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# Search for Pentaquark $\Theta^+$ in Hadronic Reaction at J-PARC

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**Abstract** The first experiment at the J-PARC hadron facility, the J-PARC E19 experiment, aims at searching for the $\Theta^+$ pentaquark in the hadronic reaction $\pi^- p \to K^- X$ using the missing-mass technique. Based on a superconducting magnet excited at 2.5 T, the spectrometer achieved the high mass resolution of 1.4 MeV/c$^2$ for the $\Theta^+$ production process. The first data taking was performed in the autumn of 2010. No significant structure was observed in the missing-mass spectrum. The upper limit obtained for the differential cross section is 0.26 $\mu$b/sr in the laboratory frame at a 90 % CL.

## 1 Introduction

Intensive search for exotic hadrons, particles that consist of four or more quarks, have been made for over 30 years, since quantum chromodynamics (QCD) allows for any multiquark system as far as it is colourless.

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Despite its success in reproducing the ground states of hadrons, the quark model does not provide an explanation for the properties of low-lying excited states, like the Roper resonance, $\Lambda$ (1405) and other candidates for multiquark states. The properties of exotic hadron give us an information of the prevailing dynamics between quarks and gluons inside the hadron.

In 2003, the LEPS Collaboration observed a narrow resonance at 1,540 MeV/$c^2$ in the $K^-$ missing-mass spectrum for the $\gamma n \to K^+K^-n$ reaction on a carbon target [1]. The observed width was consistent with the mass resolution of 25 MeV/$c^2$. This new particle, named the $\Theta^+$ pentaquark, contained four quarks and one antiquark. $\Theta^+$ is the first explicitly exotic hadron that has irreducible quark component, $uudd\bar{s}$. Following the initial discovery, many positive results were reported from various reactions [2–10], whereas negative results were reported from many high-energy experiments with high statistics [11–21] and from low energy experiments [22–25]. The positive results were reexamined in dedicated experiments or using improved analyses; some of them were confirmed [26,27] while others turned out to be not significant enough to claim evidence of $\Theta^+$ [28,29]. The existence of $\Theta^+$ is then not yet confirmed so far and today remains an urgent problem to be clarified in hadron physics.

The J-PARC E19 experiment was proposed to search for the pentaquark $\Theta^+$ in the $p(\pi^-, K^-)X$ reaction. The production mechanism is rather simple in this exclusive reaction, since s-channel process can contribute to the $\Theta^+$ production via the neutron or $N^*$ as an intermediate state. Another advantage of the reaction is that the background processes have been well studied in past experiments. The cross section is estimated to be of the order of $\mu$b assuming that the decay width of $\Theta^+$ is 1 MeV [30]. It should be noted that the search for $\Theta^+$ was performed at KEK in the $\pi^- p \to K^- X$ reaction [31]. They observed a bump structure at the mass of $\Theta^+$ in the missing-mass spectrum. However the statistical significance was 2.5 $\sigma$ which was not large enough to claim an observation. The upper limit obtained for the differential cross section is 2.9 $\mu$b/sr in the laboratory frame at 90 % confidence level (CL). The J-PARC E19 aims at studying the hadronic production of $\Theta^+$ with high statistics and high resolution. The detail of the experiment is described in the next section.

## 2 Experimental Apparatus

The J-PARC E19 experiment was carried out at the K1.8 beamline of the hadron experimental facility which delivered separated secondary particles up to 2 GeV/$c$. The last QQDQQ elements of the beamline was used

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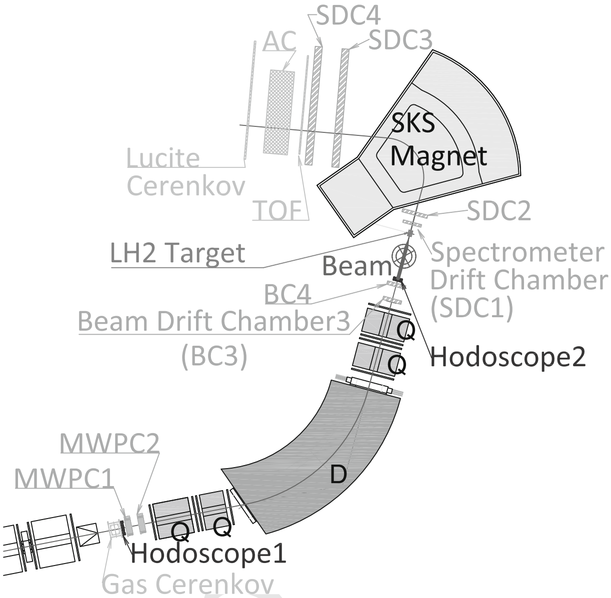

**Fig. 1** Schematic view of the K1.8 beamline and SKS spectrometer

for momentum analysis. A detailed description of the K1.8 beamline can be found elsewhere [32]. The missing-mass spectroscopy was performed with the beam spectrometer together with the superconducting kaon spectrometer (SKS) which was originally used at KEK PS [33]. The schematic view of the spectrometers is shown in Fig. 1. A liquid hydrogen target system was originally developed for the KEK-PS E559 experiment [34]. Hydrogen gas was liquefied by means of the continuous-flow helium cryostat. The target cell was a cylinder 120 mm long which corresponds to 0.86 g/cm$^2$. The beam pions incident on the liquid hydrogen target were separated from protons and electrons using a time-of-flight array and a gas Čerenkov counter, respectively. The beam particle momentum was analyzed with two MWPC's and two MWDC's which were located upstream and downstream the beam spectrometer magnet, respectively. The scattered kaons were detected with the SKS spectrometer equipped with a superconducting magnet excited at 2.5 T providing a momentum resolution of 0.2 % (FWHM). The spectrometer has an acceptance of 100 msr that covers forward angles smaller than 20°. Kaons were identified with a time-of-flight array together with an aerogel Čerenkov counter.

The E19 experiment recorded data in the autumn of 2010 and February 2012. During the first data taking, $7.8 \times 10^{10}$ beam pions were accumulated on the target at the momentum of 1.92 GeV/$c$ to examine the bump structure observed in the previous experiment. The typical beam intensity was 1M pions/spill, the spill length was 2 s. The analysis details of the first result was reported in Ref. [35]. In the second run, $8.7 \times 10^{10}$ beam pions were collected on the target at the beam momentum of 2 GeV/$c$, which is the maximum momentum at the K1.8 beamline. The acceptable intensity was increased to 1.7M pions/spill thanks to an improvement of the spill time structure.

The overall performance of the spectrometer was examined using the $\Sigma$ production in the $\pi^+ p \rightarrow K^+ \Sigma^+$ reaction. The $8.0 \times 10^3\, \Sigma^+$ events were selected after the vertex cut eliminating background events originating from the window of the target cell. The missing-mass resolution for the $\Sigma^+$ production is 1.9 MeV/$c^2$ (FWHM), which corresponds to the mass resolution for the $\Theta^+$ production of 1.4 MeV/$c^2$ (FWHM). The differential cross section of $\Sigma^+$ was found to be consistent with the past experimental result [36].

## 3 Results

The missing-mass spectrum for the 1.92 GeV/$c\,\pi^- p \rightarrow K^- X$ reaction is shown in Fig. 2. No corresponding structure to $\Theta^+$ was observed in the spectrum. The spectrum is consistent with the simulated background from $\phi$, $\Lambda(1520)$ and non resonant $KKN$ productions. Figure 3a shows the missing-mass spectrum after acceptance correction. The data was fitted with a Gaussian peak plus a polynomial background to evaluate the upper limit of the $\Theta^+$ production cross section. The 90 % CL upper limit of the differential cross section is shown in Fig. 3b. The upper limit at 90 % CL is 0.26 $\mu$b/sr in the mass range of 1.51–1.55 MeV/$c^2$. Compared with the 90 %

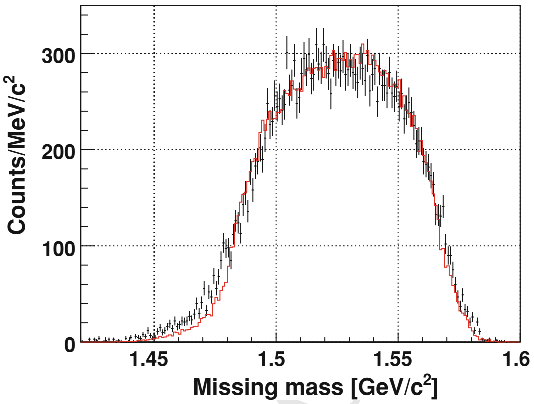

**Fig. 2** Missing-mass spectrum of the $\pi^- p \to K^- X$ reaction measured in the E19 experiment [35]. Acceptance is not corrected for. The data points are shown with *error bars*. The histogram is a simulated background from the known sources

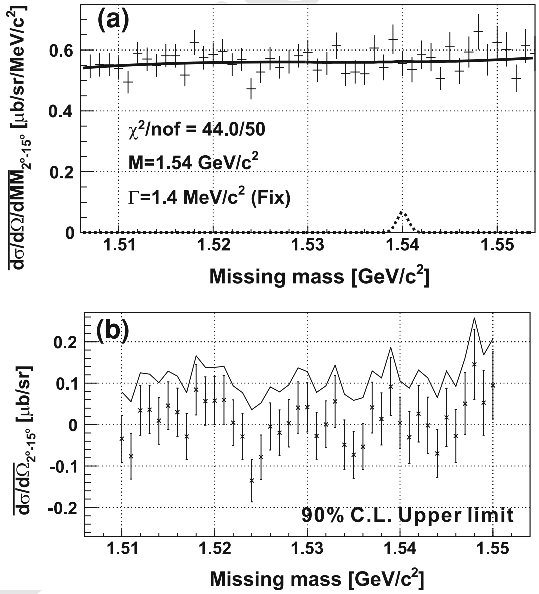

**Fig. 3** **a** Missing-mass spectrum of the $\pi^- p \to K^- X$ reaction after acceptance correction [35]. The *solid line* shows the fit result with a Gaussian peak and a third-order polynomial background. A possible peak with a 90 % CL is drawn at a mass of 1.54 GeV/$c^2$ as a *dotted line*. **b** Differential cross section of the $\pi^- p \to K^- \Theta^+$ reaction. The 90 % CL upper limit of the differential cross section is indicated with a *black line*. See Ref. [35] for details

CL upper limit measured in the previous KEK experiment, the obtained upper limit is smaller by an order of magnitude. From the upper limit of differential cross section together with the theoretical calculation [30], the upper limit of decay width for $\Theta^+$ can be extracted. Since the production cross section largely depends on the spin state of $\Theta^+$, the upper limit of the $\Theta^+$ decay width is determined to be 0.72 and 3.1 MeV for $J^P = 1/2^+$ and $J^P = 1/2^-$, respectively.

The second data taking was performed at the higher energy, beam momentum of 2.0 GeV/$c$, as the first physics run after the great east Japan earthquake in 2011. The detector configuration was optimized to cover a higher momentum region at the energy. Since the production cross section is expected to increase with energy, the more stringent limit can be given for the decay width of $\Theta^+$. The spectrometer performance was evaluated with the $\Sigma^+$ production. The obtained missing-mass resolution for $\Sigma^+$ is 2.0 MeV/$c^2$ (FWHM), which corresponds to 1.6 MeV/$c^2$ (FWHM) for the $\Theta^+$ production. The signal yield is consistent with an expectation from the analysis of first data. The preliminary result of the second data is shown in Fig. 4. No narrow signal corresponding to $\Theta^+$ is observed. The event yields is consistent with the expectation obtained from an estimation of detector and analysis efficiencies. The same sensitivity level of $\sim 0.3\mu$b/sr is expected with the new data as the previous one. An improvement of the tracking algorithm will increase the statistics

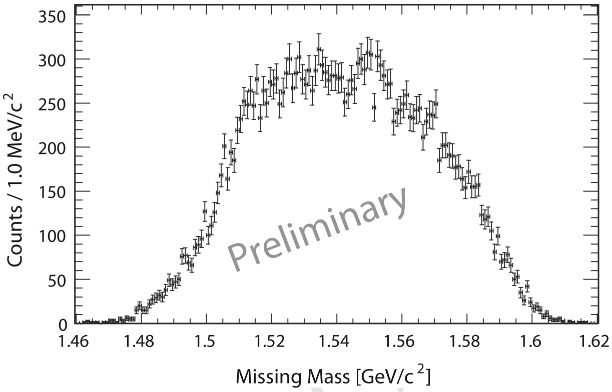

**Fig. 4** Missing-mass spectrum of the 2 GeV/$c$ $\pi^- p \to K^- X$ reaction. Acceptance is not corrected for

by a few tenths of percent. It is essential to minutely inspect the acceptance correction and detector effects to reach the final conclusion. The spectrum analysis is ongoing, the final result will be presented soon.

## 4 Conclusion and Prospects

In summary, the J-PARC E19 searched for the $\Theta^+$ pentaquark in the $\pi^- p \to K^- X$ reaction with the missing-mass resolution of 1.4 MeV/$c^2$ (FWHM). No narrow resonance was observed in the missing-mass spectrum measured with the beam momentum of 1.92 GeV/$c$. The upper limit of the differential cross section is 0.26 $\mu$b/sr in the laboratory frame. The upper limit is an order of magnitude smaller than that reported in the previous experiment performed at KEK PS. The upper limit of the differential cross section can be translated into the upper limit of the decay width of $\Theta^+$ with the help of the theoretical calculation. The obtained upper limit of width is 0.72 and 3.1 MeV/$c^2$ for $J^P = 1/2^+$ and $J^P = 1/2^-$, respectively. The preliminary result of the second data analyses is also presented. No corresponding structure is observed in the missing-mass spectrum measured in the 2 GeV/$c\pi^- p \to K^- X$ reaction. The result of the new data analysis will come soon.

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## References

1. Nakano, T., et al.: Phys. Rev. Lett. **91**, 012002 (2003)
2. Barmin, V.V., et al.: Phys. At. Nucl. **66**, 1715–1718 (2003)
3. Stepanyan, S., et al.: Phys. Rev. Lett. **91**, 252001 (2003)
4. Barth, J., et al.: Phys. Rev. Lett. **572**, 127–132 (2003)
5. Asratyan, A.E., et al.: Phys. At. Nucl. **67**, 682–687 (2004)
6. Kubarovsky, V., et al.: Phys. Rev. Lett. **92**, 032001 (2004)
7. Airapetian, A., et al.: Phys. Lett. B **585**, 213–222 (2004)
8. Abdel-Bary, M., et al.: Phys. Lett. B **595**, 127 (2004)
9. Chekanov, S., et al.: Phys. Lett. B **591**, 7–22 (2004)
10. Aleev, A., et al.: Phys. At. Nucl. **68**, 974–981 (2005)
11. Bai, J.Z., et al.: Phys. Rev. D **70**, 012004 (2004)
12. Schael, S., et al.: Phys. Lett. B **599**, 1–16 (2004)
13. Aubert, B., et al.: Phys. Rev. Lett. **95**, 042002 (2005)
14. Abe, K., et al.: Phys. Lett. B **632**, 173–180 (2006)
15. Litvintsev, D.O., et al.: Nucl. Phys. B (Proc. Suppl.) **142**, 374–377 (2005)
16. Antipov, Y.M., et al.: Eur. Phys. J. A **21**, 455 (2004)
17. Abt, I., et al.: Phys. Rev. Lett. **93**, 212003 (2004)
18. Longo, M.J., et al.: Phys. Rev. D **70**, 111101(R) (2004)
19. Link, J.M., et al.: Phys. Lett. B **639**, 604–611 (2006)
20. Pinkerton, C., et al.: J. Phys. G **30**, S1201 (2004)
21. Adamovich, M.I., et al.: Phys. Rev. C **72**, 055201 (2005)

22. Battaglieri, M., et al.: Phys. Rev. Lett. **96**, 042001 (2006)
23. De Vita, R., et al.: Phys. Rev. D **74**, 032001 (2006)
24. Niccolai, S., et al.: Phys. Rev. Lett. **97**, 032001 (2006)
25. Mizuk, R., et al.: Phys. Lett. B **632**, 173 (2006)
26. Nakano, T., et al.: Phys. Rev. C **79**, 025210 (2009)
27. Barmin, V.V., et al.: Phys. At. Nucl. **70**, 35–43 (2007)
28. McKinnon, B., et al.: Phys. Rev. Lett. **96**, 212001 (2006)
29. Abdel-Bary, M., et al.: Phys. Lett. B **649**, 252–257 (2007)
30. Hyodo, T., Hosaka, A., Oka, M. : arXiv:1203.0598 [nucl-th]
31. Miwa, K., et al.: Phys. Lett. B **635**, 72 (2006)
32. Takahashi, T., et al.: Prog. Theor. Exp. Phys. **2012**, 02B010 (2012)
33. Fukuda, T., et al.: Nucl. Inst. Meth. A **361**, 485–496 (1995)
34. Miwa, K., et al.: Phys. Rev. C **77**, 045203 (2008)
35. Shirotori, K., et al.: Phys. Rev. Lett. **109**, 132002 (2012)
36. Candlin, D.J., et al.: Nucl. Phys. B **226**, 1 (1983)