Search for the $\Theta^+$ in photoproduction experiments at CLAS

Asian-Pacific Few-Body Conference
July 30, 2005
Ken Hicks (Ohio University)
The published CLAS data
The CEBAF Large Acceptance Spectrometer

CLAS

Performance

- \( L = 10^{34} \text{ cm}^2 \text{ s}^{-1} \)
- \( \int B \, dl = 2.5 \text{ T m} \)
- \( \Delta p/p \sim 0.5-1 \% \)
- \( \sim 4\pi \) acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger (\( \Delta E/E \sim 10^{-3} \))

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CLAS: $\gamma \ d \rightarrow K^+ \ K^- \ p \ (n)$

Mass = 1.542 GeV
$\Gamma < 21$ MeV
Significance $5.2 \pm 0.6 \sigma$

Events in the $\Lambda(1520)$ peak.

Two different background shapes

$N_\Theta = 43$ events

Significance = ?
Official CLAS statement

• “Further analysis of the deuterium data find that the significance of the observed peak may not be as large as indicated.”
  – The true shape of the background is needed before the statistical significance of the peak can be calculated.

• Eventually the new experiment, with much higher statistics, will answer the question.
  – The g10 experiment (x10 statistics) is now finished.
New CLAS deuterium data
“G10” run: March 13 - May 16, 2004

- Tagged photons in the energy range from 0.8 GeV to 3.59 GeV;
- Target – 24 cm long liquid deuterium at Z=-25cm;
- Trigger – two charged particles in CLAS.
- Data are taken at 2 settings of CLAS toroidal magnet.
- At each setting integrated luminosity (25pb$^{-1}$) is about 10 times higher than in published deuterium data.
Analysis strategy for the $\Theta^+$:

- Independent analysis of several reactions by different groups:

\[
\begin{align*}
\gamma + d &\rightarrow p + K^- + K^+ + n; \Theta^+ \rightarrow nK^+ \\
\gamma + d &\rightarrow \Lambda^0 + K^{+(0)} + n(p); \Theta^+ \rightarrow nK^+, pK_S^0 \\
\gamma + d &\rightarrow p + \pi^+ + \pi^- + K^-; \Theta^+ \rightarrow pK_S^0; K_S^0 \rightarrow \pi^+\pi^- \\
\gamma + "n" &\rightarrow K^- + K^+ + n; \Theta^+ \rightarrow nK^+ \quad \text{Fermi momentum corrections}
\end{align*}
\]

- Work on cross section upper limit estimate in other channels is in progress. Requires acceptance simulations for each final state.

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Detected photonuclear reactions

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

\[ \gamma p (n) \rightarrow \Lambda^* (1520) K^+ (n) \]
\[ \Lambda^* (1520) \rightarrow K^- p \]

\[ \gamma N \rightarrow \phi (1020) N \rightarrow K^+ K^- N \]

*background*

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Comparison with published data

- Nearly identical event selections are applied to g10 data.
  - Timing cuts, missing neutron mass cut are momentum dependent in g10 analysis.
  - Fiducial cut on K- to take into account the difference of acceptance due to the target position.
  - Other cuts are same.
- Photon energy is matched to the g2a beam energy.
  - g10 ran in higher photon energy than g2a.

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MM(pK⁻) distributions

Two distributions statistically consistent with each other:
- 26% c.l. for null hypothesis from the Kolmogorov test (two histograms are compatible).
- Reduced $\chi^2=1.15$ for the fit in the mass range from 1.47 to 1.8 GeV/c²

G10 mass distribution can be used as a background for refitting the published spectrum.
Fit to the MM(pK⁻) distributions

- The same 3rd degree polynomial as a background in both fits (for g2a function was scaled by x5.9).
- For the fit to the g10 distribution Gaussian, the sigma was fixed to the known CLAS resolution (determined from MC and fits to other peaks).

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Can the peak seen in the g2a data be reproduced at higher statistics?

- Published results on $\Theta^+$ from analysis of g2a data cannot be reproduced in the analysis of high statistics g10 data.

- The statistical significance in the published data is an unlucky coincidence of a statistical fluctuation and an underestimate of the background in the mass region of 1.54 GeV/c$^2$. 

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The second question

- Beyond g2a conditions, is there statistically significant evidence for the $\Theta^+$?

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Electron Beam Energy</th>
<th>Torus Current</th>
<th>Triggers</th>
</tr>
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<tbody>
<tr>
<td>g2a</td>
<td>2.478 GeV</td>
<td>3375 A</td>
<td>1477.7 M</td>
</tr>
<tr>
<td></td>
<td>3.115 GeV</td>
<td>3375 A</td>
<td>547.1 M</td>
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<tr>
<td>g10</td>
<td>3.767 GeV</td>
<td>2250 A</td>
<td>4495.6 M</td>
</tr>
<tr>
<td></td>
<td>3.767 GeV</td>
<td>3375 A</td>
<td>4936.9 M</td>
</tr>
</tbody>
</table>
Missing momentum cut

$G10: \text{All } E_\gamma$

g2a cut $0.2 > \text{GeV/c}$

Events/4MeV/c$^2$

$M(nK^+) \text{ (GeV/c}^2\text{)}$

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Photon energy cut

G10 (3375A)  
Λ(1520)  Λ*/Σ*

G10 (3375A), pmis>0.2 GeV/c, Eγ<2.4 GeV

G10 (2250A), pmis>0.2 GeV/c Eγ<2.4 GeV

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Beyond $g2a$ conditions, is there statistically significant evidence for the $\Theta^+$?

- No peak is found under more constrained kinematical cuts (but not all physically justifiable cuts have been tried).

- Any statistically significant peak must be seen in both the low-field data and the high-field data to be “real”.

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Upper limit of the $\Theta^+$ production cross section in the reaction $\gamma d \rightarrow pK^+K^-(n)$

- Number of “signal” events - number of events fluctuating into Gaussian peak over a smooth background (3rd degree polynomial).
- Acceptance calculation - 4 body phase space event generator, modified to match kinematics of detected particles with data.

![Graphs showing simulations and acceptance](image)

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$\gamma \; n \rightarrow p \; \pi^-$ cross section

- Consistency between high field and low field data.
- $g_{10}$ data agree with world data.
- 0.5% of statistics

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Upper limit on cross section for $\gamma d \rightarrow \Theta^+ pK^-$, with $P_p > 0.35 \text{ GeV/c}$

- Fit with the sum of 3rd degree polynomial and a Gaussian function with fixed width. Gaussian $\sigma = 5.5 \text{ MeV/c}^2$, mean running from 1.48 to 1.72 GeV/c$^2$.

- Cross section upper limit around $M(nK^+)=1.525 \text{ GeV/c}^2$ for the reaction $\gamma d \rightarrow \Theta^+ pK^-$, with $P_p > 0.35 \text{ GeV/c}$, $\sigma^u = 450 \text{ pb} (95.4\% \text{ CL})$. 

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**Graphs**

Left graph:
- ID: 110033
- Entries: 2310571
- $\chi^2$/ndf: 29.93 / 50
- $P_l$: 1512 ± 1491

Right graph:
- ID: 110043
- Entries: 1725977
- $\chi^2$/ndf: 38.32 / 50
- $P_l$: 1615 ± 1509

Legend:
- Preliminary
- $p_{K^+} < 1 \text{ GeV/c}$
The elementary cross section: $\gamma n \rightarrow \Theta^+ K^-$

- With Fermi momentum being the only source of an energetic spectator proton, the cross section upper limit is $20 \text{nb}$, $Y/Y_0(0.35)=0.02$.

- A more sophisticated model for an energetic spectator: take the $L(1520)$ production as a guide, the cross section upper limit is $4-5 \text{ nb}$, $Y/Y_0(0.35)=0.1$.

\[ \int \int \frac{Y}{Y_0(\Lambda_{1520})} \left( \begin{array}{c} 10^{-2} \\ 10^{-1} \\ 0 \end{array} \right) \frac{dP_n}{dP} \]

$\Lambda(1520)$ is produced on the proton, neutron is a spectator.

$\Theta^+$ is produced on the neutron, proton is a spectator.
Summary of Deuterium Data

• A search for the $\Theta^+$ in the photon-induced reactions using photons with energies up to 3.6 GeV has been carried out with the CLAS.

• $g_{2a}$ peak cannot be reproduced. No peak is found under more constrained kinematical cuts.

• The upper limit on the measured cross section in the reaction $\gamma d \rightarrow \Theta^+ pK^-$, with $P_p > 0.35$ GeV/c, is about 450 pb (95.4% CL).

• The upper limit on the cross section of the elementary process $\gamma n \rightarrow \Theta^+ K^-$ is 4-20 nb, model dependent.
The CLAS proton data
Published: $\Theta^+$ from the proton

$\gamma p \rightarrow \pi^+ K^- K^+ (n)$

Prominent $K^{*0}$
Published: Θ⁺ from the proton

\[ \gamma p \rightarrow \pi^+ K^- K^+(n) \]

\[ M(nK^+) \text{ (GeV/c}^2\text{)} \]

Cosθ*(\(\pi^\ast\)) > 0.8

M=1555±10 MeV
\Gamma< 26 MeV
Cosθ*(K^+)< 0.6

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The nK\(^+\) mass spectrum is smooth and no structure is observed at a mass of \(\sim 1540\) MeV.
Evaluation of an Upper Limit on the $\Theta^+$ Yield

- $\Theta^+$ is searched for as narrow resonance over a smooth background in the $(nK^+)$ spectrum (integrated and in angular bins)
- Resonance width inferred from MC simulations, assuming a negligible intrinsic width
- Signal and background yields extracted fitting: binned/unbinned spectra including/excluding $\Theta^+$ mass region
- $M(nK^+)$ range (1520 - 1600 MeV) scanned in 5 MeV steps
- Upper limit derived using Feldman and Cousins approach

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Upper Limit on the $\gamma p \rightarrow \Theta^+ \bar{K}^0$ Cross Section

\[
(95\% \text{CL}) \propto \frac{\text{Yield}(95\% \text{CL})}{\text{efficiency luminosity BR}(\Theta^+ \rightarrow nK^+)}
\]

- Absolute cross section measurement
- BR $(\Theta^+ \rightarrow nK^-)=50\%$
- CLAS detection efficiency evaluated using different $\Theta^+$ production models

**Differential Cross Section**
\[d\sigma/d\cos\theta_{\text{cm}}\]

**Total Cross Section**
\[\sigma(M_\Theta)\]

**Upper limit (95\% CL)**
\[\sigma_{\gamma p \rightarrow \Theta^+ K^0} < 1-4 \text{ nb}\]

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Comparison with SAPHIR results

Kinematics

- Selection of forward angles of the $K^0$ in the $\gamma - p$ center of mass

- Energy limited to 2.6 GeV

- No hyperon rejection
Personal Opinions

• There have been too many coincidences of peaks from different experiments.

• We should not abandon the search yet.
  – Even if no $\Theta^+$, the upper limits are needed

• What about the new positive results?
  – LEPS and STAR data should be explained.

• Probably, the $\Theta^+$ does not exist.
Summary

• There is good reason to doubt the existence of the $\Theta^+$.  

• Experiments need to have better control over the background shape.  

• The new high-statistics data:  
  – CLAS $\gamma p \rightarrow K^+K^0(n)$ shows no signal  
  – CLAS $\gamma d \rightarrow K^+K^-p(n)$ shows no signal  

• We’re left with a mystery:  
  – Is it an exotic production mechanism?
General Review Article

• K. Hicks, hep-ex/0504027
  – to be published in Prog. Part. Nucl. Phys.
Backup Slides
Pentaquark on the Lattice

Adelaide Lattice Group: hep-lat/0504015

Negative parity
Positive parity

Attraction only for $(3/2)^+$
Suppression on the proton

Nam, Hosaka, Kim: hep-ph/0505134

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$3/2^+$</th>
<th>$3/2^-$</th>
<th>$1/2^+$</th>
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<tr>
<td>$g_{K\Lambda\Xi}$</td>
<td>0.53</td>
<td>4.22</td>
<td>1.0</td>
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<tr>
<td>$g_{K^*\Lambda\Xi}$</td>
<td>±0.91</td>
<td>±2</td>
<td>±1.73</td>
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</table>

<table>
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<th>$p$</th>
<th>$n$</th>
<th>$p$</th>
<th>$n$</th>
<th>$p$</th>
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</thead>
<tbody>
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<td>$\sigma$</td>
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<td>~1 nb</td>
<td>~200 nb</td>
<td>~4 nb</td>
<td>~1 nb</td>
<td>~1 nb</td>
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<tr>
<td>$d\sigma/d\cos\theta$</td>
<td>Forward</td>
<td>~60°</td>
<td>Forward</td>
<td>–</td>
<td>~45°</td>
<td>~45°</td>
</tr>
</tbody>
</table>

Note small cross section for proton
Note forward angles for the neutron
Lambda-Theta g10 analysis

Missing mass

Mass($\pi^+\pi^-$)
\( \gamma p \rightarrow K^- p K^0(p) \) at CLAS