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J-PARC E19 Experiment: Pentaquark Θ^+ Search in Hadronic Reaction at J-PARC

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A search for the Θ^+ pentaquark in the $\pi^- p \to K^- X$ reaction was performed at the J-PARC Hadron Facility. Two data samples were collected in 2010 and 2012 at π beam momenta of 1.92 and 2.0 GeV/c, respectively. No peak structure was observed in the missing mass spectra obtained from either data set. The upper limit for the production cross section averaged over the scattering-angle range of 2° to 15° in the laboratory frame was found to be 0.28 μb/sr. The decay width of the Θ^+ can be directly connected to the production cross section through a theoretical calculation using an effective Lagrangian. The estimated upper limits of the width were 0.41 and 2.8 MeV for the spin-parities of $1/2^+$ and $1/2^-$, respectively.

KEYWORDS: exotic hadron, pentaquark

1. Introduction

Fifty years ago, the quark model was proposed to explain the spectrum of baryons and mesons [1]. Although quantum chromodynamics (QCD) allows the existence of any multiquark system in a color singlet state, no evidence for exotic composite systems such as $qq\bar{q}\bar{q}$ or $qqqq\bar{q}$ had been observed until the LEPS Collaboration reported the evidence for the pentaquark Θ^+ in 2003 [2]. Since the Θ^+ has a strangeness quantum number $S = +1$, the minimal quark configuration is $uudd\bar{s}$.

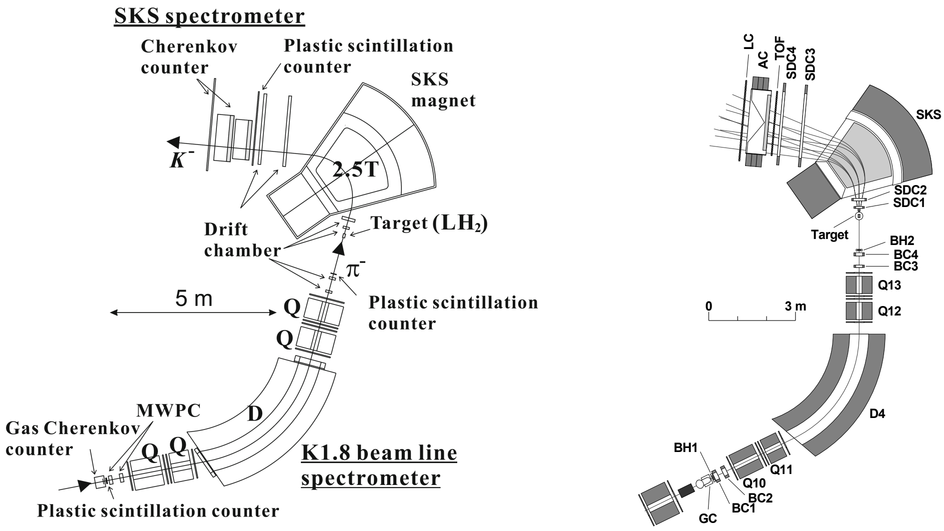
The LEPS Collaboration first reported a narrow peak structure at 1540±10 MeV/c^2 produced in the γC $\to K^+K^-X$ reaction with a statistical significance of 4.6 σ [2]. After the report, they collected new data using a liquid deuterium target to observe a narrow peak at 1524±2±3 MeV/c^2 in the $\gamma d \to K^+K^-pn$ reaction [3]. The statistical significance was 5.1 σ. Recently, they reported an analysis result with 2.6 times more statistics, but the statistical significance of the signal was reduced compared with the previous one [4]. Currently, a new analysis is underway to reduce the contribution from the quasi-free proton in the deuteron. The DIANA Collaboration analyzed old bubble-chamber data and searched for the Θ^+ in the K^+Xe $\to pK^0$Xe' reaction [5]. In their recent analysis [6], an enhancement was observed at 1538±2 MeV/c^2 in the invariant mass distribution of pK^0_s. The statistical significance of the signal was 5.5σ. They also estimated the finite intrinsic width to be 0.34±0.10 MeV, which was derived from the production cross section of $K^+n \to \Theta^+$. They claimed that this was strong evidence for Θ^+.

In addition to these two, many experiments were performed to search for Θ^+. Some of them yielded positive results whereas others yielded negative results (see [7, 8] for recent reviews of the experimental results). The existence of the Θ^+ has not yet been established. Therefore, dedicated experiments with high statistics, a high resolution and a simple reaction are desired in order to validate the positive results and confirm the Θ^+ existence (nonexistence). The J-PARC E19 experiment was designed to search for the Θ^+ in the $\pi^- p \to K^- X$ reaction.

2. Experiment and Analysis

The J-PARC E19 experiment was performed at the K1.8 beam line [9] of the Hadron Facility. The beam time was allocated in 2010 and 2012. In 2010 (2012), 7.8×10^{10} (8.1×10^{10}) beam pions with a momentum of 1.92 GeV/c (2.01 GeV/c) were incident on a liquid-hydrogen target whose thickness was 0.85 g/cm^2. The details of the spectrometer system and analysis of both the first and second data samples are described in Refs. [10], [11] and [12], respectively. Here results from an updated analysis of the first data set are reported.

Figure 1 shows a schematic view of the experimental setups in 2010 (left) and 2012 (right). The beam particles and the scattered particles were analyzed using the K1.8 beam line spectrometer and the Superconducting Kaon Spectrometer (SKS), respectively. The K1.8 beam line spectrometer comprises a $QQDQQ$ magnet system with four wire chambers (BC1–4), a gas Čerenkov counter (GC) and two segmented plastic scintillation counters (BH1 and BH2). The four wire chambers (SDC1–4) were installed for the momentum reconstruction of scattered particles. A magnetic field of 2.5 T



In the first RUN (2010). In the second RUN (2012).

Fig. 1. Schematic of experimental setups in 2010 (left) and 2012 (right). In 2012, the incident angle of the beam into the SKS was slightly modified and the sensitive area of the AC was enlarged. These modifications caused the momentum acceptance to change from 0.7–1.0 to 0.8–1.2 GeV/c.

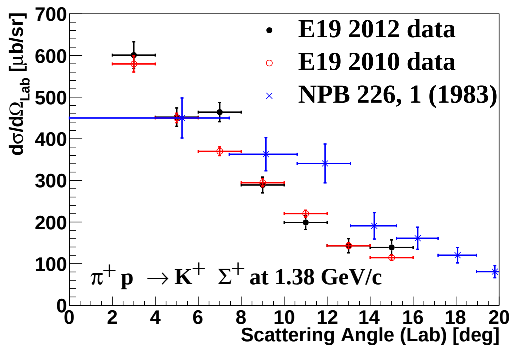


Fig. 2 Differential cross section of Σ^+ production via the $\pi^+ p \to K^+\Sigma^+$ reaction at 1.38 GeV/c. The black solid circles and red open circles are measurements by the E19 Collaboration in 2012 and 2010, respectively. The 2012 data are taken from Ref. [12], and the E19 2010 data are given after the analysis update. The blue crosses are taken from the old bubble chamber data [13]. The vertical error bars show the statistical uncertainties of the measurements, and the horizontal error bars indicate the bin widths.

was generated by the SKS dipole magnet. Particle identification was performed using a silica aerogel Čerenkov counter (AC), a segmented lucite acrylic Čerenkov counter (LC) and a large segmented plastic scintillator array (TOF). The momentum acceptance of the SKS was 0.7–1.0 (0.8–1.2) GeV/c with 2010 (2012) configurations. The difference in the acceptance was due to a slight modification of the detector setup and the change in the injection angle of the beam to the SKS.

The performance of the spectrometer systems was tested using the $\pi^\pm p \to K^+\Sigma^\pm$ reactions. The central value of the pion beam momentum was set to be 1.37–1.38 and 1.46 GeV/c for the two data sets, in order to match the momentum acceptance of the SKS for the scattered kaons to the kinematics of the Θ^+ production [11, 12].

To examine the validity of the efficiency estimation and the acceptance correction, the differential cross section of the Σ^+ production was studied. It was found to be consistent with the old experimental results [13] as shown in Fig. 2. The mass resolution for the Θ^+ was estimated as 1.72 MeV (FWHM) and 2.13 MeV (FWHM) for the first and second data sample, respectively. It should be noted that the mass resolution of the first data set was updated after the beam momentum resolution $\Delta p_{beam}/p_{beam}$ was determined from the experimental data [14]. In a previous letter [11], $\Delta p_{beam}/p_{beam}$ was fixed at the design value of the K1.8 beam spectrometer, i.e. $\delta p_{beam}/p_{beam} = 5.2 \times 10^{-4}$ (FWHM), and the

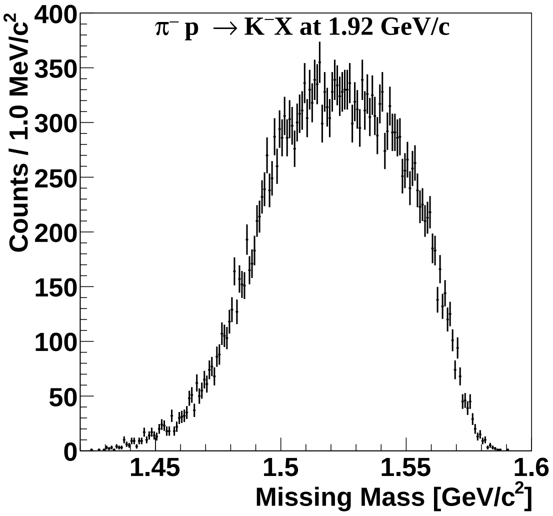


Fig. 3. The missing mass spectrum for the $\pi^- p \rightarrow K^- X$ reaction at 1.92 GeV/c. The statistics in the mass range of 1.51–1.55 GeV/c^2 were increased by ~11% compared with those in the previous letter [11] owing to the improved analysis efficiency of the tracking in the beam spectrometer.

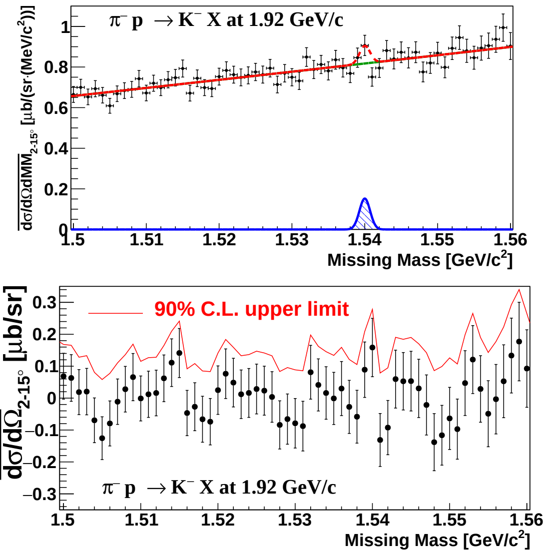


Fig. 4. (Top) Missing mass spectrum of the $\pi^- p \rightarrow K^- X$ reaction for first data set. The fitting function (red solid line) is composed of a second-order polynomial background (green dashed line) with a Gaussian function whose width is fixed to the experimental resolution of 1.72 MeV (FWHM). A Gaussian curve whose area corresponds to the 90% confidence level upper limit for the production cross section is indicated by a blue line. (Bottom) 90% C.L. upper limit for Θ^+ production cross section (red curve) for first data set. The error bars represent the statistical errors only.

realistic estimation using the $\pi^\pm p \rightarrow K^+\Sigma^\pm$ reactions and the calibration data resulted in a slightly worse value of 1.4×10^{-3} (FWHM). In addition, the acceptance of the SKS for the first data sample was recalculated under more realistic conditions, in which the outgoing particles hit the magnetic shield cases of the PMTs attached to the AC and were rejected.

3. Results and Discussion

The missing mass spectrum of the $\pi^- p \rightarrow K^- X$ reaction at 1.92 GeV/c with scattering angles from 2° to 15° is shown in Fig. 3. The statistics in the mass range of 1510–1550 MeV/c^2 were increased by ~11% with respect to Ref. [11] owing to the improvement of the analysis efficiency of the beam tracking [14]. No structure corresponding to the Θ^+ was observed. The obtained spectra were fitted with the sum of a Gaussian (signal) and second-order polynomial (background) functions in order to evaluate the upper limit of the Θ^+ production cross section. The width of the Gaussian curve was fixed at the experimental mass resolution. The fitting results for the 1.92 GeV/c and 2.01 GeV/c data are shown in the top panel of Figs. 4 and 5, respectively. The upper limit for the production cross section at a confidence level of 90% was evaluated to be 0.28 μb/sr in the mass range of 1510–1550 MeV/c^2 for the first data set (bottom panel of Fig. 4) and 1500–1560 MeV/c^2 for the second data set (bottom panel of Fig. 5). These results are one order of magnitude smaller than the value of 2.9 μb/sr obtained in the previous KEK-PS E522 experiment [15].

The obtained upper limit for the production cross section was converted to an upper limit for the

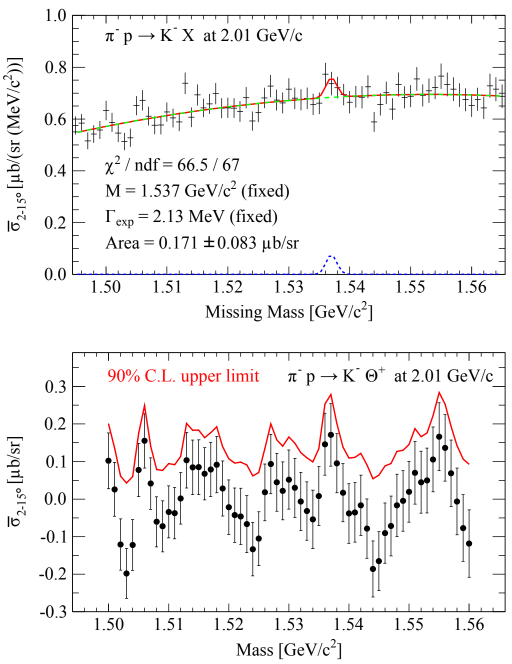


Fig. 5. (Top) Missing mass spectrum of the $\pi^- p \to K^- X$ reaction for second data set. The fitting result with a mass of 1537 MeV/c^2 is shown as an example. The fitting function (red solid line) is composed of a second-order polynomial background (green dashed line) with a Gaussian function (blue dotted line) whose width is fixed to the experimental resolution of 2.13 MeV. (Bottom) Yield of signal as a function of mass. The red solid line indicates the upper limit at the 90% confidence level. Only the statistical error bars are shown. Both plots are taken from Ref. [12].

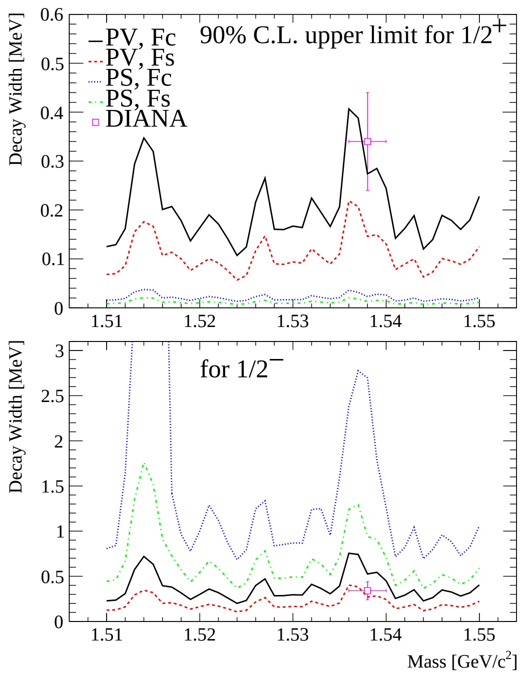


Fig. 6. 90% C.L. upper limit on Θ^+ decay width for spin-parity of $1/2^+$ (top) and $1/2^-$ (bottom) cases. Each line corresponds to a different combination of choices for the coupling scheme (pseudoscalar PS or pseudovector PV) and form factor type (static F_s or covariant F_c) in the theoretical calculation. The DIANA result [6] is also plotted as open squares (magenta).

Θ^+ decay width using a theoretical calculation based on an effective interaction Lagrangian [16]. In this energy region, both s-channel and t-channel can contribute in the $\pi^- p \to K^-\Theta^+$ reaction. However, the t-channel contribution is considered to be negligibly small because the Θ^+ peak is not observed in the K-induced reaction [17]. Therefore, only the s-channel amplitude, which is proportional to the $KN\Theta$ coupling constant, contributes to the cross section in the π-induced reaction. The cross section (σ_Θ) is written with the Θ^+ decay width (Γ_Θ) as $\frac{d\sigma_\Theta}{d\Omega} = f\Gamma_\Theta$. The coefficient of proportionality f depends on the incident momentum p_π, the Θ^+ mass m_Θ, a Yukawa coupling scheme between the meson and baryon, a form factor to include the finite size effect of a hadron, and the spin-parity J^P of Θ^+. In the theoretical model, two coupling schemes — the pseudoscalar (PS) scheme and the pseudovector (PV) scheme — and two types of form factors — the static type (F_s) and the covariant type (F_c) — were considered. Note that only the spin 1/2 case was considered in the present discussion because the spin 3/2 case is highly disfavored as described in Ref. [16]. The decay width was derived by a combined fit of the two missing mass spectra in the mass range of 1.51–1.55 GeV/c^2. In the fitting, the signal was assumed to be a Breit-Wigner function convoluted with a Gaussian function with a fixed mass resolution corresponding to the peak position. It should be noted that the mass spectrum of the first data sample used in the present calculation was different from that used in Ref. [12] owing to the acceptance correction as discussed in Sec. 2. Figure 6 shows the obtained upper limits on the decay width for the possible combinations of the aforementioned parameters. Adopting the most conservative value, an upper limit of 0.41 MeV in the mass range of 1510–1550 MeV/c^2 was derived for the $J^P = 1/2^+$ case, and the upper limit in the $J^P = 1/2^-$ case was 2.8 MeV in the mass region 1530–1540 MeV/c^2. Figure 6 also shows the latest DIANA result [6]. The obtained upper limit is comparable to the DIANA result. These two results are consistent within the error.

4. Summary

The pentaquark baryon Θ^+ has been searched for in the $\pi^- p \to K^- X$ reaction at the K1.8 beam line of the J-PARC Hadron Facility. Data were accumulated at π^- beam momenta of 1.92 and 2.01 GeV/c with missing mass resolutions of 1.72 and 2.13 MeV (FWHM), respectively. The missing mass resolution reported in the previous publication has been updated as a result of a detailed analysis of the calibration data. No narrow peak structure was observed in the missing mass spectra for scattering angles of 2–15° in the laboratory frame. From both the first and second data sample analyses, the upper limits for the differential cross section at a confidence level of 90% were estimated to be 0.28 μb/sr in the laboratory frame. The upper limit of the differential cross section of Θ^+ production was translated into constraints on the Θ^+ decay width using a theoretical calculation based on the effective Lagrangian. The obtained 90% C.L. upper limits of the decay width were 0.41 and 2.8 MeV for spin-parities of $1/2^+$ and $1/2^-$, respectively.

5. Acknowledgements

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