Nuclear Physics A

Nuclear Physics A 914 (2013) 91–94

Search for the Θ^+ pentaquark at J-PARC

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Abstract

We have been searching for the Θ^+ pentaquark via the $\pi^- p \to K^- X$ reaction at the J-PARC hadron facility. No peak structure was observed in the missing mass spectrum obtained at 1.92 GeV/c beam momentum. The upper limit for the production cross section averaged over the scattering angle from 2° to 15° in the laboratory frame was derived to be 0.26 μb/sr. In order to make a more stringent constraint we have also performed a measurement at 2.0 GeV/c. Present analysis status of this new data is reported.

Keywords: pentaquark, exotic hadron, J-PARC

1. Introduction

Searches for exotic hadrons (e.g. tetraquarks, pentaquarks and dibaryons), which cannot be interpreted as ordinary three-quark baryons or quark-antiquark mesons, have a long history. If such extraordinary states exist, they must be helpful in better understanding of low energy QCD dynamics in the non-perturbative regime. The pentaquark called Θ^+ is a genuine exotic baryon with valence quark structure of $uudd\bar{s}$ and with a mass of about 1530 MeV/c^2, first predicted by Diakonov, Petrov and Polyakov in 1997 [1]. A striking feature of this resonance is a quite narrow width of the order of 1 MeV or even less, which makes it very attractive for experimentalists to search for. In 2003, SPring-8/LEPS group first reported evidence of Θ^+ via the $\gamma n \to K^+K^-n$ reaction on ^{12}C target [2]. In the following few years, several experimental groups published supporting evidence for Θ^+, followed by a number of experiments with no evidence (see Ref. [3] for a review). Later, among positive results, some groups [4, 5] reconfirmed their findings but others [6, 7] did not reproduce their previous results with higher statistics data.

In this controversial situation, it is worth considering low energy hadronic reactions which are complementary to the photo-production one. Hadronic reactions are expected to have sizable production cross section and their production mechanism is rather straightforward. It is noted that there were two experiments using low energy meson beams at KEK-PS. The first was the E522 experiment [8]; the Θ^+ pentaquark was searched for via the $\pi^-p \to K^-X$ reaction. Although a bump was found at 1530 MeV/c^2 in the missing mass spectrum obtained at a beam momentum of 1.92 GeV/c, its statistical significance was not enough to claim the evidence for Θ^+. The second was the E559 experiment [9]; no peak structure was observed in the missing mass spectrum of the $K^+p \to \pi^+X$ reaction at 1.2 GeV/c. This implies that the t-channel process where a K^* is exchanged is quite small and the nucleon pole term which is proportional to the decay width of Θ^+ is dominant. Therefore it is essential for a potentially narrow Θ^+ search in meson-induced reactions to achieve high statistics together with better mass resolution than a few MeV.

2. Experiment

J-PARC E19 is a dedicated experiment to search for the Θ^+ with high resolution and high statistics via the $\pi^-p \to K^-X$ reaction at the K1.8 beam line [10]. In order to carry out high-resolution missing-mass spectroscopy, two high-performance spectrometers were installed [11]. The beam spectrometer (BS) was equipped with a series of QQDQQ magnets at the final part of the K1.8 beam line, whose momentum resolution was less than 0.1% (FWHM). Scattered particles were identified and momentum analyzed by the Superconducting Kaon Spectrometer (SKS), featuring large solid angle of 100 msr and momentum resolution of 0.2% (FWHM). The SKS magnetic field was set at 2.5 T and scattered particles with momentum ranging from 0.7 to 1.0 GeV/c were accepted.

Figure 1 shows the E19 experimental setup. Secondary particles generated at the production target were transported through the K1.8 beam line. Two sets of plastic scintillator hodoscopes (BH1,2) were placed at both the entrance and the exit of the BS to measure the beam timing information. Electrons in the beam were rejected by a gas Cherenkov counter (GC, n = 1.002) at the trigger level. So as to handle high rate environment up to 10^7 Hz, 1-mm pitch MWPC's (BC1,2) were placed at the entrance of BS. 3-mm or 5-mm sense wire pitch drift chambers (BC3,4 and SDC1,2) were installed at the exit of the BS and the entrance of the SKS. Large area drift chambers (SDC3,4) and a TOF wall were placed at the exit of SKS. An aerogel Cherenkov counter (AC, n = 1.05) and a lucite Cherenkov counter (LC, n = 1.49) were used for the kaon trigger. A liquid hydrogen target (ϕ67.8 × 120 mm) with a mass thickness of 0.86 g/cm^2 was used in the present measurement.

The E19 physics data were taken during two separate periods, using different beam momenta of 1.92 and 2.0 GeV/c, respectively.

The first physics run was carried out in 2010 using 1.92 GeV/c π^- beam. The incident beam momentum was set at the same value of the KEK E522 experiment [8] in order to have a direct comparison with the previous experimental result. In the missing mass spectrum of the $\pi^-p \to K^-X$ reaction, no peak structure corresponding to the Θ^+ mass was observed [12]. The upper limit of the differential cross section averaged over the scattering angle from 2° to 15° in the laboratory frame is 0.26 μb/sr at 90% confidence level in the mass region of 1.51-1.55 GeV/c^2. An order of magnitude higher sensitivity was achieved with respect to the E522 experiment. Combining the result with a theoretical calculation based on the effective Lagrangian approach [13], the upper limit of the Θ^+ decay width was estimated to be 0.72 and 3.1 MeV for $J^P_\Theta = 1/2^+$ and $1/2^-$, respectively.

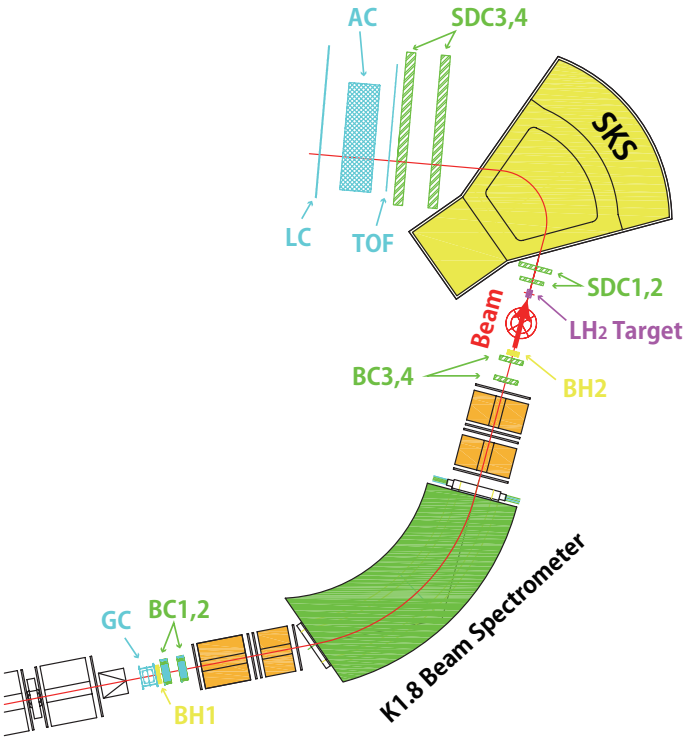

Figure 1. E19 experimental setup at J-PARC K1.8 beam line. See text for details.

The second physics run was performed in 2012 with a beam momentum of 2.0 GeV/c which is the maximum momentum of the K1.8 beam line. We chose the higher momentum because increase of the production cross section with incident energy is expected from a theoretical prediction [13]. Therefore we can achieve a higher sensitivity to search for Θ^+. In other words, a more stringent constraint on the Θ^+ decay width will be obtained even if no peak is observed again. The data were successfully taken with 8.7×10^{10} incident beam pions on the liquid hydrogen target. The present analysis status is described in the next section.

3. Analysis and Result

The incident pions were selected by the time-of-flight method with the resolution of 0.2 ns. Beam momenta were analyzed by fitting the hit positions of BC1-4 with third order transfer matrix of the BS. Trajectories of outgoing particles were reconstructed by using the hit positions of SDC1-4 and the SKS field map. Scattered kaons were identified in the mass distribution obtained from the momentum, path length and time of flight between the target and the TOF wall. The reaction vertex was determined as the point of the closest approach between tracks of beam and outgoing particles. The obtained vertex distribution was consistent with the beam profile and materials around the target. A suitable fiducial volume was defined inside the liquid hydrogen target in order to avoid background from the mechanical structure materials. Very forward scattering angle events of less than 2° were not used because of their poor vertex resolution.

In order to examine the consistency between the first and the second run and to calibrate various parameters of the spectrometers, the known $\Sigma^\pm$ hyperon productions were studied in the $\pi^\pm p \to K^+\Sigma^\pm$ reactions at 1.37 and 1.45 GeV/c. Figure 2 shows a missing mass spectrum of the $\pi^+ p \to K^+\Sigma^+$ reaction at 1.37 GeV/c. It is preliminary because several corrections including the energy-loss correction have not been optimized yet. By fitting the Σ^+ peak, missing mass resolution was obtained to be 2.0 ± 0.1 MeV (FWHM) which is almost equivalent to the first data of 1.9 ± 0.1 MeV.

Figure 3 shows a preliminary missing mass spectrum of the $\pi^- p \to K^- X$ reaction at 2.0 GeV/c. No peak structure was observed again in the region of interest. A further improvement of the statistics by a few tens of percent is

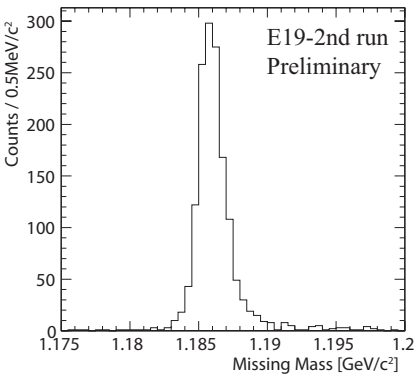

Figure 2. Missing mass spectrum of the $\pi^+ p \rightarrow K^+\Sigma^+$ reaction at 1.37 GeV/c. Σ^+ peak is clearly observed. The absolute mass scale is still being finalized.

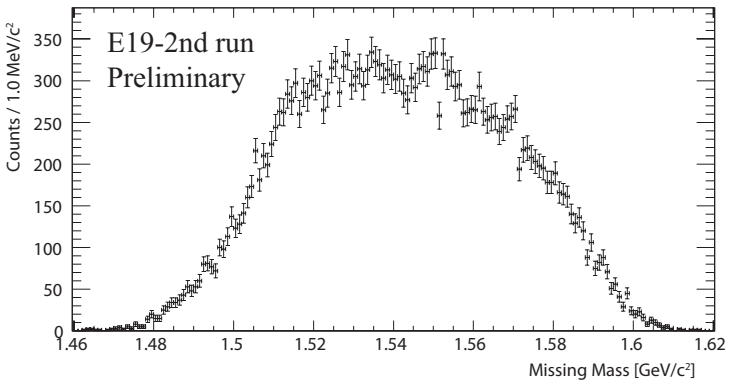

Figure 3. Missing mass spectrum of the $\pi^- p \rightarrow K^- X$ reaction at 2.0 GeV/c.

expected in the further analysis. An analysis to derive an upper limit of the cross section is in progress.

4. Summary and Outlook

We carried out the pentaquark Θ^+ search experiment via the $\pi^- p \rightarrow K^- X$ reaction at J-PARC. In the first physics run at 1.92 GeV/c, there was no significant peak structure in the missing mass spectrum, The upper limit for the production cross section averaged over the scattering angle from 2° to 15° in the laboratory frame was derived to be 0.26 μb/sr. This result imposes a strong constraint on the Θ^+ decay width of less than 0.72 and 3.1 MeV for $J^P_\Theta = 1/2^+$ and $1/2^-$, respectively.

The second physics run was completed using the 2.0 GeV/c beam, devoted to the achievement of higher sensitivity. The equivalent amount of beam pions to the first run was accumulated on the liquid hydrogen target. A suitable level of performance of both the beam spectrometer and the SKS was demonstrated by analyzing the Σ production data. The missing mass resolution obtained from the Σ^+ peak at 1.37 GeV/c is 2.0 ± 0.1 MeV in the present analysis. No peak structure was observed again in the missing mass spectrum of the $\pi^- p \rightarrow K^- X$ reaction at 2.0 GeV/c. Detailed analysis including efficiency evaluation is in progress. A complete result of the Θ^+ production data will be published soon.

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