New $\Theta^+$ results from LEPS

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- Introduction
- Experiment
- Inclusive analysis – Blind analysis
- Exclusive analysis
- Summary
Previous result of the $\Theta^+$ search by LEPS

$\gamma d \rightarrow K^+K^-pn$ reaction

- Data taken in 2002-2003.
- $2.0 < E_\gamma < 2.4$ GeV.
- Significance of $5.1 \sigma$ from shape analysis. ($\Delta(-2\ln L)$ with/without signal)
- Mass $= 1524 \pm 2 \pm 3$ MeV/c$^2$.

If the peak is real,

- It should be reproducible.
- It should appear in $M(nK^+)$.
- It should not appear in $M(nK^-)$ nor in $M(pK^+)$.
- Fermi-motion correction should work.
Experiment@SPring-8/LEPS

- **Collision**
- **a) SPring-8 SR ring**
- **b) Laser hatch**
- **c) Experimental hatch**

**Upgrade since previous experiment**

- **Two laser injection system** to increase beam intensity.
- **5W Ar laser → 8W solid state laser (Paladin by Coherent company).**
- Beam intensity of **1→2Mcps** was achieved at the maximum.
- About **2.6 times** statistics was collected in 2006-2007.
LEPS forward spectrometer

- The same setup for Common 2006-2007 data.
- Symmetric acceptance for positive/negative charged particles.

Symmetry in $\Theta^+/\Lambda(1520)$ production.
Search for $\Phi^+$ in Fermi-motion corrected $K^-$ missing mass

$\Phi^+$: $K^-$ missing mass
$\Lambda(1520)$: $K^+$ missing mass

For the further improvement

Inclusive analysis: $p/n$ unseparated

Exclusive analysis: $p/n$ separated

Separation of the two types of $K^+K^-$ events from neutron and proton largely improves the signal sensitivity.

In the previous analysis, only inclusive analysis was carried out.

Minimum Momentum Spectator Approximation (MMSA):
Assume possible minimum momentum configuration for the spectator.

- Simple MMn($\gamma,K^-$)$X$: 30 MeV/c$^2$
- $M(nK^+)$ by MMSA: 11 MeV/c$^2$
- (16 MeV/c$^2$ for $\Lambda(1520)$)
Inclusive Analysis

- New data was taken in 2006-2007 with almost the same setup.
- Blind analysis was applied to check the previous result. (Selection cut is not changed from previous analysis. calibration fixed before opening the box)
Comparison of the $\Lambda(1520)$ peak

- Is there any problems on new data?
- Is it possible to add two data sets?

$\gamma n \rightarrow K^-\Theta^+ \rightarrow K^+K^-n$

$K^- \leftrightarrow K^+$

$n \leftrightarrow p$

$\gamma p \rightarrow K^+\Lambda(1520) \rightarrow K^+K^-p$

<table>
<thead>
<tr>
<th></th>
<th>Previous</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak position (MeV)</td>
<td>1517.6 ± 1.6</td>
<td>1517.8 ± 1.0</td>
</tr>
<tr>
<td>Peak width (MeV)</td>
<td>18.5 ± 2.2</td>
<td>16.8 ± 1.6</td>
</tr>
<tr>
<td>Peak height</td>
<td>53.0 ± 5.2</td>
<td>128.3 ± 8.2</td>
</tr>
<tr>
<td>S/N ratio</td>
<td>1.74 ± 0.22</td>
<td>1.55 ± 0.15</td>
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MMn($\gamma, K^-$)$X > 1.6 GeV/c^2$

to keep the condition of the blind analysis.

- $\Lambda(1520)$ peak was found to be consistent for two data sets.
Other checks: $\phi$ events

$P_{\text{min}}$ for $\phi$ events

\[
\chi^2/\text{ndf}=96.6/90
\]
K.S test 52.4%

Other distributions are also checked and consistent. We decided to add two data sets after opening the box.
The significance is less than 2σ if we perform the same shape analysis as the previous analysis.

Λ(1520) cut $M(pK^-) > 1.55$ GeV/$c^2$
The increment of the $\chi^2$ from the best fit in the space of peak height and position of signal.

→ almost 3σ deviation from two data sets.

Unlikely to happen → Overestimation of significance by shape analysis.
Summing two data sets

$\Lambda(1520)$ cut is implemented

fitting w/o signal

fitting w/signal

Statistical significance of $\sim 4 \sigma$, peak position $\sim 1520$ MeV although it may contain large systematic error.
Exclusive Analysis

Separate

$\Lambda(1520), \phi, \ldots$

$\Theta^+, \phi, \ldots$
Proton detection by using dE/dx in Start Counter

\[
\text{Pid} = (\text{Measured energy loss in SC}) - (\text{Expectation of KK}) - (\text{Half of expectation of proton})
\]

Proton not tagged (Proton rejected)

Proton tagged (\(\varepsilon \sim 60\%\))

KKn and part of KKp

KKp only

Signal enhancement is seen in proton rejected events.

\(\rightarrow\) should be associated with \(\gamma n\) reaction.

p/n ratio:

1.6 before proton rejection
0.6 after proton rejection
LH2 \( p(\text{miss}) \) vs. \( p(\text{dEdx}) \)  
LH2 \( p(\text{MMSA}) \) vs. \( p(\text{dEdx}) \)
Proton rejected $M(NK^+)$ for exclusive samples

- Peak is seen in tagged events for the previous data while not seen in the new data.
- An enhancement is seen in proton rejected events in the both data.
Exclusive samples for summed data

- Structure seen in proton tagging becomes much smaller.
- Enhancement is seen in proton rejected events.
  → Further rejection of the proton events.
Neutron enhanced sample

Proton rejection efficiency becomes 60%→90% by selecting downstream of target $M(nK^+)$

Preliminary
Polarization dependence of the $M(nK^+)$

**Horizontal**

- ID: 1200
- Entries: 790
- Mean: 1.631
- RMS: $0.9252 \times 10^{-1}$

**Vertical**

- ID: 1100
- Entries: 503
- Mean: 1.617
- RMS: $0.9697 \times 10^{-1}$

B.G strength strongly depends on the polarization of the photon beam.
The spectrometer acceptance has approximately rectangular shape.

If $K^+$ and $K^-$ prefer to fly parallel to the polarization, the acceptance difference cause the difference of the strength. → Suggesting non-resonant $KK$ has p-wave component.
MC-based exclusive analysis

Recover 60% of events removed by the vertex cut.

1. Distributions for proton-tagged events were fitted with realistic MC distributions.

2. The whole proton contributions including events which leaked from SC are estimated based on the fit results.

3. The estimated proton contributions are subtracted from full data sample (without z-vertex and proton tagging cut).
Scematic explanation of MC-based exclusive analysis

proton “tagged” sample

Extrapolate with a help of MC

Subtract from full data sample.
→MC-based exclusive analysis.
Fitting proton-tagged events

\[ \chi^2/\text{ndf} = 33.3/37 \]

\[ \chi^2/\text{ndf} = 34.4/37 \]

\[ \chi^2/\text{ndf} = 33.9/37 \]

**Extended maximum-likelihood un-binned fit.**

- \( M(pK^+) \), \( M(pK^-) \), \( \cos(\Theta) \) of \( K^+ \) are simultaneously fitted.
- Ratio of \( \phi \) to non-resonant KK is determined from \( M(KK) \).
- \( \Lambda(1405) \) to explain threshold enhancement of \( M(pK^-) \)
- \( \chi^2/\text{ndf} \) is close to one.
MC-based exclusive analysis

Real data
Estimated proton contribution

- No $\Lambda(1520)$ peak after the proton subtraction in $M(nK^-)$ distribution.
- Enhancement is seen in $M(nK^+)$.
M(nK⁺) with two methods

MC-based exclusive events

\[ \text{MC-based exclusive events} \]

\[ \text{dE/dX-based exclusive events} \]

\[ \text{overlay with normalization by entry} \]

Subtract leaked proton contribution

\[ \text{overlay with normalization by entry} \]
1. Ratio of estimated proton contribution to the neutron contribution for the full data sample
   → 4616/2831 = 1.61

2. Ratio of tagged proton contribution to the neutron contribution for the sample with vtz cut
   (proton tagging efficiency of 0.9 was taken into account)
   → 1770/1119 = 1.58
Problem and Improvement of Exclusive analysis

We know there is a fluctuation at 1.53 GeV/c^2 in M(pK+) in the previous data.

1. Events with a proton are rejected.

2. Leaked proton contributions estimated by MC are subtracted.
   → Requires very good understanding of proton tagging efficiency.
Light collection is not good near the edge of the counter.
→ Efficiency was estimated by using both LH$_2$ and LD$_2$ data.
M(nK\(^-\)) distribution

✓ The peak did not appear in M(nK\(^-\))

n and p(leaked)

subtracted
The peak appeared in $M(nK^+)$
Downstream (vtz > -980 mm)

✓ The peak appear in low proton-leakage region.

n and p (leaked) subtracted
Upstream (vtz<-980 mm)

- The peak appears in the high proton-leakage region.

\[ n \text{ and } p(\text{leaked}) \]

The number of neutron events is consistent with the acceptance.
New data (2006-07)

✓ The peak appeared in the new data.

n and p(leaked) subtracted
Pol. dependence

✓ The large polarization dependence of the S/N ratio was seen.

Horizontal

Vertical
Fermi-motion correction by MMSA

✓ MMSA worked for $\Lambda(1520)$

w/o correction

w/ correction
Fermi-motion correction by MMSA

✓ MMSA worked for $\Theta^+$

w/o correction  

w/ correction
Summary

• The $\Theta^+$ is studied via $\gamma d \rightarrow K^+K^-pn$ reaction with high statistics data at SPring-8/LEPS. 2.6 times higher statistics compared with previous data are collected.
• The inclusive $M(NK^+)$ spectrum for new data does not show a strong narrow peak, which is inconsistent with the previous shape analysis.
  - The significance of the peak in new data is less than 2 $\sigma$ by the shape analysis.
• Exclusive analysis is performed by identifying the proton contribution using energy loss in SC.
  - A part of the inconsistency was due to fluctuation in proton tagged events.
  - Enhancement of events are seen in the region of $1.5 < M(nK^+) < 1.55$ GeV/$c^2$ for proton rejected events.
  - The enhancement is seen in the both new and previous data.
  - S/N ratio strongly depends on the beam polarization.
• These results are checked and confirmed by MC-based exclusive analysis.
• Mass and significance estimation of the enhancement is underway.
• LEPS collaboration just started new experiment with large SC.