Search for the Θ^+ Pentaquark via the $\pi^- p \rightarrow K^- X$ Reaction at 1.92 GeV/c

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The Θ^+ pentaquark baryon was searched for via the $\pi^- p \rightarrow K^- X$ reaction with a missing mass resolution of 1.4 MeV/c^2 (FWHM) at the Japan Proton Accelerator Research Complex (J-PARC). π^- meson beams were incident on the liquid hydrogen target with a beam momentum of 1.92 GeV/c. No peak structure corresponding to the Θ^+ mass was observed. The upper limit of the production cross section averaged over the scattering angle of 2° to 15° in the laboratory frame is obtained to be 0.26 μb/sr in the mass region of 1.51–1.55 GeV/c^2. The upper limit of the Θ^+ decay width is obtained to be 0.72 and 3.1 MeV for $J_\Theta^P = 1/2^+$ and $J_\Theta^P = 1/2^-$, respectively, using the effective Lagrangian approach.

The first evidence of a Θ^+ pentaquark was reported by the Laser-Electron-Photon (LEPS) collaboration operating at the SPring-8 facility [1]. A peak was observed in the missing mass spectrum of the $\gamma n \rightarrow K^- X$ reaction on a ^{12}C target at a mass of 1.54 ± 0.01 GeV/c^2. This baryon resonance should have an exotic quark content of $uudd\bar{s}$. The observed peak width was consistent with the experimental resolution of 25 MeV, which suggests that the intrinsic width is quite narrow. On the theoretical side, D. Diakonov *et al.* predicted a baryon resonance with a narrow width of less than 15 MeV at 1.53 GeV/c^2 using a chiral soliton model [2]. Good agreement between the theoretical prediction and the LEPS group's result triggered investigations of Θ^+ by research groups world wide. The LEPS group's first evidence was immediately reexamined from past experimental data by research groups at various facilities (See review Ref. [3]). Among

positive results, the DIANA collaboration reported evidence of Θ^+ in the $K^+ \text{Xe} \rightarrow K^0 pX$ reaction with a significance of 4.4σ [4]. The CLAS collaboration reported a peak with a significance of 7.8σ in the $\gamma p \rightarrow \pi^+ K^- K^+ n$ reaction [5]. Later, the LEPS and DIANA collaborations improved their first positive results with higher statistics. The LEPS group extracted a 5.1σ peak from the analysis of the second data sample in the $\gamma d \rightarrow K^- K^+ np$ reaction. The statistics was improved by a factor of 8 compared to the first measurement [6]. The DIANA collaboration also enlarged the statistics of the peak with a mass resolution of 8.2 MeV/c^2 (FWHM). From the production cross section, the intrinsic decay width of $\Gamma_{\Theta \rightarrow NK} = 0.39 \pm 0.10$ MeV [7] was estimated. Experiments such as these that reported positive results had a statistical significance ranging between 3 and 8σ; however, at the same time, many negative results with high statistics also have been reported from

high-energy experiments. For example, the *BABAR* collaboration reported that the upper limit of the Θ^+ yield per $q\bar{q}$ event was obtained to be 5.0×10^{-5} at $\sqrt{s} = 10.58$ GeV, which is a factor of 8 below the typical yield for ordinary baryons [8]. Moreover, dedicated experiments to search for Θ^+ with much higher performances disproved their first positive results, for example by CLAS [9] and COSY-TOF [10]. Therefore, the existence of Θ^+ has remained quite controversial. It should also be noted that there are no experiments which measured the intrinsic width of Θ^+ directly. Therefore, it has been long awaited for experiments having much higher statistics and high sensitivity to measure the intrinsic width in different reactions and different experimental setups in order to provide a definite answer to the existence of Θ^+.

The structure of possible Θ^+ has been investigated within different theoretical models [11,12]. Accounting for a very narrow width remains an outstanding challenge; even the introduction of quark-quark correlations has proved insufficient. Should a narrow Θ^+ be confirmed, its structure could prove crucial to understanding quark dynamics at low energies.

A cutting-edge approach to investigating Θ^+ is the use of hadron-induced reactions. Such reactions have a large production cross section, and their production mechanism is more straightforward compared to that of photo-induced reactions. In this light, experiments on the Θ^+ production using hadron beams such as π^- and K^+ have attracted considerable attention. In fact, searches for Θ^+ using hadron beams have already been performed at the High Energy Accelerator Research Organization (KEK) 12 GeV Proton Synchrotron via the $\pi^- p \rightarrow K^- X$ [13] and the $K^+ p \rightarrow \pi^+ X$ reactions [14]. Unfortunately, these experiments failed to obtain clear evidence of Θ^+. However, a peak structure at 1.53 GeV/c^2 with 2.6σ significance was reported in the $\pi^- p \rightarrow K^- X$ reaction at $p_\pi = 1.92$ GeV/c. The obtained upper limit of the differential cross section was 2.9 μb/sr at the 90% confidence level. The 90% C.L. upper limit of the cross section of the $K^+ p \rightarrow \pi^+ X$ reaction using a 1.20 GeV/c K^+ beam was obtained to be 3.5 μb/sr for the mass region of 1.51–1.55 GeV/c^2. It implies that the contribution of the K^* exchange term is small. This result was consistent with that obtained for the $\gamma p \rightarrow \bar{K}^0 K^+ n$ reaction by the CLAS collaboration [15]. From those results, the nucleon pole term that is sensitive to the decay width of Θ^+ is considered to be dominant in the production cross section [16]. A narrow width implied that the production cross section is expected to be much smaller than what is typical of hadron production. A new experiment with higher sensitivity is required to investigate the existence of a potentially narrow Θ^+.

The Japan Proton Accelerator Research Complex (J-PARC) E19 [17] experiment was specifically designed to search for the Θ^+ pentaquark with high resolution and high statistics via the $\pi^- p \rightarrow K^- X$ reaction. This was the

first experiment to be carried out at the K1.8 beam line in the Hadron Facility [18]. By using a high-intensity pion beam and a high-resolution spectrometer system at this beam line, a sensitivity of 75 nb/sr in the laboratory frame could be achieved for a narrow Θ^+ ($\Gamma_\Theta < 2$ MeV). In this Letter, we report on the results obtained from the first set of experiments that was carried out in 2010. The beam momentum was set to 1.92 GeV/c in order to have a direct comparison with the previous experimental result. The secondary pion beam intensity per pulse was typically 1.0×10^6 for the present experiment. In total, 7.8×10^{10} π^- mesons were incident on the liquid hydrogen target with a mass thickness of 0.86 g/cm^2.

The incident pions were identified and momentum analyzed using the K1.8 beam line spectrometer [19], which has a momentum resolution of less than 0.1%(FWHM). The beam pions were separated by using the time-of-flight between timing counters placed at both the entrance and the exit of the beam line spectrometer. The electrons remaining in the beam were rejected by using a gas Čerenkov counter ($n = 1.002$) placed at the most upstream point in the beam line spectrometer. The amount of electron contamination in the pion beam was less than 0.1%. The muon contamination in the beam is estimated to be 3.5% from the DECAY TURTLE code [20]. The beam momentum was reconstructed by two sets of beam line chambers placed at the entrance and the exit of the beam line spectrometer.

The scattered kaons were identified and momentum analyzed by the Superconducting Kaon Spectrometer (SKS) system [21] with an angular acceptance of 100 msr and a momentum resolution of 0.2%(FWHM). The scattered particles were identified by using an aerogel Čerenkov counter ($n = 1.05$) and an acrylic Čerenkov counter ($n = 1.49$) at the trigger level. The precise identification was carried out in the off-line analysis by using the time-of-flight technique in combination with information about the flight path and the reconstructed momentum obtained through the SKS system. The momentum was also calculated from data obtained from the two sets of chambers placed at the entrance and the exit of the SKS magnet. The SKS magnetic field was set at 2.5 T, and scattered particles with a momentum of $0.7 - 1.0$ GeV/c and scattering angles from 2° to 15° were measured in this system. The very forward angle was not used because it had very poor vertex resolution. The reaction vertex point was extracted from the closest distance between the tracks of beam pion and scattered kaon. The remaining background events due to other target cell materials were estimated to be $2.8 \pm 0.1\%$.

To evaluate various parameters of the spectrometer system, such as the missing mass resolution, absolute mass scale, detection efficiencies and kaon survival rate, the known $\Sigma^\pm$ productions were also measured via the $\pi^\pm p \rightarrow K^+ \Sigma^\pm$ reactions at 1.37 GeV/c in order to cover the same
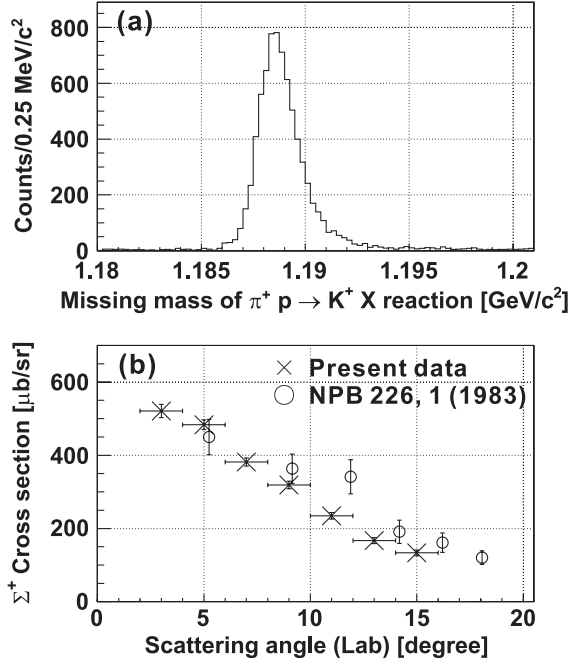
FIG. 2 (color). The missing mass spectrum and the background shape for the $\pi^- p \to K^- X$ reaction at 1.92 GeV/c. The black points with error bars are the experimental data. The contribution of the simulated background is indicated by the red histogram.

FIG. 1. (a) The missing mass spectrum of the $\pi^+ p \to K^+ X$ reactions at 1.37 GeV/c. The Σ^+ peak is clearly observed. (b) The differential cross sections of the Σ^+ production. The present data and the angular distribution reported in the old experiment [22] are indicated by crosses and open circles, respectively.

momentum region of scattered kaons from the $\pi^- p \to K^- \Theta^+$ reaction at 1.92 GeV/c. Figure 1(a) shows the missing mass spectrum of the $\pi^+ p \to K^+ X$ reaction showing a clear peak of Σ^+. The missing mass resolution for Σ^+ was 1.9 ± 0.1 MeV/c^2 (FWHM), which corresponds to a resolution of 1.4 ± 0.1 MeV/c^2 (FWHM) for Θ^+. The energy loss of both the beam and the scattered particles in the target was corrected for based on a simulation using the Bethe-Bloch formula. From the $\Sigma^\pm$ data and by measuring the beam which passed through both spectrometer systems, the error for the absolute mass scale is estimated to be ± 1.7 MeV/c^2, including that of the energy loss correction of ± 0.3 MeV/c^2. The cross section was estimated from the yields of $\Sigma^\pm$ taking all the experimental efficiencies and the kaon survival rate into account. The cross section of the Σ^+ production obtained in this experiment is consistent with the old experimental data [22], as shown in Fig. 1(b). For the K^- measurement, the polarity of the SKS magnet was changed. The performances of the SKS system of both polarities were examined by the calibration data that the pion beam passed through both spectrometers.

The missing mass spectrum for the $\pi^- p \to K^- X$ reaction is shown in Fig. 2. No structure corresponding to Θ^+ was observed in the spectrum. The spectrum was fitted with a Gaussian and a third-order polynomial background to obtain the upper limit of the cross section of the Θ^+
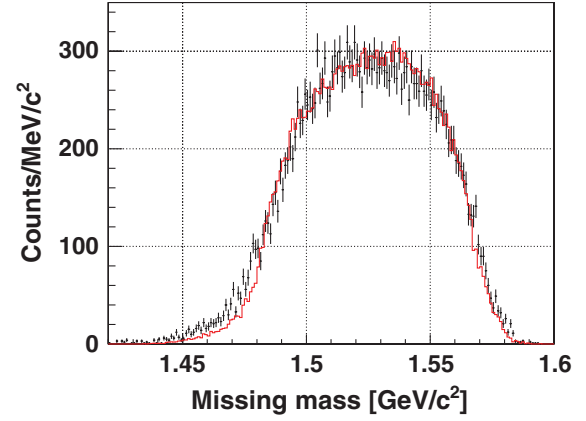
production as a function of the missing mass. Figure 3(a) shows the acceptance corrected spectrum of the $\pi^- p \to K^- X$ reaction. The label of the vertical axis indicates that the differential cross section is averaged over 2° to 15° in the laboratory frame. In the fitting, a fixed missing mass resolution of 1.4 MeV/c^2 (FWHM) was assumed in the mass region of $1.51 - 1.55$ GeV/c^2. In the figure, the size of a possible peak at 1.54 GeV/c^2 with 90% confidence level is also indicated. The upper limit of the differential cross section averaged over 2° to 15° in the laboratory frame is obtained to be 0.26 μb/sr at 90% confidence level in the region of 1.51–1.55 GeV/c^2, as shown in Fig. 3(b). Compared with the previous KEK experimental result of 2.9 μb/sr, more than 10 times higher sensitivity has been achieved. The systematic error of the differential cross section is 8–11%, which originates from the stability of the detector efficiencies, simulations of kaon survival rate and kaon absorption by detector materials and acceptance correction. The major contribution to errors in the mass region of 1.54–1.55 GeV/c^2 is the acceptance correction for the scattering angle around 15°, which is near the edge of the SKS acceptance. The typical value of the correction error is 8%. For other mass regions, the contribution of the correction error is smaller than that of the other systematic errors, which is estimated to be 6%. The associated background shape is reproduced by the Monte Carlo simulation using the GEANT4 code [23], including the acceptance of the SKS system, decay of scattered K^-, distribution of the beam profile, and beam momentum bite. The main backgrounds in the $\pi^- p \to K^- X$ reaction are the ϕ production, $\Lambda(1520)$ production and $K^- K^+ n$ and $K^- K^0 p$ productions following the three-body phase space. The cross section of each process obtained from the old experiments [24,25] was adjusted within the errors (20–30%) to reproduce the data shape. The simulation result agrees well with the backgrounds of the present data.
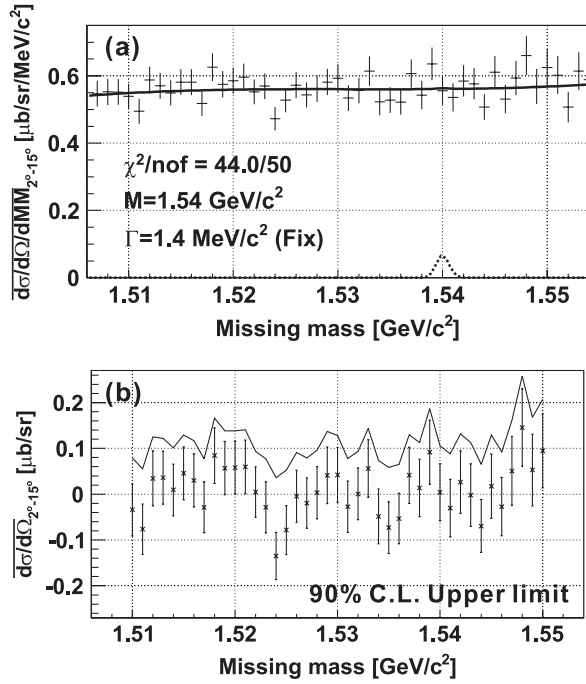
FIG. 3.   (a) The missing mass spectrum of the $\pi^- p \to K^- X$ reaction after the acceptance correction. The vertical axis is in the unit of the differential cross section. The fitted result with a Gaussian and a third order polynomial background shape is indicated by the solid line. In the fit, a Gaussian peak shape function whose peak is fixed at 1.54 GeV/c^2 was used. The width was fixed to be the experimental resolution of 1.4 MeV/c^2 (FWHM). The peak with a 90% confidence level is also indicated by the dotted line. (b) The differential cross section of the $\pi^- p \to K^- \Theta^+$ reaction averaged over 2° to 15° in the laboratory frame with the Θ^+ width fixed at 1.4 MeV/c^2 (FWHM). The black line indicates the upper limit of the differential cross section at 90% confidence level. For the calculation of the line position, the amplitude for the Gaussian peak is constrained to be a positive value. The systematic error is included in the error bars.

The cross section of the Θ^+ production was theoretically calculated by hadronic models using effective Lagrangians and form factors [16,26–28]. In these models, two schemes were used to introduce the Yukawa coupling, namely, the pseudoscalar (PS) and pseudovector (PV) scheme. The coupling constants and the form factors were used as parameters whose values were fixed based on the known hyperon reactions. To include the finite size effect of a hadron, static (F_s) and covariant (F_c) type form factors were introduced in the calculation. The Θ^+ production mechanism was comprehensively studied via the γN, NN, KN, and πN reactions near the production threshold [16,26]. The cross section of the $\pi^- p \to K^- \Theta^+$ reaction was calculated to be 9 μb using the PS scheme and the static form factor at a pion beam momentum of 1.92 GeV/c, assuming the width of Θ^+ to be 1 MeV and $J^P_\Theta = 1/2^+$. The production cross section of Θ^+ via both the $\pi^- p \to K^- \Theta^+$ and $K^+ p \to \pi^+ \Theta^+$ reactions was

TABLE I.   The total cross section calculated by the pseudoscalar (PS) and pseudovector (PV) scheme using the static (Fs) and covariant (Fc) type form factors [28]. The incident energy for the π- and K-induced reaction is 1.92 GeV/c and 1.20 GeV/c, respectively. The cross section was calculated by integrating over the whole solid angle. The decay width of Θ^+ was set to be 1 MeV at a mass of 1.54 GeV/c^2.

$J^P_\Theta = 1/2^+$	Form factor	π induced [μb]	K induced [μb]
PS	Fs	9.2	119
	Fc	5.3	595
PV	Fs	0.51	9.6
	Fc	0.29	46
$J^P_\Theta = 1/2^-$	Form factor	π induced [μb]	K induced [μb]
PS	Fs	0.18	1.9
	Fc	0.10	9.6
PV	Fs	0.40	4.2
	Fc	0.23	20

systematically studied in Ref. [27,28]. Since the K^* exchange term is considered to be extremely small based on the experimental results [14,15], thus only the nucleon pole term contributes to the reactions, the total production cross section is directly proportional to the decay width of Θ^+. The total production cross sections are summarized in Table I, assuming a decay width of 1 MeV at 1.54 GeV/c^2. This calculation is consistent with the previous experimental results obtained at KEK [13,14].

The upper limit of the total cross section was calculated from the measured forward-angle differential cross section taking into account the spectrometer acceptance and predicted angular distributions by the meson-induced production model [28]. This model predicts that angular distributions strongly depend on the coupling scheme and J^P of Θ^+. The respective upper limits of the total cross section with the theoretically calculated angular distributions are 0.31 μb ($1/2^+$ PS and $1/2^-$ PS), 0.21 μb ($1/2^+$ PV), and 0.26 μb ($1/2^-$ PV). Compared with the total cross sections theoretically calculated with a Θ^+ width of 1 MeV, the upper limits of the Θ^+ decay width were found to be 0.72 and 3.1 MeV for $J^P_\Theta = 1/2^+$ and $J^P_\Theta = 1/2^-$, respectively.

Taking into account the result of previous K-induced reaction [14] in addition to the present result, more stringent limits on the decay width can be obtained. In the case of $J^P_\Theta = 1/2^+$, F_s type form factor with the PV scheme is more favored to explain the small cross section of the K-induced reaction. In this case, the present upper limit of the total cross section (0.21 μb) corresponds to the width limit of 0.41 MeV from Table I. In the case of $J^P_\Theta = 1/2^-$, F_s type form factor with the PS scheme is more favored. In this case, the present upper limit of the total cross section (0.31 μb) corresponds to the width limit of 1.7 MeV.

In summary, the pentaquark Θ^+ was searched for via the $\pi^- p \to K^- X$ reaction at the K1.8 beam line in the

J-PARC Hadron Facility. A missing mass resolution of 1.4 ± 0.1 MeV/c^2 (FWHM) for the Θ^+ mass of 1.54 GeV/c^2 was achieved. In the missing mass spectrum, no peak structure corresponding to Θ^+ mass was observed. The upper limit of the differential cross section averaged over the scattering angle of $2°$ to $15°$ in the laboratory frame is 0.26 μb/sr at the 90% confidence level in the mass region of 1.51–1.55 GeV/c^2. Combining the theoretical calculation with the experimental result obtained from the $\pi^- p \to K^- \Theta^+$ reactions, the upper limit of the decay width is calculated to be 0.72 and 3.1 MeV for $J^P_\Theta = 1/2^+$ and $J^P_\Theta = 1/2^-$, respectively.

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