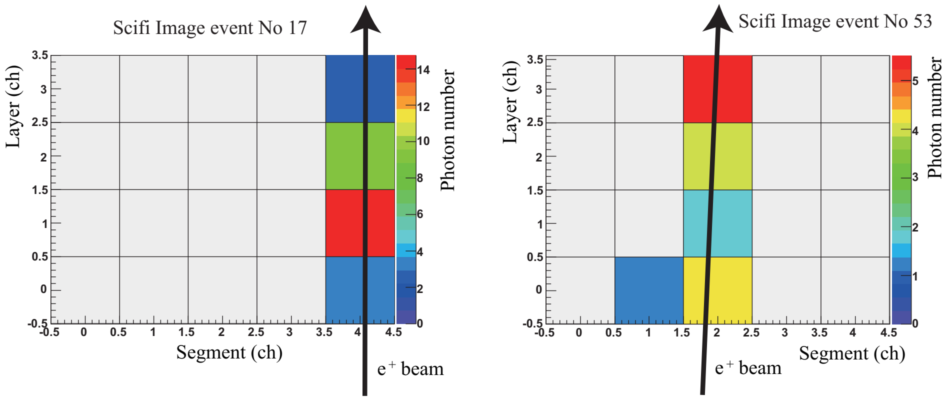

Figure 12: Image of 5 segment and 4 layer Scifi when e^+ beam passed through the Scifi.

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