Dynamical Model of $\gamma p \rightarrow K^+ \Lambda$

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F. Tabakin (Pittsburgh)
Motivated by:
New accurate data of $\gamma p \rightarrow K\Lambda, K\Sigma$

- J.W.C. McNabb et al., PRC 69 (2004) 042201 (JLab)
- K.H. Glander et al., EPJA 19 (2004) 251 (SAPHIR)
- More to come

Objectives:
- Explore the hyperon production mechanisms
- Explore several "missing" nucleon resonances
General Considerations

Unitarity Condition:

\[ S^\dagger S = 1 \quad S = 1 + iT \]

\[ \rightarrow \]

\[ \text{Im}[T_{\gamma N,KY}] \propto \sum_{MB} [T^\dagger]_{\gamma N,MB} T_{MB,KY} \]

\[ \propto \sqrt{\sigma_{\gamma N,MB}} \sqrt{\sigma_{MB,KY}} \]

- \( T_{a,b} \) : reaction amplitude
- \( MB = KY, \pi N, \pi\pi N(\rho N, \pi \Delta) \ldots \)
- \( \sigma_{a,b} \) : cross section of \( a \rightarrow b \)
$\gamma p \rightarrow \left( \pi N, \pi \pi N \right) \rightarrow KY$ must be included
First step:

- Consider only the effects due to $\pi N$ channel

Ingredients of a reaction Model:

- A direct reaction mechanism
- Accounts for coupled channel effects
Formulation

- Extend a dynamical model of $\gamma N \rightarrow \pi N$ (Sato and Lee) to include $KY$ channel

- Channels included:
  $$\gamma p, \pi^+ n, \pi^0 p, K^+ \Lambda, K^+ \Sigma^0$$

- Apply a unitary transformation to derive Hamiltonian $H$ from SU(3) Lagrangians
  $$H$$ is energy independent and hermitian

  $$\rightarrow$$
  Unitarity condition is trivially satisfied
Coupled channel equations:

\[ T_{a,b}(E) = t_{a,b}(E) + t_{a,b}^R(E), \]

Resonant term:

\[ t_{a,b}^R(E) = \sum_{N_i^*, N_j^*} \bar{\Gamma}_{N_i^*,a}(E)[G^*(E)]_{i,j} \bar{\Gamma}_{N_j^*,b}(E). \]

Non-resonant term:

\[ t_{a,b}(E) = v_{a,b} + \sum_c v_{a,c} G_c(E) t_{c,b}(E), \]

Dressed vertex:

\[ \bar{\Gamma}_{N^*,a}(E) = \Gamma_{N^*,a} + \sum_b \Gamma_{N^*,b} G_b(E) t_{b,a}(E), \]
Dressed vertex:

\[ \tilde{\Gamma}_{N^*,a}(E) = \Gamma_{N^*,a} + \sum_b \Gamma_{N^*,b} G_b(E) t_{b,a}(E), \]

Quark Model Prediction

+ [ ]

pion cloud effect
Photoproduction Amplitude

Dynamical Model:

\[ a_{\ell \pm}^{\gamma N \rightarrow KY}(q_{KY}, k) = b_{\ell \pm}^{\gamma N \rightarrow KY}(q_{KY}, k) \]

\[ + \sum_{\alpha = KY} dp_{\alpha} p_{\alpha}^2 t_{\ell \pm K}^{\alpha \rightarrow KY}(q_{KY}, k) G_{0\alpha}(p_{\alpha}) b_{\ell \pm}^{\gamma N \rightarrow \alpha}(p_{\alpha}, k) \]

\[ + \sum_{\alpha = \pi N} dp_{\alpha} p_{\alpha}^2 t_{\ell \pm N}^{\alpha \rightarrow KY}(q_{KY}, k) G_{0\alpha}(p_{\alpha}) b_{\ell \pm}^{\gamma N \rightarrow \alpha}(p_{\alpha}, k) \]

Tree-diagram models:

\[ a_{\ell \pm}^{\gamma N \rightarrow KY}(q_{KY}, k) = b_{\ell \pm}^{\gamma N \rightarrow KY}(q_{KY}, k) \]

- Not unitary
- No coupled-channel effects
Procedures

1. Determine \( \pi N \rightarrow KY \) and \( KY \rightarrow KY \)

- \( \nu_{\pi N,\pi N} : \) Sato–Lee model
- \( \nu_{\pi N,KY} \), and \( \nu_{KY,KY} : \) by SU(3)
Solve coupled-channel equation to get non-resonant $t_{\pi N,KY}$

calculate resonant amplitude $t^{R}_{\pi N,KY}$ from known $N^*$

adjust form factors and $N^*$ parameters to fit data of $\pi N \rightarrow KY$
\[ \pi N \rightarrow KY : \quad d\sigma/d\Omega \]

\[ \rightarrow K^0\Lambda \quad \rightarrow K^0\Sigma^0 \]

Parameters in the meson–baryon potential are varied to reproduce the experimental data

R.D. Baker et al, NP (1978); T.M. Knasel et al, PRD (1975);
D.H. Saxon et al. NPb (1980); J.C. Hart et al. NPB (1980)
The asymmetries are defined as: 

$$\sum \propto \frac{\sigma \perp - \sigma \parallel}{\sigma \perp + \sigma \parallel}$$

$$\rightarrow K^0 \Lambda \quad \rightarrow K^0 \Sigma^0$$

The achieved understanding of the $\pi N \rightarrow KY$ is enough for our purposes. Future data on $KY - KY$ would help to further constrain the model.
Procedures

2. Calculate $\gamma p \rightarrow K^+ \Lambda$ amplitudes

- The direct contributions $t_{\gamma p \rightarrow K^+ \Lambda}$:

  *quark model (Li-Saghai)*

\[ (a) \quad \gamma \\ \rightarrow \\ p \\ \Lambda \\ \rightarrow \\ K^+ \\ p \]

\[ (b) \quad \gamma \\ \rightarrow \\ p \\ \Lambda^*, \Sigma^* \\ \rightarrow \\ K^+ \\ p \]

\[ (c) \quad \gamma \\ \rightarrow \\ p \\ K^* \\ \rightarrow \\ \Lambda \]
The resonance term $t^{R}_{\gamma p \to K+\Lambda}$ includes:

N:
$P_{11}(1440), S_{11}(1535), S_{11}(1650), P_{11}(1710), D_{13}(1520), D_{13}(1700), P_{13}(1720), P_{13}(1900), D_{15}(1675), F_{15}(1680), F_{15}(2000)$

and

$\Delta$: $S_{31}(1900), P_{31}(1900), P_{33}(1920), D_{33}(1700)$

Non-resonant $t_{\gamma p \to \pi N}$:

$t_{\gamma p \to \pi N} = T^{\text{exp}} - t_{\gamma p \to \pi N}^{R}$

$T^{\text{exp}}$ from SAID

Resonance $t_{\gamma p \to \pi N}^{R}$ from Capstick-Roberts quark model
Adjust $N^*$ parameters to fit data

Considered $\gamma p \rightarrow K^+\Lambda$ Data

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Observable</th>
<th># of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLab</td>
<td>$d\sigma/d\Omega$</td>
<td>920</td>
</tr>
<tr>
<td>LEPS</td>
<td>$\Sigma_\gamma$</td>
<td>44</td>
</tr>
<tr>
<td>SAPHIR</td>
<td>$d\sigma/d\Omega$</td>
<td>720</td>
</tr>
<tr>
<td>JLab</td>
<td>$\Sigma_\Lambda$</td>
<td>233</td>
</tr>
</tbody>
</table>

SU(3) breaking parameters, one for each resonance, are varied in the fits.

To study the proposed new resonances, a $3^{rd} S_{11}$ and a $3^{rd} P_{13}$ are included in the fits.
\[ \gamma p \rightarrow K^+ \Lambda \] cross sections

Red: JLAB  
Black: SAPHIR

- Discrepancies in the two data sets  
- We choose to fit them independently

Most relevant:
\( S_{11}(1535), S_{11}(1650), F_{15}(1680) \)
\( P_{13}(1720), P_{13}(1900), F_{15}(2000) \)

Model A: Solid line, JLAB data  
Model B: Dashed line, SAPHIR data
Coupled channel effects

Solid: Model A
Dashed: " w/o CC

Large CC effects
which could be hidden in coupling
values in other approaches

Confirms prev. results

(WTChiang et al 2000)

Similar effect for most angles
Effects on $N^*$ properties

Bare: the resonance is directly excited by the incident photon

Dressed: The photon first excites a $\pi N$ intermediate state
Polarization data

$\gamma$ polarized

We have now included polarization data in the fits.
Polarization data

Λ polarized

- Results from new fits (Oct. 8, 2005)
Looking for $3^{rd} S_{11}$ and $3^{rd} P_{13}$

Model A and B include a $3^{rd} S_{11}$ and a $3^{rd} P_{13}$.

The fitted values, in the ranges (1.6–2 GeV and 1.6–2.4 GeV)

Effect from $3^{rd} P_{13}$ very small

$(\theta=98 \text{ deg})$ Solid, dotted and dashed:

full Model A, Model A w/o $3^{rd} S_{11}$ Model A w/o $3^{rd} P_{13}$. 
Looking for $3^{rd} S_{11}$

Our fitted values are:

<table>
<thead>
<tr>
<th>New Resonances</th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}$ Mass (GeV)</td>
<td>1.820</td>
<td>1.818</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>210</td>
<td>270</td>
</tr>
<tr>
<td>$P_{13}$ Mass (GeV)</td>
<td>2.053</td>
<td>2.045</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>158</td>
<td>390</td>
</tr>
</tbody>
</table>

similar mass in both models, different widths
other $3^{rd} S_{11}$ are

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Width (MeV)</th>
<th>Comment</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.780</td>
<td>280</td>
<td>CQM applied to $\gamma p \rightarrow \eta p$</td>
<td>Saghai-Li (2003)</td>
</tr>
<tr>
<td>1.835</td>
<td>246</td>
<td>CQM, applied to $\gamma p \rightarrow K^+\Lambda$ data from SAPHIR</td>
<td>Saghai (2003)</td>
</tr>
<tr>
<td>1.852</td>
<td>187</td>
<td>CQM, applied to $\gamma p \rightarrow K^+\Lambda$ data from JLab</td>
<td>Saghai (2003)</td>
</tr>
<tr>
<td>1.730</td>
<td>180</td>
<td>$K\ Y$ molecule</td>
<td>Li-Workman (1996)</td>
</tr>
<tr>
<td>1.792</td>
<td>360</td>
<td>$\pi N$ and $\eta N$ coupled-channel analysis</td>
<td>Zagreb group (2000)</td>
</tr>
<tr>
<td>1.800</td>
<td>165</td>
<td>$J/\Psi$ decay</td>
<td>Bai (2001)</td>
</tr>
</tbody>
</table>
Effect of $3^{rd} S_{11}$
Summary

A dynamical coupled-channel model has been developed to fit the data of

\[ \pi^- p \rightarrow K^0 \Lambda, K^0 \Sigma^0 \]
\[ \gamma p \rightarrow K^+ \Lambda \]

Coupled-channel effects due to \( \pi N \) channel are found to be important.

Our results support the 3rd \( S_{11} \) \( N^* \)
\( (M \sim 1820 \text{ MeV}, \Gamma \sim 210 - 270 \text{ MeV}) \)

No strong evidence of 3rd \( P_{13} \) \( N^* \)
\( (M \sim 2050 \text{ MeV}) \)
Future Developments

- Analyze $\gamma p \rightarrow K\Sigma$ data
- Include $\pi\pi N$ channel
- apply the unitary $\pi\pi N$ model of Matsuyama, Sato and Lee (in progress)