Evidence for $S = +1$ Pentaquark Baryon in Photoproduction from the Nucleon

Quarks are ultimate building blocks of subatomic particles although an isolated quark has never been observed. According to the quantum chromodynamics (QCD), each quark can have three colors; red, blue, or green. Only the colorless combination (superposition) of quarks can travel freely as a particle. An example of such a combination is a proton, which is made of two ‘u’ quarks and one ‘d’ quark. The relatives of a proton which are made of three quarks are called baryons. A particle consisting of one quark (q) and one anti-quark ($\bar{q}$) is called a meson. Note that an anti-quark can have the anti-colors; magenta (‘anti-red’), violet (‘anti-green’), or yellow (‘anti-blue’) so that a $q\bar{q}$ pair can be colorless. Mesons and hadrons together form a particle type called hadrons.

There were no clear experimental evidences for the existence of a hadron with a quark configuration rather than three quarks (three anti-quarks) or a $q\bar{q}$ pair, although QCD does not forbid the existence of other combinations such as $q\bar{q}\, q\bar{q}$ or $qqqqqq$. The absence of the hadron state with more than three quarks was one of the big mysteries in particle physics for decades.

Recently, we, the LEPS collaboration at beamline **BL33LEP**, have found evidence for a pentaquark state ($qqqq\bar{q}$) with the strange quark number $S = +1$ (Fig. 1).

A baryon state with $S = +1$ cannot be made of three quarks since they must contain one anti-strange ($\bar{s}$) quark. To make the baryon number equal to 1, the minimal quark configuration should be $qqqq\bar{s}$, where q stands for a ‘u’ quark or a ‘d’ quark.

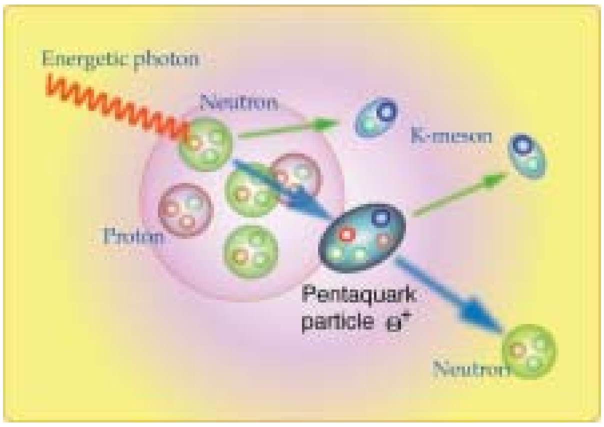

Fig. 1. Production of the pentaquark particle studied by the LEPS collaboration.

In 1997, Diakonov, Petrov and Polyakov studied anti-decuplet baryons using the chiral soliton model [1]. The mass splittings of the established octet and decuplet were reproduced with an accuracy of 1% in this model, and the lightest member of the anti-decuplet with $S = +1$, which we now call Θ^+, was predicted to have a mass of 1530 MeV and a total width of less than 15 MeV. The $S = +1$ baryon in this mass region has not been searched in the KN scattering experiments in the past because the momenta of kaons are too high, as pointed out in Refs. [1,2]. This fact together with the very narrow predicted width motivated us to search for evidence of the Θ^+ at the LEPS facility.

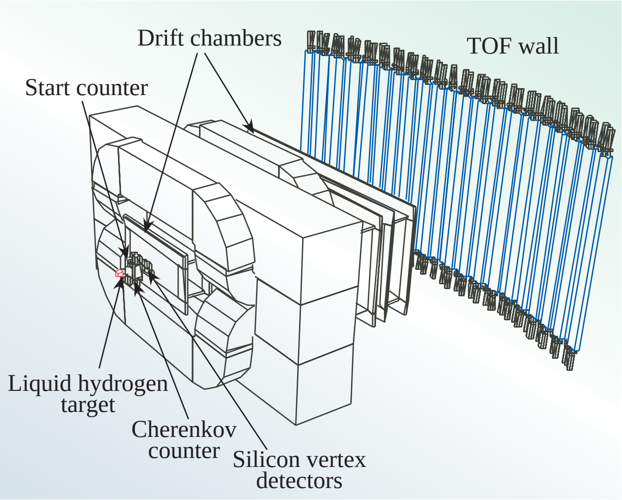

Fig. 2. The LEPS detector. It analyzes the momentum and velocity of charged particles in forward angles.

The laser-electron photon (LEP) beam is generated by backward-Compton scattering of laser photons with the 8 GeV electrons [3]. The maximum energy of the beam is currently 2.4 GeV, which is well above the threshold for $s\bar{s}$ production. Figure 2 shows a schematic drawing of the LEPS detector. For the determination of the momentum of a charged particle, tracking counters were placed before and after a 0.7 T magnet. A time-of-flight (TOF) scintillator array was positioned 3 m behind the dipole magnet to measure the velocity of a charged particle. The mass of a charged particle was reconstructed from the momentum and velocity information.

A 0.5-cm-thick plastic scintillator (SC) located 9.5 cm downstream from the 5-cm-thick liquid-hydrogen (LH_2) target ensured that at least one charged particle is produced in the LH_2 target. For the Θ^+ search at LEPS, the events from the SC were used to study the events generated from neutrons in the carbon nuclei at the SC, by searching for baryon resonances with the strangeness quantum number $S = +1$ in the K^- missing mass spectrum in the $\gamma n \rightarrow K^+K^-$ reaction [4]. Since the LH_2 target contained no neutron, events from the LH_2 target were used to estimate the background spectrum.

Figure 3 shows the K^- missing mass distribution of the signal sample. A prominent peak at 1.54 GeV (1540 MeV) is found. The broad background centered around 1.6 GeV is most likely due to non-resonant K^+K^- production and the background shape in the region above the peak has been fitted by a distribution of events from the LH_2. The upper limit for the width was determined to be less than 25 MeV. The observed narrow peak strongly indicates the existence of an $S = +1$ resonance which may be attributed to the exotic 5-quark baryon proposed as the Θ^+.

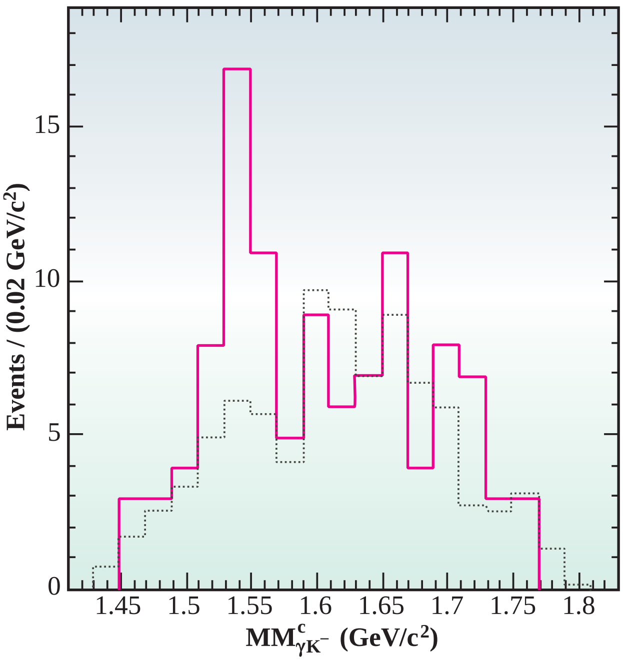

Fig. 3. K^+ missing mass spectrum for the signal sample (solid histogram) and for events from the LH_2 (dotted histogram) [4].

Soon after a result on the Θ^+ was announced by the LEPS collaboration, it was confirmed by experiments at ITEP [5], Jefferson Lab [6], and ELSA [7]. All experimental results indicate that the width of the $S = +1$ baryon, which is now called Θ^+, is very narrow. The both measured mass and which are in good agreement with a prediction by Diaknov *et al*. Intensive theoretical investigation of the Θ^+ is in progress. Further experimental efforts to determine the spin and parity of the Θ^+ are crucial.

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