Search for the $\Theta^+$ pentaquark at J-PARC

M. Moritsu (Kyoto University) for the J-PARC E19 collaboration

HYP2012 @ Barcelona, 2012/10/01
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Pentaquark $\Xi^+$

- made form five quarks ($qqqq\bar{q}$)
  - allowed combination by QCD.
- No convincing experimental evidence before 2002,
  - despite many searches in particle phys. exp.
- In 2003, SPring8/LEPS group first reported the evidence for $\Xi^+$,
  - including $\bar{s}$. $\rightarrow$ At least 5-quark components.
- Dozen experimental groups published supporting evidence for the $\Xi^+$,
- followed by a number of experiments with no evidence.
A Lot of Θ⁺ Searches

<table>
<thead>
<tr>
<th>Group</th>
<th>Reaction</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Statistical significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEPS</td>
<td>$\gamma C \to K^+K^-(n)$</td>
<td>1540 ± 10</td>
<td>&lt;25</td>
<td>4.6</td>
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<td>LEPS</td>
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<td>1524 ± 2</td>
<td>&lt;25</td>
<td>5.1</td>
</tr>
<tr>
<td>DIANA</td>
<td>$K^+Xe \to K^0_{s}pX$</td>
<td>1539 ± 2</td>
<td>&lt;9</td>
<td>4.4</td>
</tr>
<tr>
<td>DIANA</td>
<td>$K^+Xe \to K^0_{s}pX$</td>
<td>1538 ± 2</td>
<td>0.39±0.1</td>
<td>8</td>
</tr>
<tr>
<td>CLAS(d)</td>
<td>$\gamma d \to K^+K^-p(n)$</td>
<td>1542 ± 5</td>
<td>&lt;21</td>
<td>(5.2)</td>
</tr>
<tr>
<td>CLAS(p)</td>
<td>$\gamma p \to \pi^+K^+K^-(n)$</td>
<td>1555 ± 10</td>
<td>&lt;26</td>
<td>7.8</td>
</tr>
<tr>
<td>SAPHIR</td>
<td>$\gamma p \to K^+K^0_{n}X$</td>
<td>1540 ± 6</td>
<td>&lt;25</td>
<td>4.8</td>
</tr>
<tr>
<td>ITEP</td>
<td>$\nu A \to K^0_{s}pX$</td>
<td>1533 ± 5</td>
<td>&lt;20</td>
<td>6.7</td>
</tr>
<tr>
<td>HERMES</td>
<td>$e^+d \to K^0_{s}pX$</td>
<td>1528 ± 3</td>
<td>12±0</td>
<td>4.2</td>
</tr>
<tr>
<td>COSY-TOF</td>
<td>$pp \to K^0_{s}p\Sigma^+$</td>
<td>1530 ± 5</td>
<td>&lt;18</td>
<td>4.7</td>
</tr>
<tr>
<td>ZEUS</td>
<td>$e^+p \to e^+K^0_{s}pX$</td>
<td>1522 ± 3</td>
<td>8±4</td>
<td>4.6</td>
</tr>
<tr>
<td>NOMAD</td>
<td>$\nu A \to K^0_{s}pX$</td>
<td>1529 ± 3</td>
<td>2~3</td>
<td>4.3</td>
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<tr>
<td>SVD</td>
<td>$pA \to K^0_{s}pX$</td>
<td>1526 ± 5</td>
<td>&lt;24</td>
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<td>&lt;14</td>
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</tbody>
</table>

**Positive results**

<table>
<thead>
<tr>
<th>Group</th>
<th>Reaction</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>BES</td>
<td>$e^+e^- \to J/\Psi \to \Theta\Theta$</td>
<td>&lt; 1.1 x 10⁻⁵ B.R. (90% C.L.)</td>
</tr>
<tr>
<td>BES</td>
<td>$e^+e^- \to \Psi(2S) \to \Theta\Theta$</td>
<td>&lt; 8.4 x 10⁻⁶ B.R. (90% C.L.)</td>
</tr>
<tr>
<td>ALEPH</td>
<td>$e^+e^- \to Z \to pK^0_sX$</td>
<td>&lt; 6.2 x 10⁻⁴ B.R. (95% C.L.)</td>
</tr>
<tr>
<td>BarBar</td>
<td>$e^+e^- \to \Upsilon(4S) \to pK^0_sX$</td>
<td>&lt; 1.0 x 10⁻⁴ B.R. (90% C.L.)</td>
</tr>
<tr>
<td>BarBar</td>
<td>$eBe \to pK^0_sX$</td>
<td>not given</td>
</tr>
<tr>
<td>Belle</td>
<td>$e^+e^- \to B^0\bar{B}^0 \to p\bar{p}K^0_sX$</td>
<td>&lt; 2.3 x 10⁻⁷ B.R. (90% C.L.)</td>
</tr>
<tr>
<td>Belle</td>
<td>$K^+n \to K^0_s\bar{p}X$</td>
<td>$\Gamma &lt; 0.64MeV$ (90% C.L.)</td>
</tr>
<tr>
<td>CDF</td>
<td>$p\bar{p} \to K^0_spX$</td>
<td>&lt; 0.03 x $\Lambda^*$ (90% C.L.)</td>
</tr>
<tr>
<td>SPHINX</td>
<td>$pC \to K^0_spX$</td>
<td>&lt; 0.1 x $\Lambda^*$ (90% C.L.)</td>
</tr>
<tr>
<td>HERA-B</td>
<td>$pA \to K^0_spX$</td>
<td>&lt; 2.7% x $\Lambda^*$ (95% C.L.)</td>
</tr>
<tr>
<td>HyperCP</td>
<td>$pCu \to K^0_spX$</td>
<td>&lt; 0.3% $K^0_sp$</td>
</tr>
<tr>
<td>FOCUS</td>
<td>$\gamma BeO \to K^0_spX$</td>
<td>&lt; 0.02 x $\Sigma^*$ (95% C.L.)</td>
</tr>
<tr>
<td>PHENIX</td>
<td>$dAu \to K^-n\bar{X}$</td>
<td>not given</td>
</tr>
<tr>
<td>WA89</td>
<td>$\Sigma^+A \to K^0_spX$</td>
<td>&lt; 1.8µb/$\Lambda$ (99% C.L.)</td>
</tr>
<tr>
<td>CLAS</td>
<td>$\gamma p \to K^0_sK^+n$</td>
<td>&lt; 0.8 nb (95% C.L.)</td>
</tr>
<tr>
<td>CLAS</td>
<td>$\gamma d \to K^-pK^+n$</td>
<td>&lt; 0.15 – 3 nb (95% C.L.)</td>
</tr>
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<td>CLAS</td>
<td>$\gamma d \to K^+n\Lambda$</td>
<td>&lt; 5 – 25 nb (95% C.L.)</td>
</tr>
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<td>COSY-TOF</td>
<td>$pp \to \Sigma^+pK^0_s$</td>
<td>&lt; 0.15µb/$\Lambda$ (95% C.L.)</td>
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<tr>
<td>NOMAD</td>
<td>$\nu A \to K^0_spX$</td>
<td>&lt; 2.13 x 10⁻⁵$\nu$CC (90% C.L.)</td>
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**Negative results**
A Lot of $\Theta^+$ Searches

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<td>HERMES</td>
<td>$e^+d \rightarrow K^0\pi^0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COSY-TOF</td>
<td>$pp \rightarrow K^0\pi^0$</td>
<td>1556 ± 9</td>
<td>&lt;16</td>
<td>4.1</td>
</tr>
<tr>
<td>ZEUS</td>
<td>$e^+p \rightarrow e^+K^0\pi^0$</td>
<td>1522 ± 3</td>
<td>8 ±4</td>
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- **Not well established in experiments**
  - “Must confirm the existence/non-existence of $\Theta^+$ at first”

- **Positive results**
  - Low energy hadronic reaction ($\pi$ or K beam)
    - Few data
    - Expect sizable production cross section.
    - Complementary to the photo-production.
**👶 search by high-resolution spectroscopy
via \( \pi^- + p \rightarrow K^- + \Theta^+ : \) J-PARC E19

Previous KEK-PS E522 experiment
- Is this a sign of \( \Theta^+ \)?
  - Not enough sensitivity
  - They did not conclude the evidence of \( \Theta^+ \).
- Mass resolution
  \( \Delta M \sim 13.4 \text{ MeV (FWHM)} \)

**J-PARC E19 experiment**
- Same reaction as E522
- High resolution: SKS \( \Rightarrow \Delta M < 2 \text{ MeV (FWHM)} \)
- High statistics: High intensity beam at J-PARC

\( \Rightarrow \) Conclusive result by higher sensitivity.

The first physics run at the J-PARC hadron facility!
Experimental setup

K1.8 beam line spectrometer & SKS ⇒ Missing mass spectroscopy

- **K1.8 beam line spectrometer**: $p_{\pi}$
  - PID counters
    - Timing counters: TOF
    - Gas Cherenkov ($\pi/e$): $n=1.002$
  - Tracking
    - MWPCs: 1 mm pitch
    - MWDCs: 3 mm pitch

- **SKS system**: $p_K$
  - PID counters
    - Timing counter
    - Aerogel Cherenkov ($K/\pi$): $n=1.05$
    - Lucite Cherenkov ($K/p$): $n=1.49$
  - Tracking
    - MWDCs: 3 mm pitch
    - DCs: 10 mm pitch, 2m × 1m size

- **Target**: Liquid hydrogen
  - ~0.86 g/cm²
  - Free from Fermi motion effect
### History of E19

<table>
<thead>
<tr>
<th>Year</th>
<th>Comment</th>
<th>Beam Momentum</th>
<th>Beam Intensity</th>
<th>π’s on Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009/10</td>
<td>K1.8 beam line &amp; detector commissioning start</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010/10-11</td>
<td>examine the 2.6σ bump structure observed in E522</td>
<td>1.92 GeV/c</td>
<td>1.0 M /spill</td>
<td>7.8 x 10^{10}</td>
</tr>
<tr>
<td>1st RUN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012/02</td>
<td>new data at the highest beam momentum at K1.8</td>
<td>2.0 GeV/c</td>
<td>1.7 M /spill</td>
<td>8.7 x 10^{10}</td>
</tr>
<tr>
<td>2nd RUN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Successful completion of both 1st and 2nd run**
1st run result of E19

\[ \pi^- + p \rightarrow K^- + X \@ 1.92 \text{ GeV/c} \]

- **No prominent peak structure**
- **Upper limit:** \(< 0.26 \mu b/sr\)
  @ 1.51–1.55 GeV/c²

**Shirotori et al., PRL 109, 132002 (2012).**

- **s-channel dominance**
- **\( \Gamma_\Theta \propto g_{\text{KN}\Theta}^2 \propto \sigma_{\text{tot}} \)**
  \( \Rightarrow \) **Upper limit of decay width**

\[ \Gamma_{\frac{1}{2}+} \leq 0.72 \text{ MeV} \]
\[ \Gamma_{\frac{1}{2}^-} \leq 3.1 \text{ MeV} \]
2nd run of E19

- Beam time: 2012/Feb
- Higher beam momentum 2.0 GeV/c (= Max. of K1.8 B.L.)
- Expecting increased cross section ➔ higher sensitivity

➔ Stringent restriction on the Θ⁺ decay width.

Theoretical calculations:

\[ \sqrt{s} \text{ [MeV]} \]

\[ J^p=1/2^+, \Gamma_{\Theta^+} = 1\text{MeV} \]

- PV Fs 500MeV
- PV Fc 1800MeV

\[ p_{\text{lab}}=2.0 \text{ GeV/c} \]
\[ p_{\text{lab}}=1.92 \text{ GeV/c} \]
K1.8 Beam spectrometer

- K1.8 beam line spectrometer: \( p_\pi \)
  - PID counters
    - Timing counters: TOF
    - Gas Cherenkov (\( \pi/e \)): \( n=1.002 \)
  - Tracking
    - MWPCs: 1 mm pitch
    - MWDCs: 3 mm pitch

\( \pi \) is clearly identified using TOF btw 2 sets of hodoscopes

Beam mom. of 2 GeV/c is well reconstructed.

Analysis status of 2\(^{nd}\) run
SKS spectrometer

- **SKS system**: $p_K$
  - PID counters
    - Timing counter
    - Aerogel Cherenkov ($K/\pi$) : $n=1.05$
    - Lucite Cherenkov ($K/p$) : $n=1.49$
  - Tracking
    - MWDCs : 3 mm pitch
    - DCs : 10 mm pitch, 2m × 1m size

We can separate only $K$ very clearly.

**Scattered particle $M^2$**

- **Good momentum reconstruction and PID !!**
Vertex Reconstruction

Vertex-(X vs Y)

Consistent with horizontally oblate beam shape.

Target cell is clearly identified!!
Performance of the spectrometers

- $\pi^+ + p \rightarrow K^+ + \Sigma^+ \quad @ \quad 1.37 \text{ GeV/c}$
- Missing mass resolution:
  \[ \Delta M_\Sigma = 2.0 \text{ MeV (FWHM)} \]
  *Equivalent to the 1st run!!*
  Cf.) $\Delta M_\Sigma = 1.9 \pm 0.1 \text{ MeV} @ E19-1st$

$\Rightarrow$ estimate $\Theta^+$ case:
  \[ \Delta M_\Theta = 1.75 \text{ MeV (FWHM)} \]

- Yield estimation (rough):
  *Almost Consistent with the 1st run!!*

$\Gamma = 2.02 \pm 0.06$

*Enough performance!!*
Preliminary result of E19-2nd run

Missing Mass : $p (\pi^-, K^-) X \ @ p_\pi = 2.0 \text{ GeV/c}$

- Analysis parameters were not finally tuned yet.
- No clear peak structure was observed.
- Efficiency evaluation is on-going.
- Tentative expected sensitivity $\sim 0.3 \mu b/sr$. 
Summary

• J-PARC E19: High-resolution search via $\pi^- p \rightarrow K^- \Theta^+$ reaction
  – The first physics experiment at the J-PARC hadron facility!
  – 1st run result was published in PRL. (@ 1.92GeV/c beam)
    • More than 10 times higher sensitivity than E522.
    • No clear $\Theta^+$ peak $\rightarrow$ < 0.26 $\mu$b/sr
    • Strong constraint: $\Gamma < \sim$1 MeV

• 2nd run was successfully carried out. (@ 2 GeV/c beam)
  – Good performance of both K1.8BS and SKS.
  – No clear $\Theta^+$ peak (preliminary)
  – Efficiency evaluation etc. are in progress.