Search for the pentaquark Θ^+ via the $\pi^- p \to K^- X$ reaction at J-PARC

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Study of exotic hadrons, which cannot be interpreted as ordinary three-quark baryons or quark-antiquark mesons, would offer us a good opportunity to investigate low-energy quark dyanmics. The pentaquark Θ^+ has a strangeness quantum number $S = +1$ with its minimal quark configuration of $uudd\bar{s}$. The distinct features of the Θ^+ are a light mass of about 1540 MeV and a narrow width of a few MeV or less. If such an exotic pentaquark exits, it is quite interesting from a viewpoint of the hadron structure. Many experiments searched for the Θ^+ so far, but the experimental situation was still controversial. For further investigation, a high-statistics and high-resolution experiment has been required.

The differential cross section of the $\pi^- p \to K^- X$ reaction was measured in forward scattering angles to search for the Θ^+ pentaquark with the missing-mass technique. The experiment was performed in 2012 using a beam momentum of 2.01 GeV/c at the K1.8 beam line in the J-PARC hadron facility. A liquid hydrogen target with a thickness of 0.85 g/cm^2 was exposed to 8.1×10^{10} π^- beams with a typical intensity of 1.7×10^6 per 2.2-second spill. We constructed a high-resolution spectrometer system. The beam pions were measured with the beam spectrometer with a momentum resolution of 1×10^{-3} (FWHM). The outgoing kaons were identified with the SKS spectrometer with a momentum resolution of 2×10^{-3} (FWHM). We measured the missing mass of the $\pi^- p \to K^- X$ reaction at forward scattering angles of 2–15° in the laboratory frame. The missing-mass resolution for the Θ^+ was estimated to be 2.13 ± 0.15 MeV (FWHM). Using the $\Sigma^\pm$ production data and the beam-through data, the absolute scale of the missing mass for the Θ^+ production data was calibrated with an uncertainty of 1.4 MeV/c^2. Thus, it is demonstrated that we are able to observe a sharp missing-mass peak and determine the mass and, possibly, width with a good precision, if

the Θ^+ is produced. The cross section was calculated by correcting the data for the experimental efficiency and acceptance with an uncertainty of 7%. The measured differential cross sections of the $\pi^\pm p \to K^+\Sigma^\pm$ reactions were in good agreement with the past experimental data.

No sharp peak structure was observed in the missing-mass spectrum of the $\pi^- p \to K^- X$ reaction. The missing-mass acceptance was wider than the previous 2010 data owing to the improved experimental setup. The upper limit on the Θ^+ production cross section averaged over scattering angles from 2° to 15° in the laboratory frame was obtained as a function of the Θ^+ mass, and found to be less than 0.28 μb/sr at the 90% C.L. in a mass region of 1500–1560 MeV/c^2. Note that we assumed the intrinsic width of Θ^+ is negligibly smaller than the experimental resolution. If the width of Θ^+ is 1 MeV, the above upper limit rises by 0.10 μb/sr. The systematic uncertainty of the upper limit was controlled within 10%. Hence, the present upper limit is predominantly determined by the statistical uncertainty. The present upper limit is as small as the previous 2010 result of 0.28 μb/sr. This is attributed to almost the same statistics of the data.

The narrowness of the width is the most peculiar property to the Θ^+ pentaquark. The mechanism of the $\pi^- p \to K^- \Theta^+$ reaction was theoretically discussed using the KEK-E522 and E559 results. Knowing that the t-channel and contact term contributions are very small, the s-channel contribution is important in the $\pi^- p \to K^- \Theta^+$ reaction. Since the s-channel amplitude is related to the Θ^+ decay width through the $KN\Theta$ coupling constant, we can estimate the upper limit of the width from the cross section measured in the experiment. Using both the 2010 and 2012 data together with a theoretical calculation using the effective Lagrangian approach, the upper limit of the Θ^+ width was estimated as a function of the Θ^+ mass. Considering the theoretical uncertainty, we adopted the most conservative theoretical scheme that gives the largest upper limit. The upper limits of the width were estimated to be 0.36 and 1.9 MeV for the Θ^+ spin-parity of $1/2^+$ and $1/2^-$, respectively. The upper limits of the width were improved by half of the previous limits of 0.72 and 3.1 MeV for $1/2^+$ and $1/2^-$, respectively, obtained in the 2010 data. The present upper limit of the width is not sensitive enough to the $1/2^-$ state with a very narrow width in this theoretical model. For the $1/2^+$ case, the present limit is more stringent than the upper limit of 0.64 MeV reported from the Belle Collaboration. The present limit is comparable to the width of 0.34 ± 0.10 MeV reported by the DIANA Collaboration. The consistency is subtle but the present result does not completely contradict the DIANA claim.