I: Introduction: Narrow pentaquarks

II: The ZEUS $\Theta^+(1530)$ signal

III: Zeus search for charm pentaquark

IV: Conclusions

OUTLINE

August 21 - 26, 2005
Rio de Janeiro, Brazil
HADRON 05

on behalf of the ZEUS Collaboration

Weizmann Institute of Science
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Search for CHARM pentaquarks (ZEUS)
Hundreds of theory papers discuss the narrow resonances. No conclusions.

Many high statistics experiments searched but did NOT see the $\Theta^0$.

**Sept. 2004: ZEUS published the NON observation of $\Theta^0$ (3900).**

- $d_\perp \Delta$ at 3.1 GeV (See update in DIS 05).
- H1 reported in March 2004 the observation of a narrow charm pentaquark

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Pentaquarks do not exist in the naive quark model, but QCD does

Such pentaquarks cannot be made of 5 quarks (see following plots).

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**ZEUS also reported observing $\Theta^+(1520)$ (1530) at this conference.**

SEE updates of JLAB and CLAS results at this conference.

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Observations of narrow hadronic states was reported during the last 2 years

The significance was typically between 4-5$\sigma$. Some examples:
Also, ZEUS sees equal nos of $\sqrt{s}$ and $< \sqrt{s}$ in Main source - fragmentation.

\[ \mathcal{N} \approx \mathcal{N} \]

See clean $\sqrt{1920}$ \( d \rightarrow \mathcal{N} \).

Select $d$ and $N$, by $x = \frac{d}{xp}$.

Check fraction reconstruction of $M$, $Y$, and $x$.

Select proton purity $\approx 60\%$.

Cut on $d$ for primary tracks: define ionization $d$/$x$/$x$ bands.

Select $\approx 867,000$ $Y_0$ candidates with $6\%$ background.

The entire ZEUS HERA-I DIS data was used.

$E_\parallel = 27.6$ GeV; $d = 820, 920$ GeV; $< \sqrt{s}$ $\approx 300, 318$ GeV; $\sqrt{s} = 121$, $\sqrt{s}$ = $1$ GeV.

Reduced to 318 collisions.

$\mathcal{O} = \sum (d)\mathcal{O} \left\langle \right.$ $\frac{d}{xp}$ $\left. \right)$


ZEUS searched for $\mathcal{O}$, which have a net baryon number.

See if pentagaphras are created in proton fragmentation region.

1. Little sensitivity to proton remnant.

2. Look at centrality rapidity region dominated by hard fragmentation.

To understand better the $\mathcal{O}$ in high-energy experiments one should:

The $\mathcal{O}$ in the ZEUS experiment...
\[ K^0\bar{p}\ \text{fit: } 96 \pm 34 (2.8 \text{ s.d.}) \]

Signal seen in both charges (inset)

is \( > 6 \cdot 10^{-5} \)

into signal in the range 1.5 - 1.56 GeV

Probability of background fluctuation

\( p = 8 \pm 4 \text{ MeV} \)

fixed by experimental resolution yields Breit-Wigner function with a Gaussian resolution (\( \approx 2 \text{ MeV} \)). A convoluted

(6.1 \pm 1.6 \text{ MeV} \) above but compatible with at 1521.5 MeV with a Gaussian width

at a narrow peak of 3.9 - 4.6 s.d. as seen

\( \mathcal{M}(K^0\bar{p}) \) distribution to two Gaussians + threshold background func-

\textit{ZEUS Published Results on } \( Q \equiv (1520) \)
However, the $\Theta^{\pm}(1521)$ production is mostly in the proton direction. No proton remnant effect is seen. On the left plot the $V(1520)$ is shown for $u > 0$ and $u < 0$. The symmetry

ZEUS (Paper 05-013, EP2005) compared the $\Theta^{\pm}$ data with $V(1520)$ production.
\( \nu^0 D \leftarrow D^* + (d_+ D) \mathcal{W} \) in (c.c.) spectator, where signal

H1 and ZEUS at HERA searched for \( \Theta \) and

\( d_+ D \) to decay to \( \Theta \)

\( \mathcal{W} \) can decay to \( \Theta \)

\( u_0 D \) or \( d_+ D \) to \( \Theta \)

\( \mathcal{W} \) can decay to \( \Theta \)

\( \mathcal{W} \) to \( \Theta \)

Several Theoretical Predictions:

- 4qppnn = \( \Theta \)

Charm Pentagquarks should also exist.
The signal in DIS consisted of $9.6 \pm 1.2$ events.

The quoted mass resolution (in talks) was about 7 MeV.

The measured Gaussian width 12 $\pm$ 3(stat.) $\pm$ 3(syst.) MeV.


At a mass of $M = 3999 \pm 3\text{(stat.)} \pm 3\text{(syst.)} \text{MeV}$

in the decay mode $D^0 \rightarrow K^- \pi^+$ in the $D^* + c.c.$.

In a D* sample of 3400 $D^0 + c.c.$, reported observation of a narrow resonance

The HI Charm Pentagram

Signal also seen in photoproduction sample with same ratio to $D^*$

Roughly 1\% of the total $D^*$ production rate (1.59 $\pm$ 0.32\%, reported DIS 05)
for channels (1) and (2) respectively.

The wrong-charge combinations represent the background.

Cuts to reduce the combinatorial background:

- Peaks at 1.45.5 MeV in $W$ demonstrate the $D^*$ signals.
- The $D^*$ trigger efficiency was above 95%.
- The $D^*$ selected the $D^*$ candidates.
- The mass difference was $7.5 MeV$

The $D^*$ mesons were identified using the two decay channels:

(2) $^{+\mu}(c\bar{c}) + 1.45 MeV 

(1) $^{+\mu}(c\bar{c}) + 1.45 MeV $
(1) Like HI selection, without $dE/dx$ cut
(2) Clean $p_s$ from $dE/dx$
(3) HIG compatible

3 methods of p usage: (1) All Protons
(2) $dE/dx$ applied for protons

Proton selection: $P_T < 0.15$ GeV

$N(D^*)_\tau \approx 13,500$

For the DIS sub-sample $Q^2 < 1$ GeV

Yellow bands searched for with $D_s$ from $D^*$ decay modes

Clean $D^*$ signals in $2 \ D_0^*$

\[ D^0 \rightarrow K^- \pi^+ \pi^- + \text{c.c.} \]
\[ D^0 \rightarrow K^- \pi^+ + \text{c.c.} \]

D^0 decay modes:

P, K, and \( \pi \) bands separated well at low momentum for both.

At least 8 CFD hits were used. To ensure good \( dE/dx \) resolution, plots of \( dE/dx \) for \( M(D^0) > 3.6 \text{GeV} \) are used.

ZEUS search for the \( \Theta^0 \): \( dE/dx \)
After the cut became $d_I < 0.15$, it became $d_I < 0.15$.

89% for samples with $D^* s$ in channels (1) and (2), respectively.

The acceptance of the protons before the cut was, using the $\Theta$ MC, 89% and $d_I < 0.15$.

Cut to optimize the signal/background: $d_I < 0.15$.

The distribution of $d_I$ for proton candidates shows a sharp peak at $0 \sim d_I$ and or a larger value of $d_I \approx 1$.  

The resolution was parametrized empirically as $\chi^2 = \frac{(xp/\mathcal{P})_{\text{meas}} - (xp/\mathcal{P})_{\text{exp}}}{(xp/\mathcal{P})_{\text{exp}}}$, where $n$ is the number ofhits used for the measurement and $a$ is a constant determined from the sample oftagged protons.  The $\chi^2$ probability of the proton hypothesis from the sample oftagged protons is given by the probability for a proton to produce the observed distribution of $d_I$ for a proton to produce the observed  

For each particle, a $\chi^2$ value that estimates the deviation of the measured $xp/\mathcal{P}d$ from the expectation was calculated as:  

4 $\chi^2$ method was used for $dx/dE$ selection.  (O. Deppe, PhD Thesis, 1999)
No evidence for a $\Theta^0$ signal at 3.1 GeV in the $D_0^{+} K^- \mu^+ \mu^-$ channel.

Histograms are like-sign combinations. Mass resolution from MC: 4 MeV.

High-$p_T$, no $dE/dx$

Low-$p_T$

All protons

\( M(D_0^{+} p) = D_0 M_{\text{ext}} + M(D_0^{+} +) \)

PDG

\( M(D_0^{+} p) \)

ZEUS

ZEUS 1995-2000

\( Q^2 > 1 \text{ GeV}^2 \)

\( D^{\pm} \rightarrow (K\pi)\pi \)

like-sign combinations

P($p$) < 1.35 GeV, $dE/dx(p) > 1.3$ mips

P($p$) > 2 GeV

Combinations per 10 MeV

ZEUS


\( (d* p) W \) full sample

\( (s\nu\nu Y) W - (d\nu\nu Y) W = (d* p) W \)

ZEUS

ZEUS
No evidence for $\Theta_0^-$ also in the $D_0^-$ channel.

ZEUS 1995-2000, $D^* \to K_{ppp}$

$M(D_{s}p) = M(D_{s}p)_{\text{PDG}} + M(D_{s}p)_{\text{ext}}$

$Q^2 > 1 \text{ GeV}^2$

ZEUS 1995-2000, $D^* \to (K_{ppp})$
The analysis was repeated using as far as possible the HI cuts.

No evidence for $\Theta_0$ using HI proportional to relative $D^*$ nos.

ZEUS RATE relative to HI is

and $D_0 \to K^- \nu$ cuts.

$W \not\Delta$

ZEUS 1995-2000, $D^*$

$Q^2 > 1$ GeV², HI selection criteria

$Q^2 < 1$ GeV², HI selection criteria

$M(D^*p) = M(D^*p_{\text{ext}}) + M(D^*p)$ (GeV)
The decay $\bar{\Theta}/d_{*}A \leftarrow \Theta$ of reconstructed mesons yields the fraction of mesons originating from the number of reconstructed mesons that were observed in the window. This number was divided by the number of candidates in the window. The number of background functions integrated over the signal window, from the observed background function, was estimated by subtracting the range (see following figures).

The fitted curves describe the distributions reasonably well in the whole range:

$$(s^\Lambda A^\Lambda_\Lambda)^W - (d^s^\Lambda A^\Lambda_\Lambda)^W \forall x \in W \nabla$$

form the proton mass and:

$$d^s_{\text{fit}} - d^s_{\text{fit}} \forall x \in W \nabla = x$$

where $(x c + x q - )d \exp(x) d x$ from the functional

Each distribution was fitted outside the signal window to the functional

$$\nu_+ \nu_+ \nu_- \nu_- \leftarrow 0 A(\bar{\zeta}) \quad \nu_+ \nu_- \Lambda \leftarrow 0 A(\bar{\zeta})$$

obtained with $d_{*}A$ reconstructed in chains (\#) and (\#) of $D^*$ meson samples obtained with $D^*$ reconstructed in chains (\#) and (\#) of $D^*$ meson samples.

$\Theta$ upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width. The upper limits were calculated for the full mass and width.

ZEUS upper limits for $\Theta$ production.
the detailed results of both channels are given in the following table:

A plot of such expected number of events is shown in the following figures and exclusion is about 0.0. For our DIS (\(L < 1 \text{GeV} \)) sample, the statistical fluctuations larger than 9.0. Ground events could produce 68% events in the signal window only in cases

Assuming Gaussian statistics, a 1% signal with the expected number of back-

production rate a signal of 68% of (995 for a 1.29% signal, 3% • 0 % = 0.995, reported 1% %)

With the observed D* mesons in ZEUS and H1 reports i

\[ \left( \frac{d_{\text{expt}}}{d} \right) V \cdot \left( \frac{d_{\text{expt}}}{d} \right) \frac{V}{V} = \left( \frac{d_{\text{expt}}}{d} \right) \frac{V}{V} = \left( \frac{d_{\text{expt}}}{d} \right) \frac{V}{V} \]

The combined upper limit for DIS with \(L < 1 \text{GeV} \) is 0.35%, (1) and (2), respectively. The combined upper limit for both channels is 0.23%.

The 95% C.L. upper limits on \(R_\Theta \) in 1998.

The upper limits are the frequentist confidence bounds calculated for a Crus-

ZEUS upper limits for \(R_\Theta \) production II
accepted-corrected limits: $0.37 \% > B(\Theta < 1 \text{ GeV})$ for full DIS sample.

Full DIS sample

for the full DIS (combined sample) for the full DIS (combined sample).

excluded by 9 s.d. (5 s.d.)

A visible rate of $R = 1 \%$ is calculated

$R (d_+/d_0 \Theta \rightarrow 0) = 1 \%$ after HI

MC signals normalized

The yellow histograms are

MC signal on top

MC signal on top

of interpolation

ZEUS upper limits for $0 \Theta \rightarrow 0$ production

ZEUS 95-00

Combinations per 10 MeV

(0.9\% > 0.16\% > \frac{d\sigma}{d\theta} B(\Theta \rightarrow 0) c(\Theta \rightarrow 0) f(\Theta \rightarrow 0) f)
The results are shown for the full data sample, for DIS with \( \ell^+ \ell^- \) and for photoproduction with \( \gamma \gamma \rightarrow \ell^+ \ell^- \). The branching ratio of the decay of \( \ell^+ \ell^- \rightarrow \text{hadrons} \) and the branching ratio of the decay of \( \ell^+ \ell^- \rightarrow \ell^+ \ell^- \) are also shown. The branching ratio of the decay of \( \ell^+ \ell^- \rightarrow \ell^+ \ell^- \) for photoproduction is higher than for DIS.

### Table 1: Numbers of the \( N_{\text{events}} \) combinations in the signal window \( N_{\text{background}} \) and the expected numbers of reconstructed \( \ell^+ \ell^- \) events.

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DATA MAY RESOLVE THE ZEUS/H1 $\theta_0$ DISCREPANCY

FUTURE RESULTS FROM HIGH STATISTICS HERA II CONCLUSION: the ZEUS data are not compatible with the H1 report of $\theta_0$ baryon production. The limits become 0.37% and 0.51% respectively.

The limits with $Q < 1$ GeV are 0.35% (95% C.L.) using the corrected ratios, $\rho_{\theta}$, DIS with $Q < 1$ GeV. $\theta_0$ decays is 0.23% (95% C.L.) The upper limit for mesons originating from $\theta_0$ mesons. The upper limit on the fraction of $D^{*+}$ reconstructed $D^+$ mesons. $D^{*+}$ mesons were used to identify $D^+$ mesons.

$D^-$ $\leftrightarrow$ $D^+$ $\leftrightarrow$ $0D$

$D^-$ $\leftrightarrow$ $D^+$ $\leftrightarrow$ $0D$

ZEUS has searched for a resonance in the invariant-mass spectrum at $d-\bar{e}$ at HERA. Summary of ZEUS search for $\theta_0$ in $d-\bar{e}$ at HERA.
NO $\Theta_0 \Theta^\dagger$ seen in the ZEUS data with the HI cuts.

The cut $d < 0.2$ was replaced by the HI cut of normalized proton likelihood, and was excluded for photoproduction.

- In DIS or photoproduction selections, respectively, $1.5 < \zeta < 2.0$ and $1.0 > (\gamma D)^{TD}$ and $0.0 > (\gamma D)_{u}$.
- The DIS events were selected with $1.0 > (\gamma D)^{TD}$ and $0.0 > (\gamma D)_{u}$.
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- The DIS events were selected with $1.0 > (\gamma D)^{TD}$ and $0.0 > (\gamma D)_{u}$.

The HI criteria:

1. The $D^*$ tracks were set to the HI values.
2. The cut $d > 0.12$ was replaced by the HI cut $d > 0.12$.
3. The proton, the $D^*$ meson and the exchanged photon in the proton rest frame, $b \cdot d / (\gamma D)^{TD} \cdot d = (\gamma D)^{TD}$, and are the four-momenta of the incoming quark and gluons on and off the proton respectively.
4. The fraction of the photon energy carried by the $D^*$ meson. The recoil of the exchanged photon in the proton rest frame, $\gamma_{TD}^\gamma D$.
5. The $D^*$ cuts $\gamma_{TD}^\gamma D$ and $\gamma_{TD}^\gamma D$.
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12. The $D^*$ cuts $\gamma_{TD}^\gamma D$ and $\gamma_{TD}^\gamma D$.

The HI in channel $D^*_{\ell^+} \ell^- D$.
are seen!

CONCLUSION: In $\epsilon \tau$ annihilations neither the $\Theta^{+}_0 (1530)$, nor $\Theta^{0}_0 (3100)$

As well as IN Belle and Babar (see reports at this conference), in DELPHI and OPAL at LEP

ALSO no evidence for $\Theta^{+}_0 (1530)\Theta^{0}_0 (3100)$ in $d_+ \rightarrow \Theta^0 \Theta^0 \Theta^0 \Theta^0$

ATLPH sets upper limits on

Spectra: Other pentagluark searches in $\epsilon \tau$ annihilations
CDF 90\% C.L. limits:

No evidence for

CDF Run II at the

TEVATRON (220 pb⁻¹)

Other pentagon search: CDF, in pp collisions at \( p^+ = 1.96 \text{ GeV} \)
No evidence for $\Theta^0(1530)$.

Sample: 63 million $K_0^-$

$\Xi^0(1862) \rightarrow \Xi^- \omega$

$\Xi^0(1862) \rightarrow \Xi^- \omega$

Background: 10.9 MeV

With $q = 0.65$ MeV

Results / 10 MeV

FOCUS: Fixed-target, Fermilab Experiment

Other pentagonark searches: FOCUS
A peak of 5.2 s.d. is seen in $W^+$ (from the $D^+$ target). $W = 1542$ MeV

The mass from 10 experiments is 1533.6, with $\sqrt{f_{pp}} = 38.2/9$

The discussion of $\Theta^+$ production mechanisms (condensate level of 1.6x10$^7$), see Lipkin et al. (E665/0506084).

Possible $\Theta^+$ production diagrams, where the reactions studied were observed in the present CLAS results will be given in the Penetrable Session II tomorrow.


Old Results: the CLAS original report, Jlab

This is one of the most compelling positive results since it involves minimal kinematic cuts. Peaks are not due to kinematic reflection.

Mixed-event test $\not\in$ NO $V(1520)$ or $\Theta^-$ peaks. Applying same analysis procedure to neutron data confirms the charge for both charged kaons.

Detector target contains the initial observation $u - K^+ + K^- \rightarrow L_{\text{SPINS}}$ using new data on $L_{\text{SPINS}}$. Recent LEP preliminary results for $J_{\perp}$.
This removes I) $\phi$ from $s$ and $K^*\pi$ from $\bar{V}$, S)2) protons from $V$'s.

By requiring an extra $\pi$ and removing $K^*$ combination,

Signal/background improves from 1:3 to 2:1 (right plot).

$R(1^{2}S_{0}) \approx 1.6 - 3.5$.

Resonances (dotted lines).

Fit includes known baryon.

PITHA MC simulation.

Shaded histogram is

$P = 1^{\pm} \pm 9 \text{ MeV}$.

$M \approx 1528 \text{ MeV}$ with

A narrow $p^{+}d$ peak of

$S\gamma d \leftrightarrow \pi^{+}d$.

The HERMES Collaboration searched for the $\Theta^{+}$ in inclusive

The HERMES experiment at HERA.