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Results of the searches for pentaquarks with strangeness in DIS at HERA

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The $K^0_S\, p$ invariant mass spectrum was reconstructed in several kinematic regions with the main emphasis on the studies of the production mechanism of the Θ^+ candidate recently observed by ZEUS. The candidate Θ^+ signal was found to be produced predominantly in the forward hemisphere in the laboratory frame. This is unlike the case for the $\Lambda(1520)$ or the Λ_c, and indicates that the Θ^+ may have an unusual production mechanism related to proton-remnant fragmentation. H1 does not observe a signal and sets an upper limit at 95% C.L. which does not exclude the ZEUS observation.

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1. Introduction

Recently, ZEUS made an observation [1] of a narrow signal in the vicinity of 1530 MeV which can be interpreted as a bound state of five quarks, i.e. as a pentaquark, $\Theta^+ = uudd\bar{s}$ [2]. The experimental search was performed using inclusive ep collisions with the proton energy 820/920 GeV and the electron/positron energy of 27.6 GeV. The data were collected using an integrated luminosity of 121 pb^{-1} from HERA I.

The Θ^+ candidate decaying to $K^0_S\, p\,(\bar{p})$ was seen in deep inelastic scattering (DIS) at $Q^2 > 20$ GeV^2, while no signal was reported in photoproduction ($Q^2 \sim 0$). This decay channel is not exotic since 3-quark states, such as Σ baryons, can also decay to the $K^0_S\, p\,(\bar{p})$. Therefore, it is essential to study the kinematics of the observed signal and to compare it with that for established 3-quark states.

The absence of a guiding principle of how to compose three quarks to form a baryon at the quark-fragmentation stage leads to a few possible baryon-production mechanisms. In the case of baryons with five quarks, the situation could be even more complicated. For collisions involving incoming baryon(s), the fragmentation mechanism could be influenced by a contribution from the proton-remnant system, thus the baryonic yield in certain kinematic regions of ep collisions is expected be higher than in e^+e^- annihilation.

2. Evidence for a baryonic state near 1530 decaying to $K^0_S\, p$

$K^0_S\, p\,(\bar{p})$ invariant masses reconstructed in photoproduction and DIS using HERA I data are shown in Fig. 1(left). The $K^0_S\, p\,(\bar{p})$ distribution has two peaks, at around 1522 MeV ($Q^2 > 20$ GeV^2) and near 2286 MeV. The first peak is attributed to the Θ^+ candidate state [1]. The second peak corresponds to the established Λ_c baryon. Both peaks are best seen for $Q^2 > 20$ GeV^2, i.e. in the region where the Λ_c peak has the largest signal-over-background ratio (S/B=0.22). Since the average charged-track multiplicity is 50% higher[1] for photoproduction than for DIS at $Q^2 > 1$ GeV^2, the S/B ratio is small for photoproduction. Therefore, the significant combinatorial background for the $K^0_S\, p\,(\bar{p})$ spectrum could explain the non-observation of the Θ^+ candidate for photoproduction [1].

It is important to note that the decrease of the S/B ratio for high-multiplicity events exists only for the states whose production is not driven by pure quark fragmentation. A typical example is Λ_c: there could be at most two Λ_c per event independent of the energy contributing to the hadronic-final state. The production of charmed quarks is significantly suppressed at the fragmentation stage, therefore, a hard QCD subprocess, like $\gamma^* g \to c\bar{c}$, is the necessary mechanism for the Λ_c formation. If the Θ^+ production is driven by the diquark system (in which the diquark is produced by the incoming proton), then the Θ^+ peak should also have a small S/B ratio for high multiplicity events.

In contrast, the S/B ratio for $\Lambda(1520)$ reported by ZEUS [3] is almost the same for photoproduction and DIS. This is a clear indication that $\Lambda(1520)$ is solely produced by the quark fragmentation, and, therefore, this baryon cannot be used as a reference state for experimental Θ^+ searches.

[1]This is due to the fact that photoproduction events were taken using a specific trigger requirement (jets with $E_T > 6-8$ GeV). The hadronic-final state of DIS data sample is almost completely trigger-unbiased.

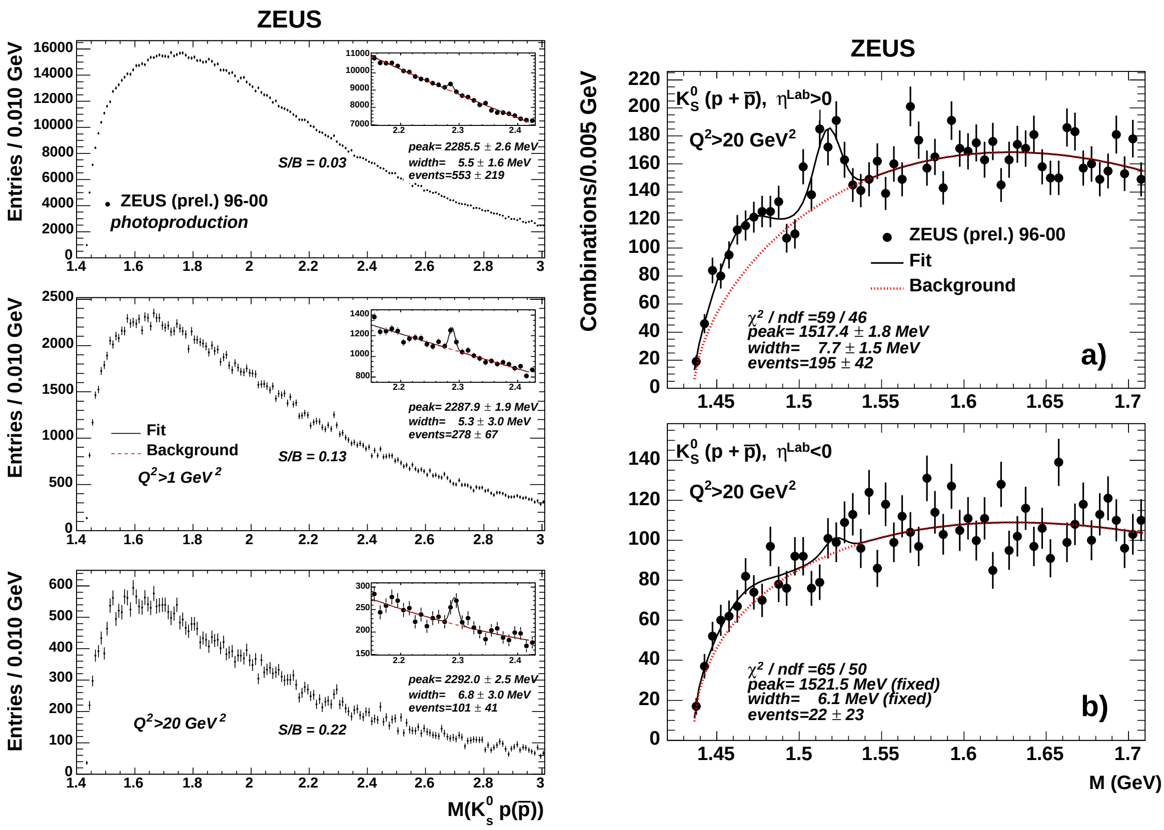


Figure 1. Left: $K^0_S\, p\, (\bar{p})$ *invariant-mass spectra in photoproduction and DIS* ($Q^2 > 1$ GeV^2 *and* $Q^2 > 20$ GeV^2) *with the indicated signal-over-background ratio (S/B) for the* Λ_c *peak. The insets show the invariant-mass distribution near the* Λ_c *mass region.* Right: $K^0_S\, p\, (\bar{p})$ *invariant-mass distribution near the* 1520 MeV *mass for the forward* ($\eta > 0$) *and rear* ($\eta < 0$) *region. The fit was performed using a double Gaussian with the threshold function.*

If the observed $K^0_S\, p\, (\bar{p})$ peak near 1522 MeV indeed corresponds to a new baryonic state, then the studies of this peak in different pseudorapidity regions can help to understand the production mechanism of this state. The 1522 MeV peak should be seen for both forward and rear pseudorapidity regions if the Θ^+ is produced by pure quark fragmentation, as any established 3-quark state with strangeness. In contrast, if the production mechanism of the Θ^+ state involves the fragmentation of the diquark system from the incoming proton, then the Θ^+ state should mainly be seen for $\eta > 0$ (towards the incoming proton direction) and at low transverse momenta. In addition, high Q^2 DIS is more favorable [4] as in this case the incoming proton can receive a sufficient kick from the virtual boson and the color string can drag the diquark towards the central pseudorapidity region (small η). Indeed, Fig. 1(right) shows that the 1522 MeV signal is found to occur predominantly for $\eta > 0$. Known baryons, produced either via boson-gluon mechanism (Λ_c) or by quark-fragmentation process ($\Lambda(1520)$), are distributed uniformly over the whole measured pseudorapidity region $-1.5 < \eta < 1.5$ (see Fig. 2).

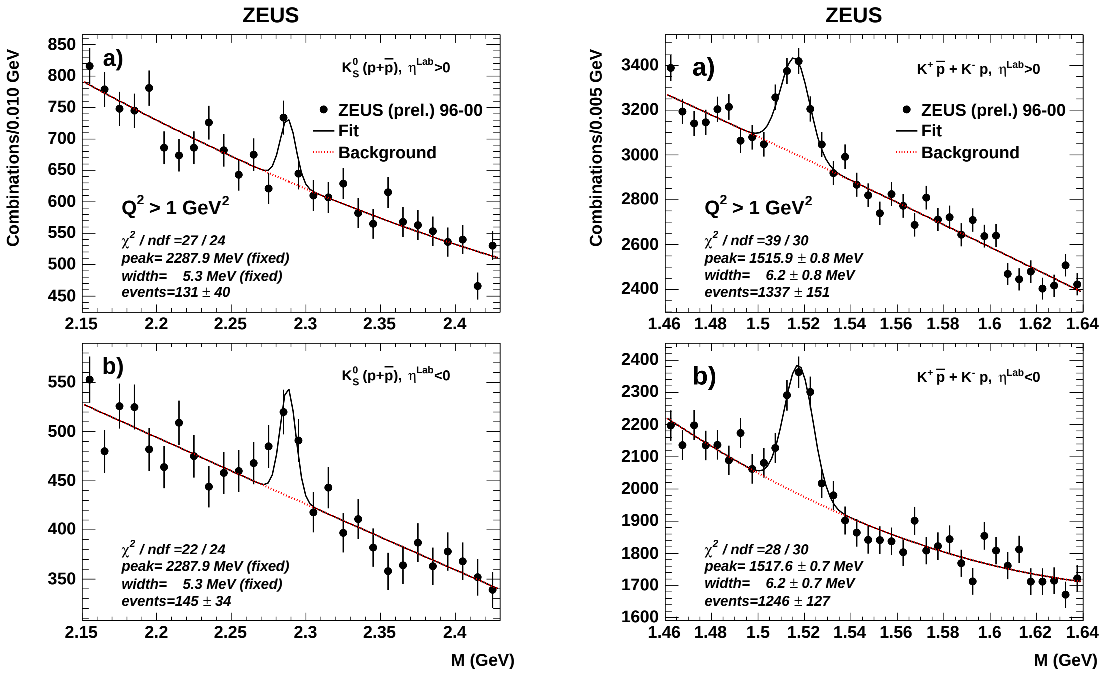


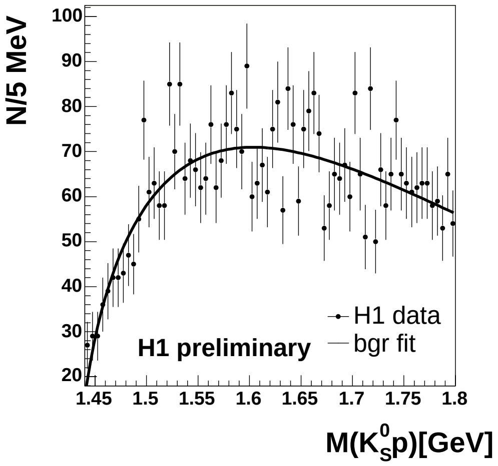
Figure 2. Left: $K^0_S\, p\, (\bar{p})$ *invariant-mass distribution near the* Λ_c *mass for* $\eta > 0$ *and* $\eta < 0$ *regions for* $Q^2 > 1$ GeV^2. *The peak position and the width were fixed from the fit to the sum of these two mass distributions.* Right: *The* $K^- p (K^+ \bar{p})$ *invariant-mass distribution near the* $\Lambda(1520)$ *mass in the forward* ($\eta > 0$) *and in the rear* ($\eta < 0$) *regions for* $Q^2 > 1$ GeV^2. *The fits were performed using a Gaussian with a second-order polynomial function.*

3. H1 results

The H1 Collaboration has performed Θ^+ searches using a similar $K^0_S\, p\, (\bar{p})$ reconstruction procedure [5] as for the ZEUS analysis, but the DIS selection was somewhat tighter than in the ZEUS case. An integrated luminosity of 71 pb^{-1} was used from HERA I. The $K^0_S\, p\, (\bar{p})$ spectrum is shown in Fig. 3(left). No signal is observed. Given the absence of the Θ^+ signal, 95% C.L. limits were set on the production of new states decaying to $K^0_S\, p\, (\bar{p})$ in the mass range 1480–1700 MeV in DIS for $Q^2 > 20$ GeV^2. The limits shown in Fig. 3(right) were obtained assuming that the production kinematics of Θ^+ is similar to the Σ^+ state produced by pure quark-fragmentation process. Around the mass of 1520 MeV, an upper limit on the cross section of roughly 100–120 pb was found, which is about the signal cross section observed[2] by ZEUS.

In addition, H1 investigated the $K^0_S\, p\, (\bar{p})$ invariant masses at lower Q^2, using an alternative selection which uses higher-momentum protons, $p > 1.5$ GeV. In this case, a lower proton purity is expected. The $K^0_S\, p$ and $K^0_S\, \bar{p}$ mass combinations were analysed separately. As for the ZEUS studies [1], a Θ^+ signal was not seen at low Q^2 and for high-momentum protons.

[2] The ZEUS cross section [6] for the Θ^+ candidates and their antiparticles measured in the kinematic region given by $Q^2 \geq 20$ GeV^2, $0.04 < y < 0.95$, $p_T > 0.5$ GeV and $|\eta| < 1.5$ was $\sigma(e^{\pm} p \rightarrow e^{\pm}\, \Theta^+ X \rightarrow e^{\pm}\, K^0 p\, X) = 125 \pm 27(\text{stat.})^{+36}_{-28}(\text{syst.})$ pb



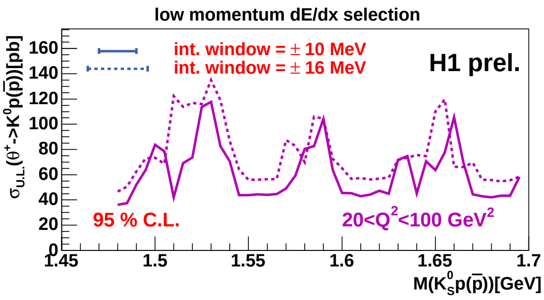


Figure 3. Left: $K^0_S\, p\,(\bar{p})$ *invariant-mass distribution near the* 1520 MeV *mass in DIS for* $Q^2 >$ 20 GeV^2 *reconstructed by H1*. Right: *Upper limits on the cross section* $\sigma(e^{\pm} p \to e^{\pm}\,\Theta^+ X \to e^{\pm} K^0 p X)$.

4. $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ states?

The Θ^+ lies at the apex of a hypothetical anti-decuplet of pentaquarks with spin $1/2$ [2]. The baryonic states $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ at the bottom of this antidecuplet are also manifestly exotic. A support for this picture came from the NA49 experiment which recently made observations [7] of both states near 1862 MeV in the $\Xi^-\pi^{\pm}$ and $\bar{\Xi}^+\pi^{\pm}$ decay channels in fixed-target pp collisions at the CERN SPS.

ZEUS has performed a similar analysis [8] by combining Λ with π using displaced tertiary vertices. With more than 190 reconstructed $\Xi^0(1530)$ near the mass threshold of $\Xi\pi$ spectrum, no pentaquark signal was observed near the 1860 MeV mass region. The 95% C.L. upper limit on the ratio $\Xi^{--}_{3/2}(\Xi^0_{3/2})$ to $\Xi^0(1530)$ was in the range $0.2-0.45$.

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