Results on searches for exotic baryon states at HERA

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Recent results from H1, HERMES and ZEUS on searches for exotic baryons in ep collisions and eD scattering at HERA are summarized. Evidence for the production of the strange pentaquark Θ^+ and of a narrow anti-charmed baryon state decaying into $D^{*-}p$ together with negative results of pentaquark searches at HERA are presented.

1. INTRODUCTION

Several experiments have recently reported evidence for a narrow resonance with a mass of about 1.540 GeVdecaying to K^+n or K^0_Sp [2][1]. Since K^+n has both baryon number and strangeness of +1, the minimal composition of such a state in the constituent quark model is $uudd\bar{s}$. It thus has been interpreted as the strange pentaquark *(PQ)* [2,3], the Θ^+. There is also evidence for two related states with strangeness of -2 [4]. Various models have been put forward to explain the nature of these states and the structure of the multiplet that contains them [3,5,6]. The possibility of PQ states in the charm sector has also been discussed [7], and their expected properties [5,8] have been calculated.

This paper presents the results of the searches for strange PQs from HERMES [9] and ZEUS [10] and for an anti-charmed baryon state decaying into $D^{*-}p$ from H1 [11] and ZEUS [12].

2. KINEMATICS AT HERA

At HERA electrons with an energy of 27.6 GeV are collided on protons of 820-920 GeV in two interaction regions (H1 and ZEUS) yielding a centre-of-mass *(cms)* energy of $\sqrt{s} = 300 - 318$ GeV. In the third interaction region (HERMES) both beams are separated and the electrons interact on a deuteron target at $\sqrt{s} = 7.2$ GeV.

The kinematics is described by three independent variables, the cms energy $\sqrt{s}$, the four-momentum transfer squared $q^2 = -Q^2$ and either one of the scaling variables $y = (q \cdot P)/(l \cdot P)$, the inelasticity of the eN interaction, or Bjorken-x $x = Q^2/(2P \cdot l)$. Here P and l denote the four-momentum of the nucleon and the electron, respectively. The γp center-of-mass energy squared is given by $W^2_{\gamma p} = W^2 \approx y \cdot s - Q^2$.

3. STRANGE PENTAQUARKS

The production of Θ^+ has been studied via its decay into K^0_Sp in two different kinematic regions by HERMES [9] and ZEUS [10], respectively. Furthermore the ZEUS collaboration has searched for the $S = -2$ baryons $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ [13].

3.1. Θ^+ results

It is the comparision of Θ^+ cross sections in different kinematic regions which is of specific interest because it offers the possibility of some understanding of the Θ^+ production mechanism.

At low energies HERMES has collected eN scattering data having an integrated luminosity of 250 pb^{-1} on a deuteron gas target. The analysis is restricted to photoproduction ($Q^2 \approx 0$).

The Θ^+ search uses the decay chain $\Theta^+ \rightarrow pK^0_{\rightarrow}p\pi^+\pi^-$. Hadron identification is accomplished with the Ring-Imaging Cerenkov detector which provides good separation of pions, kaons and protons. Identified protons are combined with K^0_S candidates from well identified secondary vertices with an invariant $M_{\pi^+\pi^-}$ mass within 2σ of the reconstructed K^0_S mass. Possible Λ contamination is suppressed by rejecting K^0_S candidates with a $M_{p\pi^-}$ mass within 2σ of

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[2]The charge conjugate state is always implied if not otherwise stated.

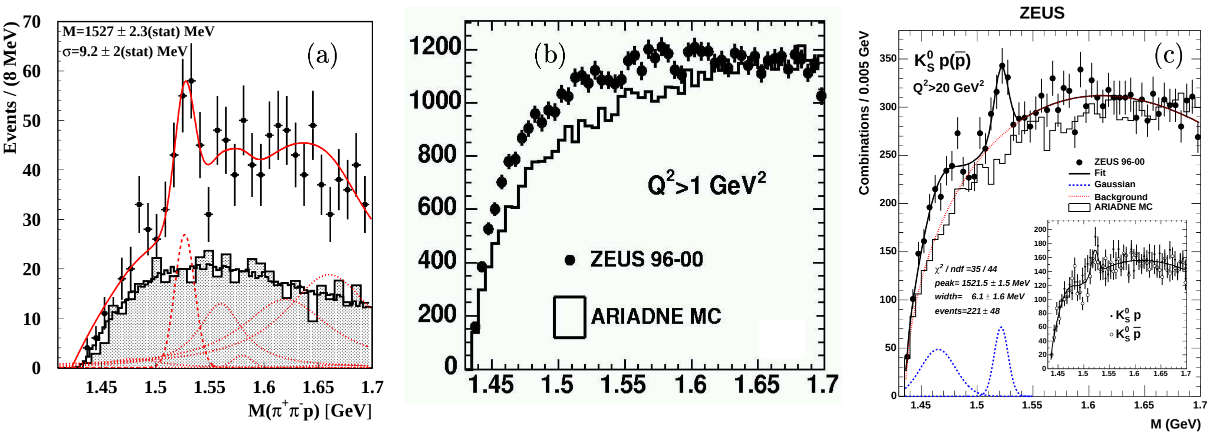

Figure 1. Invariant $M_{p\pi^+\pi^-}$ mass distribution observed by (a) HERMES at $Q^2 > 1$ GeV^2 and ZEUS at (b) $Q^2 > 1$ GeV^2 and (c) $Q^2 > 20$ GeV^2. See text for explanations.

the nominal Λ mass.

The resulting $M_{p\pi^+\pi^-}$ mass distribution is shown in Figure 1a. A narrow peak structure is observed around the Θ^+ mass. No such structure is obtained when the $\pi^+\pi^-$ mass combinations from the K^0_S side bands are used instead. The data is also compared with expectations from the PYTHIA6 Monte Carlo simulation (shaded histogram) and from the mixed-event model (open histogram) normalized to PYTHIA6. No peak structure is visible in these expectations but they fall about a factor of 2 below the data. The PDG [14] reports the possible existence, with at most fair evidence, of several Σ bumps decaying to $N\overline{K}$ in this mass region not included in the simulation, which may account for the discrepancy.

The fit to the data based on the mixed-event model, the Σ bumps and a Gaussian for a possible Θ^+ signal yields a good description. A peak of about 80 Θ^+ events with a significance of 4.3σ is observed at a mass $M = 1.527 \pm 0.0023(stat.)$ GeV.

A similar analysis has been performed by ZEUS at higher energies using the *ep* data taken in the years 1996−2000 with an integrated luminosity of 121 pb^{-1}. The kinematic region is restricted to $Q^2 > 1$ GeV^2 and $0.01 \leq y \leq 0.95$.

The decay chain $\Theta^+ \to pK^0_S \to p\pi^+\pi^-$ has also been used here. About 866,800 K^0_S candidates are selected for $Q^2 > 1$ GeV^2. They are combined with proton candidates selected via dE/dx.

The $M_{p\pi^+\pi^-}$ mass distribution does not show any significant peak structure below 1.7 GeV (Fig. 1b). When raising the lower Q^2 cut, however, a peak emerges at a mass of about 1.52 GeV. In Figure 1c the $M_{p\pi^+\pi^-}$ mass distribution is shown for $Q^2 \geq 20$ GeV^2. For this Q^2 region the number of K^0_S is reduced to 171,000. The figure includes the Monte Carlo expectation from ARIADNE scaled to the data for $M_{p\pi^+\pi^-} >$ 1.65 GeV. Even after scaling ARIADNE does not describe the data at low masses because of the absence of the Σ bumps in the simulation.

A fit to the data of a smooth background function and two Gaussians, also shown in Figure 1c, gives a signal of 221±48 events at a mass of $1.5215 \pm 0.0015(stat.)$ GeV with a significance of 4.6σ. The Gaussian width of 6.1 MeV is found to be consistent with the experimental resolution. The signal is observed at similar rate for protons and for antiprotons suggesting the existence of the anti-pentaquark Θ^-.

Both experiments have also searched for a Θ^{++} signal via its possible decay $\Theta^{++} \to K^+\pi^+$. No signals are found in the Θ^+ mass range suggesting that the Θ^+ is isoscalar.

Unfortunately it is not possible to get further insight in the Θ^+ production physics since only event rates are available from the experiments. However, the Θ^+ signal from deep inelastic *ep*

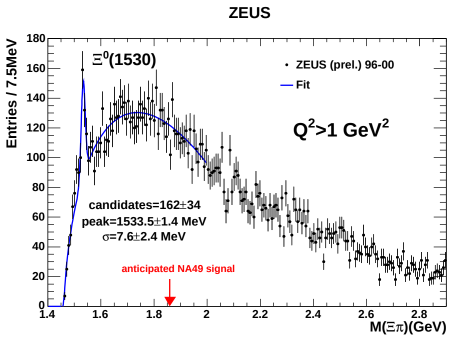

Figure 2. $M_{\Xi\pi}$ mass distribution.

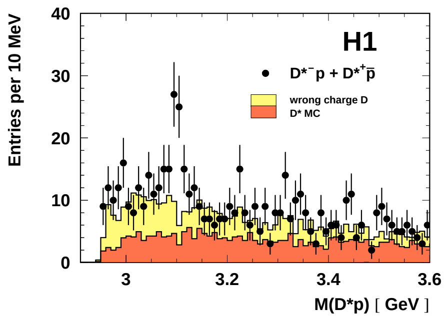

Figure 3. $M_{D^{*-}p}$ mass distribution from H1 for $Q^2 > 1$ GeV^2. See text for explanations.

scattering suggests that it is formed by fragmentation. On the other hand, if one assumes that the Q^2 dependence of Θ^+ and K^0_S production are similar, as expected from fragmentation, one would expect about 1100 Θ^+ candidates visible in the ZEUS data for $Q^2 > 1$ GeV^2 which is not supported by the data. This indicates a different Q^2 dependence of either the Θ^+ and K^0_S production mechanism or their acceptances.

3.2. Search for $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$

ZEUS has performed an analysis in the channel $\Xi^-\pi^\pm$ to search for Ξ^{--} and its neutral partner. Λ candidates, which are selected in a similar way to K^0_S mesons, are combined with pions to form Ξ candidates using tertiary vertices. These are then combined with another pion from the primary vertex. Figure 2 shows the $M_{\Xi\pi}$ mass distribution for all possible $\Xi\pi$ charge combinations for $Q^2 > 1$ GeV^2. While the $\Xi^{0*}(1530)$ is clearly visible, no signal is observed around 1.86 GeV where the exotic Ξ signals are expected [4]. Even when restricting to $Q^2 > 20$ GeV^2 where the Θ^+ signal was best, nothing is observed here. It is currently unclear to what extent this analysis contradicts the observation of Reference [4].

4. ANTI-CHARMED BARYON STATE

If Θ^+ production at high energies is driven by the QCD vacuum, PQs with charm should also exist. Experimentally, final states with D^{*+} mesons are most promising because of its clean signature. This has motivated the search by H1 for exotic anti-charmed baryons decaying to $D^{*-}p$. The analysis is based on the data taken in the years 1996−2000 with an integrated luminosity of 75 pb^{-1} in the kinematic region $1 \leq Q^2 \leq 100$ GeV^2 and $0.05 \leq y \leq 0.7$.

The D^{*+} is reconstructed in its decay mode $D^{*+} \to D^0\pi^+_s \to K^-\pi^+\pi^+_s$ using a D^* selection similar to the $F_2^{c\bar{c}}$ analysis [15] with additional cuts for further background reduction. About 3400 D^* mesons are selected. D^* candidates having a mass difference $\Delta M_{D*} = m(K\pi\pi_s) - m(K\pi)$ within 2.5 MeV around the nominal $M(D^{*+}) - M(D^0)$ mass difference are combined with proton candidates selected via dE/dx.

The resulting $M_{D^{*-}p}$ distribution in Figure 3 shows a clear narrow peak close to threshold. The data is compared with the absolute expectations from the D^{*+} Monte Carlo (dark histogram) and the non-charm induced background[3] (light histogram). No enhancement is seen in any of the background samples. The sum of the two samples reproduces the data well except for the signal region. No peak is observed when selecting either $K\pi\pi_s$ combinations from the D^{*+} side band or $K\pi$ combinations with masses above the region where charm contributes or selecting pions instead of protons. The signal is observed in both, the $D^{*-}p$ and in the $D^{*+}\overline{p}$ sample with compatible mass, width and rate. No significant enhancement is observed in the like sign D^*p sample.

Possible kinematic reflections that could fake the signal have been ruled out by studying invariant mass distributions and correlations involving the K, π, π_s and proton candidates under various

[3]This background is estimated from the data by forming "D" candidates from same charge $K\pi$ combinations.

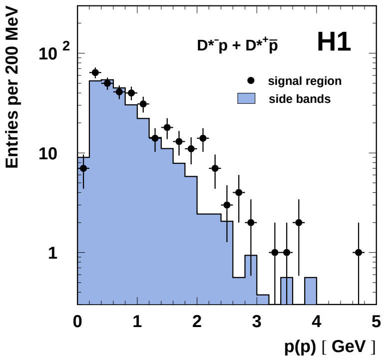

Figure 4. Momentum distribution of charged particles yielding M_{D^*p} values falling in the signal and side band regions.

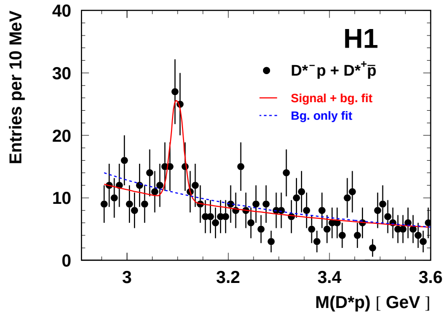

Figure 5. $M_{D^{*-}p}$ mass distribution from H1 for $Q^2 > 1$ GeV^2 together with the fit results with two hypotheses: (full line) signal plus background and (dashed line) background only.

particle mass hypotheses. In particular, the possible contamination from orbitally excited D_1 and D_2 mesons is found to be negligible. All events in the M_{D^*p} signal region have been scanned visually. No anomalies are observed in the reconstruction of the candidate tracks.

Several studies were performed to test the D^* and proton content of the signal. It was shown that the D^*p signal region has a larger D^* yield compared to the side bands. The observed excess of D^* mesons in the D^*p signal region compared to the sidebands is found to be consistent with the signal seen in the M_{D^*p} distribution when selecting the D^* signal region. The signal is also observed for low momentum proton candidates where protons are unambiguously identified and in the independent photoproduction sample.

In order to check that the signal is due to the decay of a new particle the momentum distribution of the proton candidates without dE/dx cuts has been studied. A background fluctuation should show the same distribution in the signal region and in the side bands. It is governed by the steeply falling inclusive spectra of the particles randomly combined. For a real decay, however, a harder spectrum is expected because of the Lorentz boost from the decaying particle, irrespective of the angular momentum involved in the decay. As expected, Figure 4 reveals a significantly harder spectrum in the M_{D^*p} signal region compared to the side bands. The same difference is observed when selecting events in the M_{D^*p} signal region but comparing the D^* signal region with the side band in the ΔM_{D^*} distribution.

The log-likelihood fits to the $M_{D^{*-}p}$ distribution are shown in Fig. 5. The background is parameterised with a power law while a Gaussian is used for the signal. A signal of 51 events is observed with a mass of $3.099 \pm 0.003(stat.) \pm 0.005(syst.)$ GeV and a width of $12 \pm 3(stat.)$ MeV consistent with the experimental resolution. The background fluctuation probability is obtained from a fit using the background-only hypothesis. Different background functions have been investigated. The most conservative limit of 4×10^{-8} is obtained from the power law fit. This corresponds to 5.4σ in terms of Gaussian standard deviations. The change in maximum log-likelihood $\Delta(\ln \mathcal{L})$ between the two fits gives a statistical significance of 6.2σ for a signal in the $M_{D^{*-}p}$ mass distribution.

A similar search has been performed by ZEUS in both photoproduction and DIS. Data from the years 1995-2000 with an integrated luminosity of 126 pb^{-1} are analysed. About 9700/43000 D^* candidates for $Q^2 > 1$ GeV^2 and all Q^2, respectively, are combined with proton candidates selected via dE/dx. The preliminary results on the M_{D^*p} mass distributions are shown in Figure 6 for $Q^2 > 1$ GeV^2. The points with error bars and the histogram correspond to the opposite sign and the like-sign D^*p samples respectively. The momentum region in which pions and protons have the same dE/dx is excluded in this analysis. Therefore the data are shown in Fig. 6a for low momentum protons, where protons are well identi-

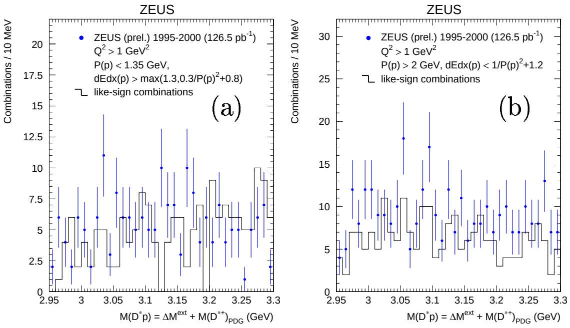

Figure 6. $M_{D^{*-}p}$ mass distribution from ZEUS for $Q^2 > 1$ GeV^2 for (a) low and (b) high momentum protons.

fied, and in Fig. 6b for proton candidates with $p > 2$ GeV where according to Fig. 4, a good signal to background ratio is expected. No signal at 3.1 GeV is observed. A similar conclusion is drawn from the all-Q^2 sample.

5. CONCLUSIONS

Recent results on searches for exotic baryons in *ep* and *eD* scattering at HERA have been presented. The observation of Θ^+ in different kinematic regions allows an understandig of PQ production physics at high energies. The Θ^+ signal in *ep* collisions suggests Θ^+ production by fragmentation but the Q^2 dependence seems not to meet naive expectation.

The situation on the $D^{*-}p$ resonance is unclear. The observation by H1 has passed all tests for a real particle decaying to $D^{*-}p$ but is not confirmed by the preliminary ZEUS result in a similar kinematic region.

It is too early to judge the consistency of all results. Cross section measurements or limits in comparable kinematic regions and information on the production dynamics from the positive observations are needed to finally decide on the issue.

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