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RESULTS OF THE SEARCHES FOR NARROW BARYONIC STATES WITH STRANGENESS IN DIS AT HERA

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Searches for narrow baryonic states in the $K^0_S\,p$, K^+p, $\Xi^-\,\pi^\pm$ and $\bar{\Xi}^+\,\pi^\pm$ decay channels are reported. The data were collected with the ZEUS detector at HERA using an integrated luminosity of 121 pb^{-1}. The searches were performed in the central rapidity region of inclusive deep inelastic scattering at an ep centre-of-mass energy of 300–318 GeV for exchanged photon virtuality, Q^2, above 1 GeV^2. The results support the existence of a narrow baryonic state with strangeness in $K^0_S\,p$ and $K^0_S\,\bar{p}$ decay channels, consistent with the pentaquark prediction. No pentaquark signals were found in the K^+p, $\Xi^-\,\pi^\pm$ and $\bar{\Xi}^+\,\pi^\pm$ channels.

1 Introduction

This paper discusses recent ZEUS searches for pentaquark baryons with strangeness in the $K^0_S\,p\,(\bar{p})$, K^+p, $\Xi^-\,\pi^\pm$ and $\bar{\Xi}^+\,\pi^\pm$ invariant-mass spectra in ep collisions measured with the ZEUS detector at HERA. The measurements were based on the central pseudorapidity region, $|\eta| \leq 1.5$, where the contribution from the fragmentation of the proton remnant is negligible. If a baryon with five quarks is produced without the net baryon number carried by the proton remnant, emerging from the emissions of gluons and quarks in the hadronisation process, this would open a new chapter in our understanding of non-perturbative QCD.

Even in case of production of the standard baryons, the absence of a guiding principle of how to compose three quarks to form a baryon at the fragmentation stage leads to a few possible baryon-production mechanisms ("diquark" and "popcorn"). In case of baryons with five quarks, the situation is expected to be even more mysterious. Alternatively, in ep collisions, one may assume a small contribution of the net baryon number to the central fragmentation region. In this case, the pentaquark production is expected to be not very different from fixed-target experiments. However, this effect, which should also be responsible for baryon-antibaryon production-rate asymmetry, is expected at the level of a few percents. Obviously, no antipentaquarks are expected for this mechanism.

The pentaquark baryons have been observed by a number of fixed-target experiments in the K^+n decay channel [1]. According to the predictions of the chiral soliton model [2], such a state can be interpreted as a bound state of five quarks, i.e. as a pentaquark, $\Theta^+ = uudd\bar{s}$. According to its quantum numbers, $K^0_S\,p$ and $K^0_S\,\bar{p}$ decays are also possible. For the $K^0_S\,p$ channel, evidence for a corresponding signal has been found by low-energy fixed-target experiments [3]. Recently, other strange pentaquarks ($\Xi^{--}_{3/2} = dsds\bar{u}$ and $\Xi^{0}_{3/2} = dsus\bar{d}$) were reported in pp collisions by the NA49 experiment [4]. At present, however, this experiment does not confirm the Θ^+ state, production rate of which is expected to be higher.

2 Evidence for a baryonic state decaying to $K^0_S\,p\,(\bar{p})$

ZEUS has performed a search for pentaquarks in $K^0_S\,p\,(\bar{p})$ decay channel [5]. The analysis used deep inelastic scattering events measured with exchanged-photon virtuality $Q^2 \geq 1$ GeV^2. The data sample corresponded to an integrated luminosity of 121 pb^{-1}. The charged tracks were selected in the central tracking (CTD) with $p_T \geq 0.15$ GeV and $|\eta| \leq 1.75$, restricting this study to a region where the CTD track acceptance and resolution are high.

The total number of K^0_S with $p_T(K^0_S) > 0.3$ GeV and $|\eta(K^0_S)| < 1.5$, identified using the decay mode $K^0_S \to \pi^+\pi^-$, was 867K. To eliminate contamination from $\Lambda(\bar{\Lambda})$ decays, candidates with a proton mass hypothesis $M(p\,\pi) < 1121$ MeV were rejected.

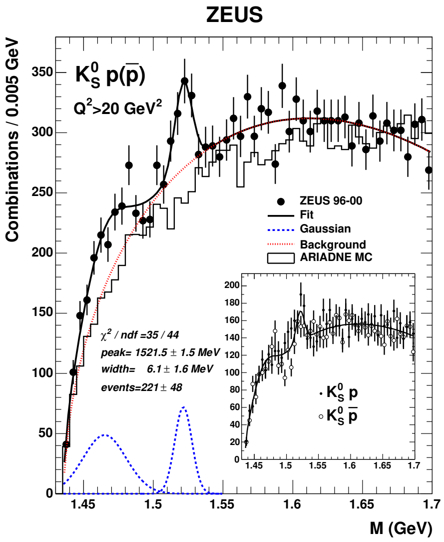

Figure 1: Invariant-mass spectrum for the $K^0_S\,p\,(\bar{p})$ channel for $Q^2 > 20$ GeV^2. The solid line is the result of a fit to the data using the threshold background plus two Gaussians. The dashed lines show the Gaussian components, while the dotted line indicates background. The prediction of the Monte Carlo simulation is normalised to the data in the mass region above 1650 MeV. The inset shows the $K^0_S\bar{p}$ (open circles) and the $K^0_S p$ (black dots) candidates separately, compared to the result of the fit to the combined sample scaled by a factor of 0.5.

The (anti)proton-candidate selection used the energy-loss measurement in the CTD, dE/dx. $K^0_S p(\bar{p})$ invariant masses were obtained by combining K^0_S candidates in the mass region $480-510$ MeV with (anti)proton candidates in the (anti)proton dE/dx band with the additional requirements $p < 1.5$ GeV and $dE/dx > 1.15$ mips in order to reduce the pion background. The CTD resolution for the $K^0_S\,p\,(\bar{p})$ invariant-mass near 1530 MeV, estimated using Monte Carlo simulations, was 2.0 ± 0.5 MeV for both the $K^0_S\,p$ and the $K^0_S\,\bar{p}$ channels.

Figure 1 shows the $K^0_S\,p\,(\bar{p})$ invariant mass for $Q^2 > 20$ GeV^2, as well as for the $K^0_S\,p$ and $K^0_S\,\bar{p}$ samples separately (shown as inset). The data is above the Ariadne Monte Carlo model near 1470 MeV and 1522 MeV, with a clear peak at 1522 MeV. The signal extraction was found to be difficult for very low Q^2 due to a large background and acceptance effects.

To extract the signal seen at 1522 MeV, the fit was performed using a background function plus two Gaussians. The background has the form $F(M) = P_1(M - m_K - m_p)^{P_2}(1 + P_3(M - m_K - m_p))$, where m_K and m_p are the masses of the kaon and the proton, respectively, and $P_{i=1,2,3}$ are free parameters. The first Gaussian, which significantly improves the fit at low masses, may correspond to the unestablished PDG $\Sigma(1480)$. The peak position determined from the second Gaussian was $1521.5 \pm 1.5(\mathrm{stat.})^{+2.8}_{-1.7}(\mathrm{syst.})$ MeV. It agrees well with the measurements by HERMES, SVD and COSY-TOF for the same decay channel [3]. If the width of the Gaussian is fixed to the experimental resolution, the extracted Breit-Wigner width of the signal was $\Gamma = 8 \pm 4(\mathrm{stat.})$ MeV.

The number of events ascribed to the signal by this fit was 221 ± 48. The statistical significance, estimated from the number of events assigned to the signal by the fit, was 4.6σ. The number of events in the $K^0_S\,\bar{p}$ channel was 96 ± 34. It agrees well with the signal extracted for the $K^0_S p$ decay mode. If the observed signal corresponds to the pentaquark, this provides the first evidence for its antiparticle with a quark content of $\bar{u}\bar{u}\bar{d}\bar{d}s$.

The measured mass and the width of the observed state are close to those observed in the K^+n channel[a], and agree well with the theoretical expectations [2]. The PDG reports no Σ states in the invariant-mass region 1480–1560 MeV, and no peak at a similar mass was observed in $\Lambda\pi$ decays. This favours the pentaquark explanation of the signal.

This is the first observation of such resonance in high-energy colliding experiments. Since the signal was observed in the central rapidity region, and since the number of reconstructed particles agrees with the the number of reconstructed antiparticles, this indicates the fragmentation origin of the observed state.

3 Θ^{++} state?

If Θ^+ is an isotensor state, a Θ^{++} signal can be expected in the K^+p spectrum [6]. The $K^{\pm}p(K^{\pm}\bar{p})$ invariant mass spectra were investigated in a wide range of minimum Q^2 values, identifying proton and charged kaon candidates using the dE/dx information. The proton candidates inside the dE/dx proton band were required to have $dE/dx > 1.8$ mips, while the kaon candidates were reconstructed in the kaon band after the restriction $dE/dx > 1.2$ mips. For $Q^2 > 1$ GeV^2, no peak was observed near 1522 MeV in the K^+p and $K^-\bar{p}$ spectra, see Fig. 2, while a clean signal was seen in the $K^-p(K^+\bar{p})$ channel at $1518.5 \pm 0.6(\mathrm{stat.})$ MeV, corresponding to the PDG $\Lambda(1520)D_{03}$ state. No pentaquark was observed for $Q^2 > 20$ GeV^2, where the signal in the $K^0_S\,p\,(\bar{p})$ channel was best seen.

[a]The systematical mass-scale uncertainties for this decay mode are usually larger than for the $K^0_S\,p\,(\bar{p})$ channel.

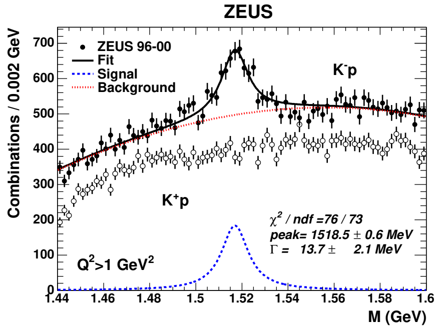

Figure 2: Invariant-mass spectra for the K^+p and K^-p channels (plus charge conjugates) for $Q^2 > 1$ GeV^2.

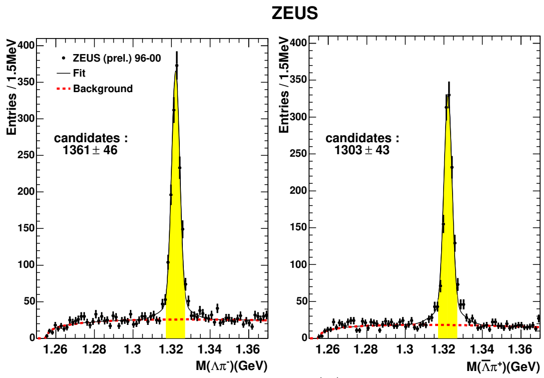

Figure 3: Λ π invariant-mass spectra for the Ξ^- and $\bar{\Xi}^+$ states for $Q^2 > 1$ GeV^2.

The failure to observe Θ^{++} indicates that the Θ^+ state is not isovector or isotensor. Note that direct comparisons of the production rates of possible pentaquarks and $\Lambda(1520)$ states are not possible before taking into account the detector acceptance effects.

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. Strong support for this picture came from the NA49 experiment which recently made observations of both states near 1862 MeV in the Ξ^- $\pi^{\pm}$ and $\bar{\Xi}^+$ $\pi^{\pm}$ decay channels in pp collisions at the CERN SPS.

ZEUS has performed a similar analysis. First, Λ candidates were reconstructed using a selection similar to that used for the K^0_S reconstruction. The Ξ signals, shown in Fig. 3, were reconstructed by combining Λ with π using displaced tertiary vertices [8].

Figure 4 shows the Ξ π invariant masses for four separate channels at $Q^2 > 1$ GeV^2, while Fig. 5 illustrates the combined sample. No pentaquark signal was observed near the 1860 MeV mass region. A similar analysis was performed for $Q^2 > 20$ GeV^2, a kinematic region where Θ^+ was best seen. However, again, no NA49 signal was found.

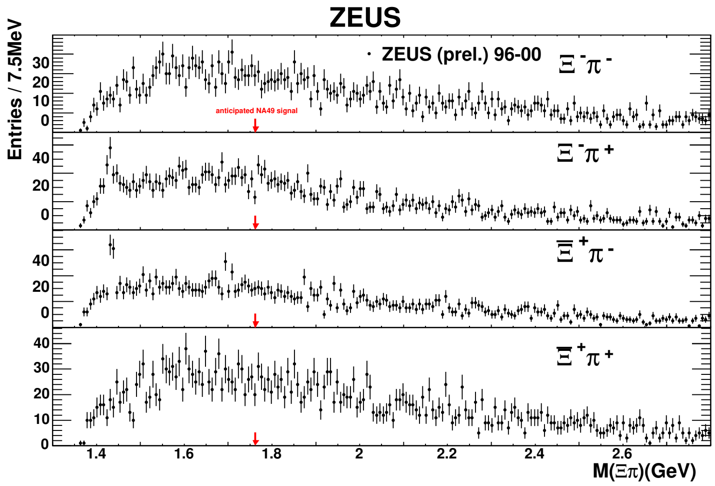

Figure 4: Invariant-mass spectra for separate $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\bar{\Xi}^+\pi^-$ and $\bar{\Xi}^+\pi^+$ decay channels for $Q^2 > 1$ GeV^2.

In this decay channel, ZEUS clearly observes the $\Xi^*(1530)$ state, which can be used as gauge for the comparison of the sensitivity to the pentaquark signal. With more than 160 $\Xi^*(1530)$ candidates reconstructed, the statistical sensitivity exceeds the one of the NA49 measurement [4], thus the pentaquark signal should be difficult to miss. However, it should be noted that NA49 is a fixed target experiment, which has good acceptance in the forward region. Therefore, the absence of the signal in ZEUS data may indicate that ZEUS has a little sensitivity to this state, which may predominantly be produced in the forward region. Interestingly, NA49 collaboration does not see the Θ^+ state, the production mechanism of which is unlikely to be very different from that of the $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ states. Clearly, this contradiction will need to be solved using future high-luminosity HERA data and results from other experiments.

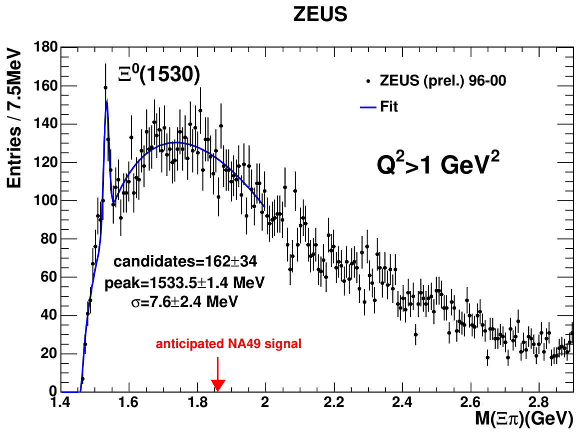

Figure 5: Invariant-mass spectra for sum of the $\Xi^-\pi^\pm$ and $\bar{\Xi}^+\pi^\pm$ channels for $Q^2 > 1$ GeV^2.

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