Pentaquark Search at HERMES

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for the HERMES Collaboration

- Particle ID
- Search for $pK_s$ resonances
- Systematic Studies
- Summary and Conclusions

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The HERMES Spectrometer

Beam: 27.6 GeV $e^+/e^-$ from HERA accelerator
Track reconstruction: $\Delta p/p < 2\%$, $\Delta \theta < 0.6$ mrad
Particle ID: TRD, Preshower, Calorimeter (hadron/lepton sep.)
dual radiator RICH ($\pi$, K, p separation)
Particle Identification

hadron/positron separation
combining signals from: TRD, calorimeter, preshower, RICH

hadron separation
Dual radiator RICH for $\pi$, $K$, $p$
**Event Reconstruction**

\[ e^+ + D \rightarrow \Theta^+ + X \rightarrow pK_S^0 + X \]

- **Hadron identification:** RICH
  - \( \pi: 1 - 15 \text{ GeV} \)
  - \( p: 4 - 9 \text{ GeV} \)
- **Reject events from** \( \Lambda(1116) \rightarrow p\pi^- \) within \( \pm 2\sigma \) of \( M_\Lambda \)
- **Define appropriate event topology**
- **invariant mass calibration** \( \pm 2\text{MeV} \)

**direct reconstruction:** detection of each decay particle, invariant mass reconstruction
K_{S}^{0} Identification

- after all constraints on event topology
- proton present in event sample
- only events with \(M(\pi^{+}\pi^{-})\) within \(\pm2\sigma\) of \(M(K_{S})\)
Results

Peak at:
M = 1528 ± 2.6 MeV
σ = 8 ± 2 MeV

Significance:
\[ \frac{N_s^{2\sigma}}{\sqrt{N_b^{2\sigma}}} = 4.7 \text{ (naïve)} \]
\[ \frac{N_s}{\delta N_s} = 3.7 \text{ (realistic)} \]

Unbinned fit is used: result independent of bin size and starting point
The Signal Width

Θ⁺ Monte Carlo with complete detector simulation

- generated:
  M = 1540 MeV, σ = 2 MeV

- reconstructed:
  M = 1539.5 MeV, σ = 6.2 MeV

Production kinematics are those observed for Λ(1116)
  • p_z monotonically falling
  • p_t gaussian
The Signal and its Background

Peak at:
M = 1527 ± 2.3 MeV
σ = 9.2 ± 2 MeV

Significance:

\[ \frac{N_s^{2\sigma}}{\sqrt{N_b^{2\sigma}}} = 6.1 \text{ (naïve)} \]
\[ \frac{N_s}{\delta N_s} = 4.3 \text{ (realistic)} \]
A Non-Zero Width for $\Theta^+$?

- Observed width FWHM: $19 - 24$ MeV
- Detector resolution (from MC)
  FWHM: $10 - 14.6$ MeV
- Re-fit spectra with Breit-Wigner convolved with a Gaussian (fixed by MC)

→ HERMES intrinsic width: $\Gamma = 17 \pm 9 \pm 3$ MeV
Well established \( \Lambda(1520) \rightarrow pK^- \) with acceptance: 1.5%  

No peak structure for \( \Theta^{++} \rightarrow pK^+ \)  
zero counts at 91% CL  

\( \Theta^+ \) not isotensor  
→ probably isoscalar
Production Cross Section

- Integrated luminosity: \( 250 \text{ pb}^{-1} \)
- Acceptance from MC:
  - 1.5% for \( \Lambda(1520) \)
  - 0.05% for \( \Theta^+ \)
- Branching ratio to \( pK^0_s \): ¼

\[ \rightarrow \text{HERMES estimate: } \sigma(\Lambda(1520)) = 62 \pm 11 \text{ nb} \]
\[ \sigma(\Theta) = 100-220 \text{ nb} \pm 25\% \text{ (stat)} \]
  (additional factor 2 from production kinematics)
Comparison with other experiments

World Average: $1532.5\pm2.4$ MeV

Large variation in mass not uncommon for new, decaying particles but need to better estimate exp. uncertainties
## Summary of Null Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Theta^+(1540)$ ($uudd\bar{s}$)</th>
<th>$\Xi^{--}(1862)$ ($ddss\bar{s}$)</th>
<th>$D^{*-}p(3100)$ ($uudd\bar{c}$)</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA-B</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$pA \to \Theta^+X, \Xi^{--}X$</td>
</tr>
<tr>
<td>E690</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$pp \to \Theta^+X, \Xi^{--}X$</td>
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<tr>
<td>CDF</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$p\bar{p} \to \Theta^+X, \Xi^{--}X, \Theta^cX$</td>
</tr>
<tr>
<td>HyperCP</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$\pi, K, p \to \Theta^+X$</td>
</tr>
<tr>
<td>BaBar</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \to \Theta^+X, \Xi^{--}X$</td>
</tr>
<tr>
<td>ZEUS</td>
<td>yes</td>
<td>NO</td>
<td>NO</td>
<td>$ep \to \Theta^+X, \Xi^{--}X, \Theta^cX$</td>
</tr>
<tr>
<td>ALEPH</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \to \Theta^+X$</td>
</tr>
<tr>
<td>DELPHI</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \to \Sigma^+K^0p$</td>
</tr>
<tr>
<td>PHENIX</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$AuAu \to \Theta^+X$</td>
</tr>
<tr>
<td>FOCUS</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$\gamma A \to \Theta^cX$</td>
</tr>
<tr>
<td>BES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \to J/\Psi \to \Theta^+\Theta^-$</td>
</tr>
</tbody>
</table>

0 null results published, only 3 on arXiv so far (7-18-04)  
⇒ need null results to be published
Open Questions

How real are positive results?
- check if peaks are generated by “kinematic reflections” (?)
  ghost tracks
  acceptance or cuts

How real are negative results?
- need to published
  scrutinized as hard as positive results

- Mass?
- Width?
- Spin and Parity
- etc.
How real is the Peak?

- check for
  - fake peaks ("kinematic reflections")
  - detector acceptance and cuts (PYTHIA6 MC / Toy MC)
- $\Theta^+$ vs $\Sigma^{*+}$
  - is $\Theta^+$ a pentaquark or a previously unobserved $\Sigma^{*+}$?
- add a fourth hadron
  - is the peak still there?
  - can we guess the production process for the $\Theta^+$?
  - can we suppress background?
Fake Peaks?

- particle miss-assignment
  - ghost tracks
  - PID “leaks”

- remove $\Lambda(1116)$ contribution

**Spectrum of events associated with $\Lambda(1116)$**

Expect peak in $M(\pi^{-}p)$ if $\pi^{+}$ is $p$ and $K_{S}$ is $\Lambda(1116)$

![Graph of spectrum with expected peak](image)
Θ⁺ vs Σ*⁺

- Is peak a new Σ*⁺ or a pentaquark state?
- If peak is Σ*⁺ ⇒ also see a peak in M(Λπ⁺)
  - if member of baryon octet: b.r.(Λπ⁺)/(pKₛ) ≥ 3/2
  - if member of decuplet: ~ 3/2 (M. Polyakov)

No peak in Λπ⁺ spectrum near 1530 MeV
relatively large BG, although good PID for proton and $K_S$
what if we require one additional hadron?
could additional hadron help remove $K_S$ from other process?
Mass Spectrum after requiring
4th hadron as $\pi$

Black requires 4th hadron (all species)

Red specifies 4th hadron as $\pi$

Green specifies 4th hadron as not $\pi$
Why does additional $\pi$ help?

- remove $\gamma p \to \phi p \to K_L^0 K_S^0 p \to \pi^+ \pi^- p$
- remove $p(K^\pm) \to p K_S^0 \pi^\pm$
- add new cut: $|M(K_S\pi)-892|<75$ MeV

![Graph showing high statistics K*]
The Mass of $p\pi_{4th}^- (K^* \text{ removed})$

- there is a $\Lambda(1116)$ peak from $p\pi_{4th}^-$
- it only contributes 3 events under the $\Theta^+$ peak
- add $\Lambda$ veto as a new cut

$|M(p\pi^-) - 1.116| < 0.006 \text{ GeV}$
$\Theta^+$ Mass spectrum with additional $\pi$

- standard cuts applied
  + $K^*$ and $\Lambda$ veto

- signal/background: \[2:1\]

- signal/background: \[1:3\]
can 4\textsuperscript{th} hadron come from exclusive processes?

\[ \gamma p \rightarrow \bar{K}^0 K^0 p \rightarrow \bar{K}^0 \Theta^+ \]

\[ \pi^+ \pi^- \rightarrow K_S^0 p \rightarrow \pi^+ \pi^- p \]

\[ \gamma n \rightarrow K^- K^0 p \rightarrow K^- \Theta^+ \]

\[ K_S^0 p \rightarrow \pi^+ \pi^- p \]

associated \( K^- \) or \( K_S \) from exclusive processes goes backward

- even decay pions from \( K_S \) are inaccessible
- PID threshold requires \( p(\Theta^+) > 7 \text{ GeV} \)

tagged pions events cannot come from these exclusive processes

\[ \Rightarrow \text{production process has to be at least partially inclusive} \]

- inclusive processes increase with higher energy
- exclusive processes decrease with higher energy
Conclusions and Outlook

Direct reconstruction of $\Theta^+$ invariant mass

$$eD \rightarrow \Theta^+ + X \rightarrow K^0_s p + X$$

- Mass: $M = 1528 \pm 2.6\,(stat) \pm 2.1\,(syst) \text{ MeV}$
- Intrinsic Width: $\Gamma_{\Theta^+} = 17 \pm 9 \pm 3 \text{ MeV}$
- Significance: $\sim 4 \sigma$

$\Theta^+$ is probably an isosinglet

- Requiring additional $\pi$ improves signal/background, it eliminates $K_S$ contamination from various processes
- Production process is at least partially inclusive
- Anticipate doubling statistics by end of this summer
- Will soon report on $\Xi^{--}$ search and $\Theta^+$ from TOF (low p)
## Detector Mass Calibration

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</thead>
<tbody>
<tr>
<td>$K^0_S p \rightarrow \pi^+ \pi^-$</td>
<td>496.8±0.2</td>
<td>497.67</td>
<td>6.2±0.2</td>
<td>5.4</td>
<td>206</td>
</tr>
<tr>
<td>$\Lambda(1116) \rightarrow p \pi^-$</td>
<td>1115.70±0.01</td>
<td>1115.68</td>
<td>2.6±0.1</td>
<td>2.1</td>
<td>101</td>
</tr>
<tr>
<td>$\Lambda(1520) \rightarrow pK^-$</td>
<td>1522.7±1.9</td>
<td>1519.5±1.0</td>
<td>4.4±3.7</td>
<td>3.5</td>
<td>244</td>
</tr>
<tr>
<td>$\Xi^-(1321) \rightarrow p\pi^-\pi^-$</td>
<td>1321.5 ±0.3</td>
<td>1321.31±0.13</td>
<td>3.1 ±0.3</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

→ invariant mass reconstruction of known particles  
→ full MC simulation reproduces data well  
→ ±2MeV systematics
Fake Peaks?

- particle miss-assignment
  - ghost tracks
  - PID “leaks”

- cut of $\pm 2\sigma$ on $M(K_S)$
- $<10$ events within $\pm 3\sigma$ of $M_\Lambda$