Nucleon resonances in $\gamma p \rightarrow K^{*+} \Lambda$

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Outline

- Why $\gamma p \rightarrow K^{*+} \Lambda$?
- Current experimental & theoretical status
- Our approach
- Results & discussions
- Summary
Why $\gamma p \rightarrow K^{*+}\Lambda$?

- Extraction $N^{*}$'s from data & understanding their nature are essential to our understanding of NPQCD
- Our current knowledge of most of the $N^{*}$'s is coming from $\pi N \rightarrow \pi N \& \gamma N \rightarrow \pi N$
- Quark models predict more $N^{*}$’s than found
- $N^{*}$’s may couple weakly to $\pi N$ but strongly to other channels
- $K^{*+}\Lambda$ threshold higher than that of $\pi N$: more suited to study $N^{*}$’s with higher masses
- $K^{*+}\Lambda$ has isospin 1/2: “isospin filter”

“missing $N^{*}$’s problem”
Available data for $\gamma p \rightarrow K^{*+}\Lambda$ all reported by CLAS@JLab:

① Preliminary $\sigma$ from threshold up to 2.85 GeV:
   L. Guo et al. [CLAS Collaboration], NSTAR 2005 proceedings

② Preliminary $d\sigma/d\Omega$, $W = 2.22 \sim 2.42$ GeV:
   K. Hicks et al. [CLAS Collaboration], MENU 2010 proceedings

③ High statistics $d\sigma/d\Omega$ & $\sigma$, from threshold up to $W \sim 2.85$ GeV:
   W. Tang et al. [CLAS Collaboration], PRC 87, 065204 (2013)
High statistics data from CLAS


W: 2.04~2.26 GeV

W: 2.30~2.50 GeV
**N**\(^*\)’s near \(K^*\Lambda\) threshold


<table>
<thead>
<tr>
<th>(N^*)</th>
<th>Status</th>
<th>Mass</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N(2000)5/2^+)</td>
<td>**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N(2040)3/2^+)</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N(2060)5/2^-)</td>
<td>**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N(2100)1/2^+)</td>
<td>*</td>
<td>(~2100)</td>
<td></td>
</tr>
<tr>
<td>(N(2120)3/2^-)</td>
<td>**</td>
<td>(~2120)</td>
<td></td>
</tr>
<tr>
<td>(N(2190)7/2^-)</td>
<td>****</td>
<td>2100~2200</td>
<td>300~700</td>
</tr>
</tbody>
</table>

Four-star \(N^*\) needs further investigation to improve the accuracy of its parameters; One- or two-star \(N^*\)'s need more information to improve the evidences of their existences and to extract their parameters.
Theoretical status

Based on $\sigma$ & $d\sigma/d\Omega$ reported at NSTAR 2005 & MENU 2010

④ S. H. Kim, S. Nam, Y. Oh, & H. C. Kim, PRD 84 (2011) 114023.

Based on high statistics $d\sigma/d\Omega$ & $\sigma$ from PRC 87 (2013) 065204

  N(2000)5/2^+, N(2060)5/2^-, N(2120)3/2^-, N(2190)7/2^-

  Regge approach, no resonance, focus on t-channel $K^*$
\[ N(2000)5/2^+ \]
\[ N(2060)5/2^- \]
\[ N(2120)3/2^- \]
\[ N(2190)7/2^- \]
Rooms to be improved

S. H. Kim, A. Hosaka, & H. C. Kim, PRD 90 (2014) 014021

Our results (will be discussed later)
Aims of our work

Perform a better description of the data, and then answer the following questions:

- What’s the reaction mechanism of $\gamma p \rightarrow K^+ \Lambda$?
- How many N*’s are really needed to describe the data?
- What are the associated resonances parameters?
s-, t-, u-channel diagrams can be calculated straightforwardly;
The exact calculation of the interaction current is impractical
Prescription for gauge invariance

Full amplitude:

\[ M^{\nu \mu} = M_s^{\nu \mu} + M_t^{\nu \mu} + M_u^{\nu \mu} + M_{int}^{\nu \mu} \]

Interaction current:

\[ M_{int}^{\nu \mu} = \Gamma_\Lambda^{\nu} N K^* (q) C^{\mu} + M_{KR}^{\nu \mu} f_t. \]

Kroll-Ruderman term:

\[ M_{KR}^{\nu \mu} = g_{\Lambda NK^*} \frac{\kappa_{\Lambda NK^*}}{2M_N} \sigma^{\nu \mu} Q_{K^*} \]

Auxiliary current:

\[ C^{\mu} = -Q_{K^*} \frac{f_t - \hat{F}}{t - q^2} (2q - k)^{\mu} - Q_N \frac{f_s - \hat{F}}{s - p^2} (2p + k)^{\mu} \]

\[ \hat{F} = 1 - \hat{h} (1 - f_s) (1 - f_t) \]
Strategy of choosing resonances

Strategy: Introduce N*’s as few as possible to fit the data

N*’s near K*+Λ threshold in PDG 2016:

<table>
<thead>
<tr>
<th>N*</th>
<th>Status</th>
<th>Mass</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(2000)5/2+</td>
<td>**</td>
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<tr>
<td>N(2040)3/2+</td>
<td>*</td>
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<tr>
<td>N(2060)5/2−</td>
<td>**</td>
<td></td>
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<tr>
<td>N(2100)1/2+</td>
<td>*</td>
<td>~2100</td>
<td></td>
</tr>
<tr>
<td>N(2120)3/2−</td>
<td>**</td>
<td>~2120</td>
<td></td>
</tr>
<tr>
<td>N(2190)7/2−</td>
<td>****</td>
<td>2100~2200</td>
<td>300~700</td>
</tr>
</tbody>
</table>

We allow all of them and perform numerous trials with different number of N*’s and different combination of them.
How many N*’s are really needed?

Strategy: Introduce N*’s as few as possible

- 1 N*: Data cannot be described. Particularly, the shape of angular distribution near threshold cannot be reproduced

- 2 N*: 5 among 15 sets can well describe the data

\[ N(2060)5/2^- + \text{one of } N(2000)5/2^+, N(2040)3/2^+, N(2100)1/2^+, N(2120)3/2^-, N(2190)7/2^- \]

- 3 N*: \( \chi^2 \) improves less than 12%

Conclusion: One needs at least 2 N*’s to describe the high statistics differential cross section data from CLAS

Analysis with 3 or more N*’s postponed until data for spin observables become available
Data can be described by 2 N*’s

5 acceptable fits

Differences are seen at forward & backward angles where data are sparse
## Extracted N*’s parameters

<table>
<thead>
<tr>
<th>PDG</th>
<th>ratings</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
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<tbody>
<tr>
<td>N(2060)5/2⁻</td>
<td>**</td>
<td>2033±2</td>
<td>2009±5</td>
<td>2032±3</td>
<td>2043±4</td>
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<td>65±4</td>
<td>213±20</td>
<td>81±8</td>
<td>202±16</td>
<td>77±8</td>
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<tr>
<td>N(2000)5/2⁺</td>
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<td>2115±22</td>
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<td></td>
<td></td>
<td>450±10</td>
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<tr>
<td>N(2040)3/2⁺</td>
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<td>2200±62</td>
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<td></td>
<td></td>
<td>540±7</td>
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<tr>
<td>N(2120)3/2⁻</td>
<td>**</td>
<td></td>
<td></td>
<td>2203±9</td>
<td></td>
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<tr>
<td>~2120</td>
<td></td>
<td></td>
<td></td>
<td>433±33</td>
<td></td>
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<tr>
<td>N(2190)7/2⁻</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2243±6</td>
<td></td>
</tr>
<tr>
<td>[2100~2200]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>450±33</td>
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<tr>
<td>[300~700]</td>
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<tr>
<td>N(2100)1/2⁺</td>
<td>**</td>
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<tr>
<td>~2100</td>
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<td>2100±15</td>
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<td></td>
<td></td>
<td></td>
<td>450±9</td>
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</table>
K dominates the cross sections at high energy

N(2060)5/2−: significant contributions

Near threshold shape: Interference of K & N(2060)5/2−
Contribution of $N(2060)_{5/2}^-$

Our work

--- S. H. Kim et al., PRD90(2014)014021, small $N(2060)_{5/2}^-$

--- Our results with significant $N(2060)_{5/2}^-$

--- S. H. Kim et al., PRD90(2014)014021
Reaction mechanism of $\gamma p \rightarrow K^{*+}\Lambda$

- K-exchange dominates the high energy cross sections
- 2 N*’s are needed, one is $N(2060)5/2^-$, the other could be one of $N(2000)5/2^+$, $N(2040)3/2^+$, $N(2100)1/2^+$, $N(2120)3/2^-$, $N(2190)7/2^-$
- Interference of $N(2060)5/2^-$ & K is responsible for the near threshold shape of the cross sections
Predictions on spin observables
Summary

- Cross section data for $\gamma p \rightarrow K^{*+}\Lambda$ from CLAS have been well described in an effective Lagrangian approach.
- K-exchange dominates the high energy behavior.
- At least 2 N*’s are needed, one is N(2060)5/2−, the other could be one of N(2000)5/2+, N(2040) 3/2+, N(2100)1/2+, N(2120)3/2−, N(2190)7/2−.
- Interference of N(2060)5/2− & K is responsible for the near threshold shape of the cross sections.
- Further data on spin observables are needed to further pin down the resonance contents & parameters.
Thank you for your patience!
## Model Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2/N$</td>
<td>1.35</td>
<td>1.79</td>
<td>1.85</td>
<td>2.09</td>
<td>2.18</td>
</tr>
<tr>
<td>$g^{(1)}_{\Sigma^+ \Lambda \gamma}$</td>
<td>$0.74 \pm 0.16$</td>
<td>$-0.90 \pm 0.17$</td>
<td>$-0.87 \pm 0.14$</td>
<td>$-0.60 \pm 0.18$</td>
<td>$-0.22 \pm 0.16$</td>
</tr>
<tr>
<td>$\Lambda_K$ [MeV]</td>
<td>1000 ± 6</td>
<td>1019 ± 4</td>
<td>993 ± 7</td>
<td>1030 ± 3</td>
<td>1018 ± 4</td>
</tr>
<tr>
<td>$N^*$ Name</td>
<td>$N(2060)5/2^-$</td>
<td>$N(2060)5/2^-$</td>
<td>$N(2060)5/2^-$</td>
<td>$N(2060)5/2^-$</td>
<td>$N(2060)5/2^-$</td>
</tr>
<tr>
<td>$M_R$ [MeV]</td>
<td>2033 ± 2</td>
<td>2009 ± 5</td>
<td>2032 ± 3</td>
<td>2043 ± 4</td>
<td>2038 ± 3</td>
</tr>
<tr>
<td>$\Gamma_R$ [MeV]</td>
<td>65 ± 4</td>
<td>213 ± 20</td>
<td>81 ± 8</td>
<td>202 ± 16</td>
<td>77 ± 8</td>
</tr>
<tr>
<td>$\Lambda_R$ [MeV]</td>
<td>1188 ± 20</td>
<td>965 ± 16</td>
<td>1126 ± 12</td>
<td>889 ± 13</td>
<td>981 ± 22</td>
</tr>
<tr>
<td>$\sqrt{\beta_{\Lambda K^*} A_{1/2}} [10^{-3} \text{ GeV}^{-1/2}]$</td>
<td>$0.69 \pm 0.06$</td>
<td>$0.03 \pm 0.01$</td>
<td>$0.33 \pm 0.03$</td>
<td>$0.60 \pm 0.06$</td>
<td>$-0.21 \pm 0.02$</td>
</tr>
<tr>
<td>$\sqrt{\beta_{\Lambda K^*} A_{3/2}} [10^{-3} \text{ GeV}^{-1/2}]$</td>
<td>$-1.39 \pm 0.13$</td>
<td>$-0.10 \pm 0.01$</td>
<td>$-1.10 \pm 0.10$</td>
<td>$-1.94 \pm 0.19$</td>
<td>$-1.56 \pm 0.15$</td>
</tr>
<tr>
<td>$N^*$ Name</td>
<td>$N(2000)5/2^+$</td>
<td>$N(2040)3/2^+$</td>
<td>$N(2120)3/2^-$</td>
<td>$N(2190)7/2^-$</td>
<td>$N(2100)1/2^+$</td>
</tr>
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<td>$M_R$ [MeV]</td>
<td>2115 ± 22</td>
<td>2200 ± 62</td>
<td>2203 ± 9</td>
<td>2243 ± 6</td>
<td>2100 ± 15</td>
</tr>
<tr>
<td>$\Gamma_R$ [MeV]</td>
<td>450 ± 10</td>
<td>540 ± 7</td>
<td>433 ± 33</td>
<td>450 ± 33</td>
<td>450 ± 9</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}_{RN}^{1/2\pm} = \frac{g_{RN}}{2M_N} \overline{R} \Gamma^{(\mp)} \sigma_{\mu\nu} \left( \partial^{\nu} A^{\mu} \right) N + \text{H. c.} , \]

\[ \mathcal{L}_{RN}^{3/2\pm} = -ie \frac{g_{RN}}{2M_N} \overline{R}_\mu \gamma_\nu \Gamma^{(\pm)} F^{\mu\nu} N + e \frac{g_{RN}}{(2M_N)^2} \overline{R}_\mu \Gamma^{(\pm)} F^{\mu\nu} \partial_\nu N + \text{H. c.} , \]

\[ \mathcal{L}_{RN}^{5/2\pm} = e \frac{g_{RN}}{(2M_N)^2} \overline{R}_\mu \sigma_{\nu\rho} \left( \partial^{\alpha} F^{\mu\nu} \right) N \pm ie \frac{g_{RN}}{(2M_N)^3} \overline{R}_\mu \Gamma^{(\pm)} \left( \partial^{\alpha} F^{\mu\nu} \right) \partial_\nu N + \text{H. c.} , \]

\[ \mathcal{L}_{RN}^{7/2\pm} = ie \frac{g_{RN}}{(2M_N)^3} \overline{R}_\mu \sigma_{\nu\rho} \left( \partial^{\alpha} F^{\mu\nu} \right) N - e \frac{g_{RN}}{(2M_N)^4} \overline{R}_\mu \Gamma^{(\pm)} \left( \partial^{\alpha} F^{\mu\nu} \right) \partial_\nu N + \text{H. c.} , \]

Effective Lagrangians