Structure and reactions of $\Theta^+$

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- hep-ph/0507105
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Outline

1. Full 5-body calculation

2. Photoproduction reconsidered
   
   \( p n \) asymmetry when \( J = 3/2 \)

   \( \gamma n \rightarrow K^- \Theta^+ \) vs. \( \gamma p \rightarrow \bar{K}^0 \Theta^+ \) [\( \Theta^+ \) or \( \Lambda(1520) \)]
   
   \( K^* \) production
1. Full 5-body calculation

Hiyama-Kamimura-Yahiro-Hosaka-Toki

hep-ph/0507105
Need to handle the (at least) 5-body system

- So far calculations were only approximate and only for bound state
- Better method with scattering states included

Method available developed in nuclear-physics

**Assumption: NRQM**

- Validity of the use of the Schrodinger picture
- What is the effective hamiltonian
  
  e.g. $const$ is not known $\Rightarrow$ confinement?

Clarify what this hamiltonian tells for 5-body system
Then improve this method or choose others?
Decay (fall-apart) is very sensitive to WFs

Hadronic (color-singlet) or colored correlations?

SU(3) qqq or qqbar are enough to make color singlets

Diquark correl.  Five quarks random  Hadronic correl.

Difficult to decay  Easy to decay
Dependence on $J^P$

$J^P = 1/2^- : \ l = 0$ (ground state)

$\sim$ KN scattering $\Rightarrow$ can not be narrow

Excited or complicated state may be a narrow res.

$J^P = 1/2^+ : \ l = 1$

$(3/2^+)$ Depends much on the configuration

$J^P = 3/2^- : \ l = 0$

D-wave KN decay is forbidden, can be narrow

Seems consistent with phenomenology

$\Rightarrow$ Hyodo, PRD, hep-ph/0509104

Method

Most serious calculation for 5-body system with scattering states included
Gaussian expansion method

$\Theta^{+-}$-confined

+ NK-scattering

Compute phase shifts

Oct 20-22, 2005
Pentaquark05 at J-Lab
Hamiltonian

NR quark model of Isgur-Karl

\[ H = \sum_i \left( m_i + \frac{p_i^2}{2m_i} \right) - T_G + V_{\text{Conf}} + V_{\text{CM}} \]

\[ V_{\text{Conf}} = -\sum_{i<j} \sum_{\alpha=1}^{8} \frac{\lambda_i^\alpha}{2} \frac{\lambda_j^\alpha}{2} \left[ \frac{k}{2} (x_i - x_j)^2 + v_0 \right] \]

\[ V_{\text{CM}} = \sum_{i<j} \sum_{\alpha=1}^{8} \frac{\lambda_i^\alpha}{2} \frac{\lambda_j^\alpha}{2} \frac{\xi_\sigma}{m_i m_j} e^{-\frac{(x_i - x_j)^2}{\beta^2}} \sigma_i \cdot \sigma_j \]
Good for conventional baryons

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV)</th>
<th>Magnetic moments (nm)</th>
<th>Charge radii (fm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>939</td>
<td>2.7737</td>
<td>$(0.60)^2$</td>
</tr>
<tr>
<td>$n$</td>
<td>939</td>
<td>-1.826</td>
<td>-0.04</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1058</td>
<td>-0.602</td>
<td>-0.01</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>1119</td>
<td>2.691</td>
<td>0.35</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>1119</td>
<td>0.819</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>1119</td>
<td>-1.054</td>
<td>-0.30</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>1309</td>
<td>-1.414</td>
<td>-0.01</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>1309</td>
<td>-0.507</td>
<td>-0.28</td>
</tr>
<tr>
<td>$\Delta^Q$</td>
<td>1232</td>
<td>2.843$Q$</td>
<td>0.41$Q$</td>
</tr>
<tr>
<td>$\Sigma^{**+}$</td>
<td>1320</td>
<td>3.18</td>
<td>0.64</td>
</tr>
<tr>
<td>$\Sigma^{*0}$</td>
<td>1320</td>
<td>0.33</td>
<td>0.12</td>
</tr>
<tr>
<td>$\Sigma^{*-}$</td>
<td>1320</td>
<td>-2.51</td>
<td>-0.38</td>
</tr>
<tr>
<td>$\Xi^{*0}$</td>
<td>1512</td>
<td>0.67</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Xi^{*-}$</td>
<td>1512</td>
<td>-2.17</td>
<td>-0.35</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>1506</td>
<td>-1.840</td>
<td>-0.32</td>
</tr>
</tbody>
</table>
KN-phase shifts 1/2$^+$

$E_{\text{res}} \sim 530$ MeV
$\Gamma_{\text{res}} \sim 110$ MeV

$\begin{array}{c}
\text{• Strong } q\bar{s} \text{ correlation favors KN} \\
\text{Rather than } [\text{ud}][\text{ud}]s \\
\Rightarrow \\
\text{• Formation of the JW type conf.} \\
\text{is a dynamical problem}
\end{array}$
KN-phase shifts 1/2-

(0s)^5: KN scattering state
Likely to be 1s(0s)^4
Γ < 1 MeV

The nature of the narrow resonance is interesting to analyze.
We have seen:

- **5-body calculation** of the Isgur-Karl quark model
  - Two states at \( \sim 500 \text{ MeV} \) above the KN threshold
  - \( \Gamma(1/2^-) \sim \text{Very narrow, } < 1 \text{ MeV} \)
  - \( \Gamma(1/2^+) \sim 100 \text{ MeV} \)

  *When the same \textit{const}*-parameter is used as for conventional baryons*

- The ground \((0s)^5\) configuration melts into the continuum

- The \(1/2^+\) state is dominated by \(qqq-qq\) configuration
2. Photoproductions

1. K-production

2. K*−production
(1) K-production with new J-Lab data

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

This is serious, but leads immediately to the absence of \( \Theta^+ \)?

Teaken from DeVita’s talk at spring APS meeting
Effective Lagrangian approach

hep-ph/0505134 Nam-Hosaka-Kim

For $J = 3/2$, only PV scheme is possible

appears only for n-target
Before the Θ-production

\[ \gamma n \rightarrow K^- \Lambda(1520) \] and \[ \gamma p \rightarrow K^0 \Lambda(1520) \]
was studied and large pn asymmetry was found

Comparison

<table>
<thead>
<tr>
<th>Form factor</th>
<th>$F_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactions</td>
<td>$\gamma p \rightarrow K^+ \Lambda^*$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$\sim 900 \text{ nb}$</td>
</tr>
<tr>
<td>$d\sigma/d(\cos \theta)$</td>
<td>Forward peak</td>
</tr>
<tr>
<td>$d\sigma/dt$</td>
<td>Good</td>
</tr>
</tbody>
</table>

The presence (for $p$) or absence (for $n$) contact term is important

LEPS data seems to support this result
Theta production, $J^P = 3/2^-$

Total $\sigma$

Angular dist

- neutron ~ forward peak
- Contact term
- proton ~ rather flat
$J^P = 1/2^+$

The role of the contact term is more important for $J^P = 3/2^-$ than $1/2^+$
Predictions

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$3/2^+$</th>
<th>$3/2^-$</th>
<th>$1/2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{KN\Theta}$</td>
<td>0.53</td>
<td>4.22</td>
<td>1.0</td>
</tr>
<tr>
<td>$g_{K^* N\Theta}$</td>
<td>$\pm 0.91$</td>
<td>$\pm 2$</td>
<td>$\pm 1.73$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target</th>
<th>$n$</th>
<th>$p$</th>
<th>$n$</th>
<th>$p$</th>
<th>$n$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>~ 25 nb</td>
<td>~ 1 nb</td>
<td>~ 200 nb</td>
<td>~ 4 nb</td>
<td>~ 1 nb</td>
<td>~ 1 nb</td>
</tr>
<tr>
<td>$\frac{d\sigma}{d\cos\theta}$ Forward</td>
<td>~ 60°</td>
<td>Forward</td>
<td>~ 45°</td>
<td>~ 45°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- We see a large asymmetry between pn targets
- Cross section for proton ~ few nb is consistent with the upper limit estimated by CLAS
Different exp. config.

Beam line

J-Lab

LEPS
Angular dist. in lab frame

\[ \gamma n \rightarrow K^- \Theta^+(3/2^+) \text{ in the lab frame} \]

- \( E_\gamma = 1.8 \text{ GeV} \)
- \( E_\gamma = 2.6 \text{ GeV} \)

At \( E_\gamma = 2 \text{ GeV} \)
\[ \sigma(\theta < 25^\circ) \sim 5 \sigma(\theta > 25^\circ) \]
Special kinematics

\[ k_\gamma \text{ (lab)} = 2.4 \text{ GeV} \]

\[ M_{\text{KN}(\text{min})} \text{ [GeV]} \]

\[ \text{Angle (Lab) [deg]} \]

Virtual \( \Theta \)

Real \( \Theta \)

At rest

\[ \Lambda(1520) \]

\[ \gamma(k) \]

\[ M_{NK} \]

\[ \theta \]

\[ N \]

\[ K \]
(2) $K^*$ ($1^-$) production

• Physics in the t-channel
  Now $\kappa$ ($0^-$) is allowed to be exchanged

Exotic tetraquark $\kappa$ may couple strongly to $\Theta^+$


• Using polarizations of $\gamma$ and $K^*$, we can distinguish the exchanged particles
Polarizations as a particle filter

Pol. of $\gamma$ perp. to react. plane

If parallel [∥], only $\kappa$ is exchanged
If perpendicular [⊥], only $K$ is exchanged
Summary

• 5-body calc.
  \[1/2^-\] \(E \sim 2\) GeV, \(\Gamma \sim 1\) MeV
  \[1/2^+\] \(E \sim 2\) GeV, \(\Gamma \sim 100\) MeV Configurations mix

(cf: quark model calc. Hosaka-Oka-Shinozaki

• Photoproduction, revised
  *There is a large *pn asymmetry*, especially for \(J = 3/2\)
  *No signal from the CLAS does not lead immediately to the absence of \(\Theta^+\)
  *Kinematics at LEPS is very interesting
  *\(K^*\) can be used as a *particle (t-channel) filter*
Interpretation of results

If $1/2^-, 3/2^-$

$1/2^+, 3/2^+$

Diquark
Tri-quark
Chiral

correlations

$(0s)^5$ $(0s)^40p$