Evidence for S=+1 Pentaquark baryon

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I report the recent experimental studies for pentaquark baryons whose quark configuration is $qqqq\bar{q}$. The evidence for a pentaquark particle with $S = +1$, Θ^+, was first observed at LEPS at SPring-8. Several experimental groups confirmed the Θ^+ with a mass of ∼1540 MeV and a narrow width.

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There were no clear experimental evidence for existence of a hadron with a quark configuration rather than three quarks or a quark-antiquark pair although QCD does not forbid the existence of other combination such as $qqqq\bar{q}$ or $q\bar{q}q\bar{q}$. The absence of the baryon state with more than three quarks was one of the big mysteries in particle physics for decades. In fact, the summary of the search for baryon resonances with the strangeness quantum number S=+1, that cannot be formed by three quarks, has been dropped from the Particle Data Group (PDG) listings although the possible exotic resonances were noted in the 1986 baryon listings [1].

Recently Diakonov, Petrov and Polyakov [2] calculated masses and widths of an anti-decuplet baryons by using chiral quark soliton model. The lightest member of the anti-decuplet is the Θ^+ which is an exotic 5-quark state with a quark configuration of $uudd\bar{s}$ that subsequently decays into a K^+ and a neutron. The model predicts the mass of the Θ^+ to be ∼ 1530 MeV with a narrow width of ∼ 15 MeV. This narrow width was very attractive for experimentalists because the search could be done without a partial wave analysis with a wide detector acceptance.

The first evidence for the Θ^+ was reported by the LEPS collaboration at SPring-8 [3]. The experiment was carried out by using a laser-electron photon (LEP) beam which was generated by Backward-Compton scattering of laser photons with the 8-GeV electrons.

Figure 1 shows a schematic drawing of the LEPS detector. The detailed information about the detector can be found elsewhere [3]. The most important detector component for the the present analysis was a 0.5-cm thick plastic scintillator (SC) located 9.5 cm downstream from the 5-cm thick liquid-hydrogen (LH_2) target. The events from the SC is turned out to be very useful to study events generated from neutrons in carbon nuclei at the SC.

In the analysis, we selected K^+K^- pair events produced in the SC, which accounted for about half of the K^+K^--pair events. The missing mass $MM_{\gamma K^+K^-}$ of the N(γ, K^+K^-)X reaction was calculated by assuming that the target nucleon (proton or neutron) has the mean nucleon mass and zero momentum. Subsequently, events with the $MM_{\gamma K^+K^-}$ to be consistent with the nucleon mass were selected. The main physics background events

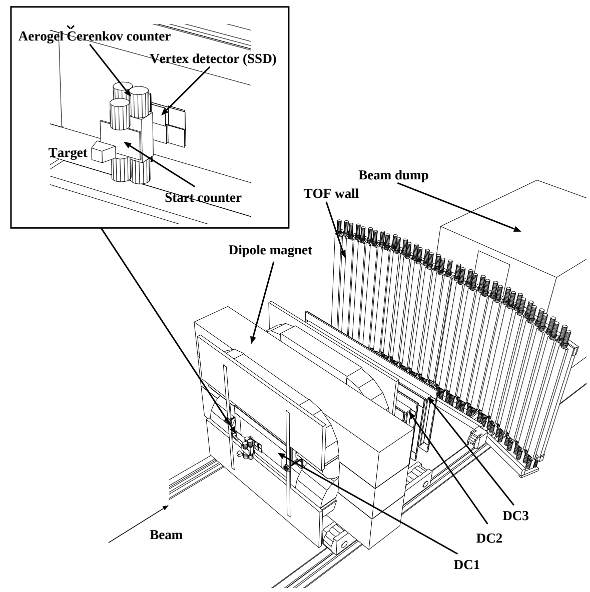

FIG. 1: The LEPS detector setup.

due to the photo-production of the ϕ meson were eliminated by removing the events with the invariant K^+K^- mass from 1.00 GeV/c^2 to 1.04 GeV/c^2. In order to eliminate photo-nuclear reactions of $\gamma p \to K^+K^-p$ on protons in the SC, the recoiled protons were detected by a vertex counter.

In case of reactions on nucleons in nuclei, the Fermi motion has to be taken into account to obtain appropriate missing-mass spectra. The missing mass corrected for the Fermi motion, $MM^c_{\gamma K^\pm}$, is deduced as

$$MM^c_{\gamma K^\pm} = MM_{\gamma K^\pm} - MM_{\gamma K^+K^-} + M_N, \qquad (1)$$

where M_N is the nucleon mass.

The corrected K^+ missing-mass distribution for the events that satisfy all the selection conditions is compared with that for the events for which a coincident proton hit was detected in the SSD. In the latter case, a clear peak due to the $\gamma + p \to K^+\Lambda(1520) \to K^+K^-p$ reaction is observed while the $\Lambda(1520)$ peak does not exist in the signal sample. This indicates that the signal sample is dominated by events produced by reactions on neutrons. Fig. 2 shows the corrected K^- missing mass distribution

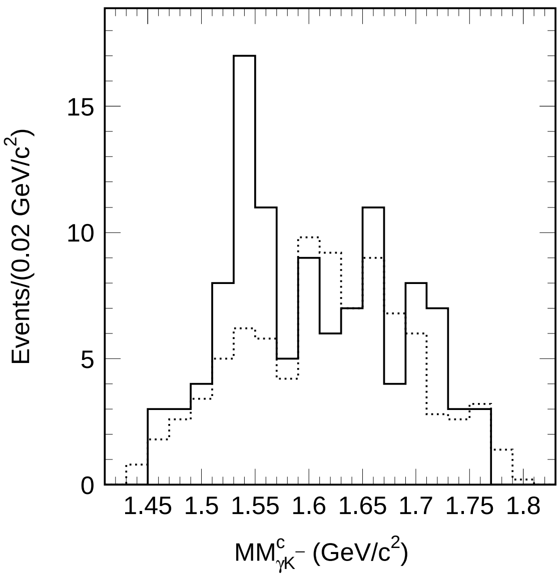

FIG. 2: The $MM^c_{\gamma K^-}$ spectrum for the signal sample (solid histogram) and for events from the LH_2 (dotted histogram) normalized by a fit in the region above 1.59 GeV.

of the signal sample. A prominent peak at 1.54 GeV/c^2 is found. We assumed the broad background centered around 1.6 GeV/c^2 is due to non-resonant K^+K^- production and it can be fitted by a distribution of events from the LH_2.The estimated number of the events above the background level is 19.0, which corresponds to a Gaussian significance of 4.6 σ. This narrow peak indicates the existence of an $S = +1$ resonance which may be attributed to the exotic 5-quark baryon proposed as the Θ^+.

Soon after a preliminary result on the was announced by the LEPS collaboration at the international conference PANIC in October 2002, the CLAS collaboration at Jefferson Lab re-analyzed photo-reaction data which were collected in 1999 by using a liquid deuterium target. They observed a peak at 1542 MeV in the nK^+ invariant mass spectrum of the reaction $\gamma d \to K^+K^-pn$, where all charged particles in the final state were detected [4]. Since the momentum of the final neutron was fully determined by using total momentum conservation law, their result was not affected by a Fermi motion of the initial neutron. The CLAS collaboration also announced an evidence for the Θ^+ by analyzing the reaction $\gamma p \to K^+K^-\pi^+n$ in a different data set [5].

Prior to the CLAS reports, the DIANA collaboration at the Institute of Theoretical and Experimental Physics (ITEP) in Russia reexamined low-energy K^+ Xe collision events in the Xenon bubble chamber, which were taken in 1986. They found a 4.4 σ peak at 1539 MeV with a very narrow width of < 9 MeV in the invariant pK^0 invariant mass spectrum of the charge-exchange reaction $K^+\mathrm{Xe}' \to \mathrm{K}^0\mathrm{pXe}'$ [6]. Since the production cross-section is proportional to the decay width, it can be estimated to be 0.9 MeV assuming the background under the peak is due to the charge exchange reaction of $K^+n \to K^0p$ outside of the resonance region [7]. This narrow width is consistent with the KN phase shift analysis of the old data [8, 9].

In addition to these experiments, many experiments found an evidence for the Θ^+ by mainly analyzing old data. Positive results for the Θ^+ are summarized in Table I [3–6, 10–14].

At the time of writing this manuscript, there are several experimental groups which have reported null results for the pentaquarks [15–19]. Those experiments were carried out at very high energy, and some of the experiments give very stringent upper limits on the production rate of the pentaquarks with high statistics. If the pentaquarks exist, their production at high energy must be heavily suppressed with respect to normal baryons.

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TABLE I: Summary of positive experimental results for the Θ^+.

Where	Reaction	Mass	Width	Significance	Ref.
LEPS	$\gamma C \to K^+ K^- X$	1540±10	<25	4.6	[3]
DIANA	$K^+ Xe \to K^0 p X$	1539±2	<9	4.4	[6]
CLAS	$\gamma d \to K^+ K^- p(n)$	1542±5	<21	5.2	[4]
SAPHIR	$\gamma p \to K^+ K^0 (n)$	1540±6	<25	4.8	[10]
ITEP	$\nu A \to K^0 p X$	1533±5	<20	6.7	[11]
CLAS	$\gamma p \to \pi^+ K^- K^+ (n)$	1555±10	<26	7.8	[5]
HERMES	$e^+ d \to K^0 p X$	1528±3	13±9	∼5	[12]
ZEUS	$e^+ p \to e' K^0 p X$	1522±3	8±4	∼5	[13]
COSY-TOF	$pp \to K^0 p \Sigma^+$	1530±5	<18	4-6	[14]