Search for Θ^+ via $K^+p \to \pi^+X$ reaction with high-resolution spectrometer system

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Abstract. A search for the Θ^+ pentaquark in the $K^+p \to \pi^+X$ reaction was performed utilizing a high-resolution spectrometer at the K6 beam line of the KEK 12GeV Proton Synchrotron. Incident K^+ beams of 1.2 GeV/c were irradiated to a liquid hydrogen target. No significant evidence of the Θ^+ was found. The upper limit of the differential cross section averaged over 2° to 20° in the laboratory frame for the $K^+p \to \pi^+\Theta^+$ reaction was obtained to be 1.9 μb/sr at 90 % confidence level. From the present result, the t-channel process is excluded or the coupling constant $g_{K^*N\Theta}$ is quite small.

PACS. 13.75.Jz Kaon-baryon interactions – 13.85.Rm Limits on production of particles – 14.80.-j Other particles (including hypothetical)

1 Introduction

Since the LEPS collaboration was the first to report the evidence of the Θ^+ ($uudd\bar{s}$) pentaquark with a positive strangeness [1], an intense experimental activity has been carried out to search for exotic baryon states with charge and flavor requiring a minimal valence quark configuration of four quarks and one antiquark (such states are called as "pentaquark"). After the LEPS report, additional experimental evidences were also reported from DIANA, CLAS, SAPHIR, ITEP, HERMES, SVD, COSY-TOF, and ZEUS [2]. In these experiments, a narrow peak in the invariant mass distributions of pK^0 or nK^+ pairs was observed around the mass region from 1520 MeV/c^2 to 1560 MeV/c^2 with significances of 4∼8 σ. However, in these cases, the signals were based on small statistics. Therefore these experiments are not sufficient to claim the establishment of the Θ^+.

After these positive results, negative results were reported from high energy and high statistics experiments [2]. As possible explanations for such a controversial experimental situation, the production mechanism of the Θ^+ in the high energy reactions may differ strongly from that for conventional baryonic states [3]. However, the null results cast additional doubt on the existence of the Θ^+.

Recently, the CLAS collaboration reported null results with high statistics in the $\gamma p \to \bar{K}^0K^+n$ reaction [4] and in the $\gamma d \to pK^-K^+n$ reaction [5]. On the other hand, the LEPS collaboration showed new evidence in the $\gamma d \to \Lambda(1520)\Theta^+$ reaction [6]. The DIANA collaboration confirmed the initial positive evidence with two times larger statistics [7]. New experimental result at the KEK was recently published [8]. In the result, a bump with a significance of 2.5 σ in the missing mass spectrum in the $\pi^-p \to K^-X$ reaction is shown.

We report on the preliminary results of experimental search for the Θ^+ via the $K^+p \to \pi^+X$ reaction with a high-resolution spectrometer system at the K6 beam line of the KEK 12 GeV Proton Synchrotron. The experimen-

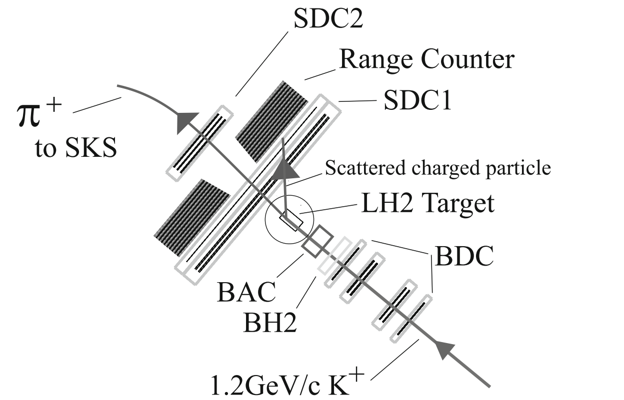

Fig. 1. The experimental setup for E559 around the liquid hydrogen target. The SDC1 and RC were newly installed in order to detect the charged particles other than a π^+ detected with the SKS.

tal objective is to confirm whether the Θ^+ does exist or not with good missing mass resolution for the Θ^+. By deducing the production cross section of the $K^+p \to \pi^+\Theta^+$ reaction, we would like to give information to understand the production mechanism of the Θ^+.

2 Experiment

The experiment was performed at the K6 beam line of the KEK 12 GeV Proton Synchrotron (KEK-PS E559). The K6 beam line had two parts. One part was the beam spectrometer which analyzed incident beams. Another part was the SKS spectrometer which detected scattered particles from a target. The experimental setup around the target is shown in Fig. 1.

The beam spectrometer consisted of the QQDQQ magnet system, two hodoscopes (BH1, 2), an aerogel cherenkov counter (BAC) and four drift chambers (BDC1,2,3,4). The incident K^+'s were irradiated to a liquid hydrogen target (length 125 mm). BAC rejected π^+'s in the beams at the trigger level. Incident K^+'s were clearly identified with the time-of-flight measurement between BH1 and BH2. The momenta of K^+'s were analyzed with BDC and the QQDQQ magnet system.

Scattered particles were detected by the SKS spectrometer which was comprised of a large superconducting dipole magnet (SKS), drift chambers (SDC1,2,3,4), and trigger counters. The trigger counters were comprised of a scintillator wall (TOF), two aerogel cherenkov counters (AC1, AC2), and a lucite cherenkov wall (LC). Scattered π^+'s were identified with the coincidence of TOF and LC in the trigger level. The momenta of scattered particles were analyzed with the SKS and SDC. We installed a large acceptance drift chamber (SDC1) and a range counter (RC), whose effective area was $1200(mm) \times 1100(mm)$, just downstream of the target. We detected all possible charged particles other than a π^+ detected with the SKS. The SDC1 was used to suppress backgrounds mainly due to the decays of the K^+ beams (See Sec. 3.1).

The experiment was carried out during about one month from June 2005 (1st run) and two weeks from December 2005 (2nd run). We took the $K^+p \to \pi^+X$ reaction data. The total number of the K^+ beams in the 1st run and 2nd run were 2.8×10^9 and 2.1×10^9, respectively. We took the $\pi^+p \to K^+\Sigma^+$ reaction data for the calibration. By analyzing this calibration data, we observed a clear peak due to Σ^+. The width of the peak was obtained to be 1.93 ± 0.07 MeV/c^2. In order to check the validity of the analysis of the spectrometer, we compared the results with a Monte Carlo simulation. In the Monte Carlo simulation, we considered the momentum resolutions of $\delta p/p$ =0.047 % (FWHM) for the beam spectrometer and 0.43 % (FWHM) for the SKS spectrometer. From the Monte Carlo simulation, the missing mass resolution for Σ^+ was 2.0 MeV/c^2 (FWHM), which was consistent with the data. We also estimated the missing mass resolution for the Θ^+. By using the same Monte Carlo simulation, the resolution for the Θ^+ was obtained to be 2.4 MeV/c^2.

3 Data analysis

3.1 Decay background suppression

The (K^+, π^+) reaction events are divided into two classes. One is the K^+p reaction events such as $K^+p \to \Delta K \to \pi^+KN$ and $K^+p \to NK^* \to \pi^+KN$. The other is the 3-body decays of K^+ beams such as $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^0\pi^0$, $K^+ \to \mu^+\pi^0\nu_\mu$ and $K^+ \to e^+\pi^0\nu_e$. The 3-body decay events are 10 times larger than the K^+p reaction events. Therefore the suppression of the decay events of incident K^+'s is essential for the search for the Θ^+. In the K^+p reactions such as Δ production or the Θ^+ production, there are even charged particles in the final state, and the scattered particles have broad angle distribution. On the other hand, in the case of the 3-body decays of the K^+ beams, there are odd charged particles, and the scattered particles have forward-focusing angle distribution. Therefore it is possible to reject the 3-body decay events by selecting even charged particles which have large scattered angles. The number and scattered angles of the charged particles in the final state can be analyzed with SDC1 which had a large acceptance (60 degrees angle). According to a Monte Carlo simulation, 98 % of the K^+ decay events were suppressed by applying the selection.

We also checked the efficiency for the Θ^+ of the selection by using a Monte Carlo simulation assuming that the production and the decay of the Θ^+ were isotropic in the center of mass system. According to the simulation, 70 % of the Θ^+ events could be detected by the same selection. The vertex distribution at 2nd run after applying the background cut is shown in Fig. 2. The open histogram titled with "LH2 target" shows the vertex distribution of the data with the liquid hydrogen target. The hatched histogram titled with "Empty Target" shows the vertex distribution of the data without the liquid hydrogen target. The solid histogram titled with "Subtraction" shows the difference between these histograms. The image of the liquid hydrogen target was clearly observed in Fig. 2. In the target region ($-40 <$ z (mm) < 85), there were approximately 17,000 and 12,000 K^+p reaction events at 1st and 2nd runs, respectively.

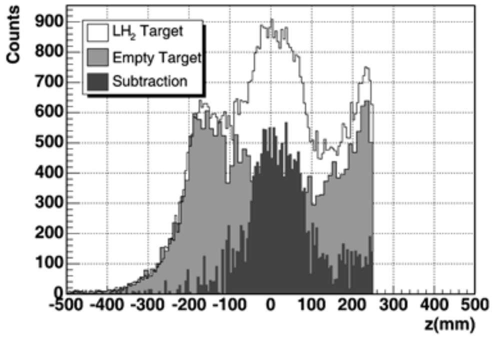

Fig. 2. The vertex distribution of the $K^+p \to \pi^+X$ reaction at 2nd run. The image of the liquid hydrogen target was clearly observed ($-40 < \mathrm{z\ (mm)} < 85$).

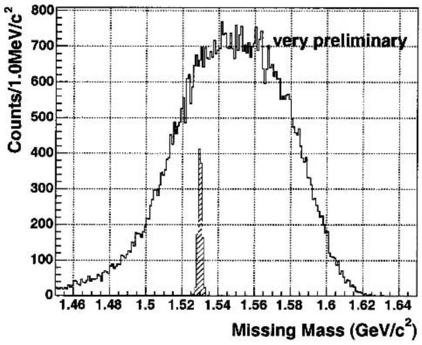

Fig. 3. The missing mass spectrum of the $K^+p \to \pi^+\mathrm{X}$ reaction of 1st and 2nd runs. The hatched one shows the expected one assuming that the Θ^+ is produced isotropically in the center of mass system and the total cross section of the $K^+p \to \pi^+\Theta^+$ reaction is 50 μb.

3.2 Missing mass and cross section

Fig. 3 shows the missing mass of the 1st and 2nd runs. The hatched spectrum shows the expected one assuming that the Θ^+ is produced isotropically in the center of mass system and the total cross section of the $K^+p \to \pi^+\Theta^+$ reaction is 50 μb. There is no significant peak in the spectrum. Therefore we derived the upper limit of the cross section with the following equation,

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{1}{N_{target}} \cdot \frac{1}{N_{K^+beam} \cdot \epsilon_{K6}} \cdot \frac{1}{\epsilon_{LC} \cdot \epsilon_{TOF}} \cdot \frac{1}{f_{\pi^+decay} \cdot f_{\pi^+int}} \cdot \frac{1}{\epsilon_{SdcIn} \cdot \epsilon_{SdcOut} \cdot \epsilon_{SKS}} \cdot \frac{1}{\epsilon_{Sdc1} \cdot \epsilon_{vtx} \cdot d\Omega} \cdot N_{\Theta^+}.$$

Here the N_{target} represents the number of protons in the liquid hydrogen target and was estimated to be 5.0×10^{23}. The N_{K^+beam} represents the number of the incident K^+'s which were irradiated to the target and it was estimated to be 4.9×10^9. The values of the f's, ϵ's and $d\Omega$ are summarized in Table 1. The ϵ_{K6} represents the tracking efficiency of the beam spectrometer. The ϵ_{SdcIn} and ϵ_{SdcOut} represent the efficiencies of the local tracking upstream and downstream of the SKS magnet, respectively. The ϵ_{SKS} represents the efficiency of Runge-Kutta method to connect these local tracks. The ϵ_{LC} and ϵ_{TOF} represent the efficiencies of LC and TOF, respectively. The ϵ_{Sdc1} represents the efficiency of the SDC1 analysis for background suppression described in the previous section and it was estimated to be 0.70 from a Monte Carlo simulation. The ϵ_{vtx} represents the efficiency of the vertex cut which was used to select the K^+p reaction in the liquid hydrogen target. The f_{π^+decay} represents the correction factor due to the decay in flight of the π^+'s. The f_{π^+int} represents the correction factor due to the interaction of the π^+'s in the materials of the target and the SKS. From a Monte Carlo simulation, the f_{π^+decay} and f_{π^+int} were estimated to be 0.86 and 0.94, respectively. We have not yet estimated the errors of these efficiencies and the estimation of the errors is in progress.

In order to calculate the cross section, we fitted the missing mass spectrum assuming that the background was a cubic function and the peak was a Gaussian function. First we fitted the spectrum with a cubic function in order to determine the background shape and then fitted with the cubic function which was fixed and the Gaussian function whose width was fixed to 2.4 MeV/c^2 which was the expected resolution for the Θ^+. We searched the mass region from 1.52 to 1.56 GeV/c^2. The results are shown in Fig. 4. The upper figure shows the result of the fitting. The bottom figure shows the obtained number of the Gaussian function (N_{Θ^+}). In order to obtain the upper limit of the differential cross section, we assumed that the number fluctuation obeys the Gaussian statistics. For example, N_{Θ^+} was 105 ± 49 at 1.528 GeV/c^2 and the 90 % confidence upper limit of the count was obtained to be $105 + 49 \times 1.28 = 168$. From these values, the upper limit of the differential cross section averaged over 2° to 20° in the laboratory frame was estimated at 1.9 μb/sr at 90 % confidence level (See Fig. 5).

Table 1. Summary of the cuts and their efficiency.

	Cut	Efficiency
ϵ_{K6}	tracking efficiency of beam spectrometer	0.94
ϵ_{LC}	LC efficiency	0.95
ϵ_{TOF}	TOF efficiency	0.99
f_{π^+decay}	π^+ decay factor	0.86
f_{π^+int}	π^+ interaction factor	0.94
ϵ_{SdcIn}	SdcIn tracking efficiency	0.88
ϵ_{SdcOut}	SdcOut tracking efficiency	0.95
ϵ_{SKS}	SKS tracking efficiency	0.93
ϵ_{Sdc1}	Sdc1 cut efficiency	0.70
ϵ_{vtx}	vertex cut efficiency	0.85
$d\Omega$	acceptance at laboratory frame	0.11 sr.

We compared our experimental values with the theoretical values calculated by Y. Oh *et al.* [9]. In the $K^+p \to \pi^+\Theta^+$ reaction, two production diagrams shown in Fig. 6 were considered. Their calculation was controlled by two parameters. One parameter was the coupling constant $g_{KN\Theta}$. The other one was the coupling constant $g_{K^*N\Theta}$. The coupling constant $g_{KN\Theta}$ can be calculated

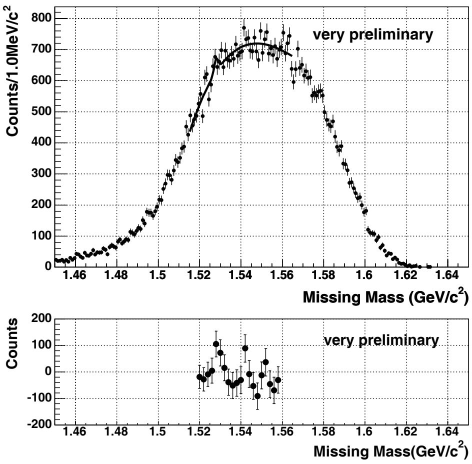

Fig. 4. The missing mass spectrum with the fit function (Gaussian and cubic function), and the counts of the Gaussian function.

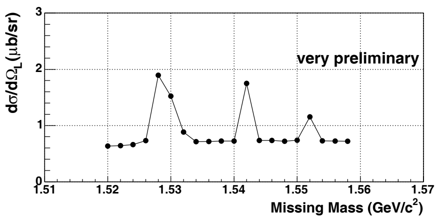

Fig. 5. The 90 % confidence level upper limit of the differential cross section averaged over 2° to 20° in the laboratory frame.

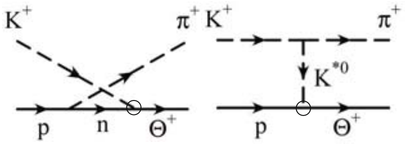

Fig. 6. Two diagrams for the $K^+p \to \pi^+\Theta^+$ reaction.

from the decay width of the Θ^+. They assumed that the decay width of the Θ^+ was 1 MeV. On the other hand, there is no experimental information for determination of $g_{K^*N\Theta}$. Therefore they calculated in three cases ($g_{K^*N\Theta} = 0$, $g_{K^*N\Theta} = +g_{KN\Theta}$ and $g_{K^*N\Theta} = -g_{KN\Theta}$). The theoretical calculation of the differential cross section of the $K^+p \to \pi^+\Theta^+$ reaction are shown in Fig. 7. In the Figure, the solid line is obtained with $g_{K^*N\Theta} = +g_{KN\Theta}$, the dotted one is obtained with $g_{K^*N\Theta} = 0$ and the dashed one is obtained with $g_{K^*N\Theta} = -g_{KN\Theta}$. The 90 % confidence level upper limit of the differential cross section averaged over 2° to 20° in the laboratory frame is also shown in Fig. 7. If there is t-channel process where the K^{0*} is exchanged, the theoretical calculation has a forward peak structure (See Fig. 7). However, the experimental value of the differential cross section is much smaller than the theoretical calculation. Therefore the experimental value gives a strong constraint on the production mechanism where the K^{0*} is exchanged. If the contribution from only the u-channel process is considered, the theoretical calculation of the differential cross section shows a backward

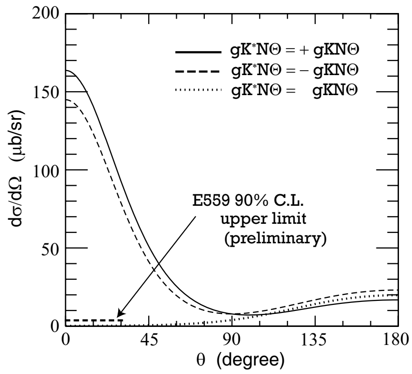

Fig. 7. The theoretical differential cross section calculated by Y. Oh *et al.* [9]. The solid line is obtained with $g_{K^*N\Theta} = +g_{KN\Theta}$, the dotted line is obtained with $g_{K^*N\Theta} = 0$, and the dashed line is obtained with $g_{K^*N\Theta} = -g_{KN\Theta}$. The experimental upper limit of the differential cross section averaged over 2° to 20° in the laboratory frame is also shown.

peak structure. Our experiment does not have a sensitivity to exclude the u-channel process.

4 Conclusion

We have performed a search for the Θ^+ via $K^+p \to \pi^+X$ reaction with the SKS spectrometer at the K6 beam line of the KEK 12GeV Proton Synchrotron. Our experimental missing mass resolution for the Θ^+ was estimated to be 2.4 MeV/c^2. However, there was no significant peak in the missing mass spectrum. Therefore we estimated the upper limit of the differential cross section of the $K^+p \to \pi^+\Theta^+$ reaction averaged over 2° to 20° in the the laboratory frame. The upper limit was obtained to be 1.9 μb/sr (very preliminary). The experimental differential cross section was much smaller than the theoretical one taking into account the production mechanism where the K^{0*} is exchanged [9]. Our result gives a strong restriction on such production mechanism of the Θ^+.

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References

1. T. Nakano *et al.*, Phys. Rev. Lett. **91**, (2003) 012002.
2. K. Hicks *et al.*, arXiv:hep-ex, (2005) 0510067.
3. A. I. Titov, A.Hosaka, S. Data, Y. Ohahi, Phys. Rev. C **70**, (2006) 042202.
4. M. Battaglieri *et al.*, Phys. Rev. Lett. **96** (2006) 042001.
5. B. McKinnon *et al.*, Phys. Rev. Lett. **96**, (2006) 212001.
6. N. Muramatsu *et al.*, JPS meeting, (2006).
7. V. V. Barmin *et al.*, arXiv:hep-ex, (2006) 0610166.
8. K. Miwa *et al.*, Phys. Lett. B **635**, (2006) 72.
9. Y. Oh *et al.*, Phys. Rev. D **69**, (2004) 074016