Nucleon resonances from dynamical coupled channel approach of meson production reactions

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Report on our extended analysis of meson production reactions (ANL-Osaka)


Contents

➢ Coupled channel approach of meson production reactions

➢ Analysis of meson production reactions

➢ Extraction of N* parameters:
  N* spectrum, residue of $\pi N$ amplitude

May 27 NSTAR2013
Extraction of mass, width, coupling constants, electromagnetic transition form factors from analysis of meson production reactions are important task to learn structures of baryons.
Feature of $N^*,\Delta$ resonances

- excite states of nucleons are unstable particles and appear as resonances
- strong coupling of excited states with meson-baryon continuum
  large width ($\sim 100\text{MeV}$) and overlapping resonances
Extraction of N*,Δ resonances properties

- excited states of nucleons are unstable particles and appear as resonance
- strong coupling of excited states with meson-baryon continuum
  large width (~> 100MeV) and overlapping resonances

Extraction of resonance properties requires systematic analysis of meson production reactions [channels, wide energy region, observables].

\[ W < 2 \text{GeV}, \text{open channels: } \pi N, \eta N, \pi \pi N, K \Lambda, K \Sigma, \omega N \]

- Our approach: Dynamical coupled channel approach
  ANL-Osaka, Julich (M. Doring 27AM), Dubna-Taipei-Mainz,…

- Complementary approaches: ..
  Bonn-Gatchina (A. Sarantev 28AM),
  George Washington U. (I. Strakovsky 28AM),
  Jlab-Yerevan (V. Mokeev 28AM)
  MAID
Collaborators

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K. Tsushima (Adelaide, JLab)
dynamical coupled-channels (DCC) model
$G_M(Q^2)$ for $\gamma N \rightarrow \Delta (1232)$ transition

- meson-baryon reaction dynamics is part of the resonance properties

Note: Most of the available static hadron models give $G_M(Q^2)$ close to “Bare” form factor.
Dynamical Coupled Channel Approach


start from Hamiltonian of meson-baryon system

\[ |N^*\rangle \quad |\pi N\rangle, |\eta N\rangle, |K\Lambda\rangle, |K\Sigma\rangle, |\pi\pi N\rangle \]

\[ \Gamma_{N^*\leftrightarrow MB} \quad V_{MB, M'B'} \]

\[ \rightarrow \text{Solve scattering equation that satisfies three-body unitarity} \]
Scattering amplitude of pion and photon induced meson production amplitudes are obtained by solving coupled channel integral equation (3-dim reduction) in momentum space (partial waves $[I,J,P]$)

$$T_{\beta,\alpha}^{IJP}(k', k, W) = V_{\beta,\alpha}^{IJP}(k', k) + \sum_\gamma \int dq q^2 V_{\beta,\gamma}^{IJP}(k', q) G_\gamma^0(q, W) T_{\gamma,\alpha}^{IJP}(q, k, W)$$

$$\alpha, \beta, \gamma = (\gamma^{(*)}N, \pi N, \eta N, \pi \Delta, \sigma N, \rho N, K\Lambda, K\Sigma, \ldots)$$

$\pi \pi N$

\[\begin{aligned}
&\text{s-channel} \\
&\begin{array}{c}
V \\
\rho, \sigma \\
N, \pi \\
N, \Delta \\
N^\ast_{\text{bare}}
\end{array} \\
&\text{u-channel} \\
&\begin{array}{c}
\Delta \\
\Delta \\
N \\
\pi, \rho, \sigma, \omega, \ldots
\end{array} \\
&\text{t-channel} \\
&\begin{array}{c}
\pi, \rho, \sigma, \omega, \ldots
\end{array} \\
&\text{contact}
\end{aligned}\]
Analysis of meson production reactions
New ANL-Osaka Dynamical Coupled-Channels analysis

<table>
<thead>
<tr>
<th>(JLMS) 2006-2009</th>
<th>(ANL-Osaka) 2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>channels</td>
<td>6 channels</td>
</tr>
<tr>
<td>reactions</td>
<td>$(\gamma N, \pi N, \eta N, \pi\Delta, \rho N, \sigma N)$</td>
</tr>
<tr>
<td>$\pi p \rightarrow \pi N$</td>
<td>$W &lt; 2 \text{ GeV}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \pi N$</td>
<td>$&lt; 1.6 \text{ GeV}$</td>
</tr>
<tr>
<td>$\pi^- p \rightarrow \eta n$</td>
<td>$&lt; 2 \text{ GeV}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \eta p$</td>
<td>—</td>
</tr>
<tr>
<td>$\pi p \rightarrow K\Lambda, K\Sigma$</td>
<td>—</td>
</tr>
<tr>
<td>$\gamma p \rightarrow K\Lambda, K\Sigma$</td>
<td>—</td>
</tr>
</tbody>
</table>

- Extended to include KY production reaction, higher $W$
- Fully combined analysis of $\gamma N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ reactions
- SU(3) Meson ($P,V$ octet), Baryon (octet, decuplet)
- Omega $N$, $\pi\pi N$ are not included in fit
- Total 22,348 data points

### Data sets

\( \pi N \rightarrow \pi N \)

20 partial waves

Single energy solution of SAID

<table>
<thead>
<tr>
<th>Partial Wave</th>
<th>Partial Wave</th>
</tr>
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<tbody>
<tr>
<td>( S_{11} )</td>
<td>( S_{31} )</td>
</tr>
<tr>
<td>( P_{11} )</td>
<td>( P_{31} )</td>
</tr>
<tr>
<td>( P_{13} )</td>
<td>( P_{33} )</td>
</tr>
<tr>
<td>( D_{13} )</td>
<td>( D_{33} )</td>
</tr>
<tr>
<td>( D_{15} )</td>
<td>( D_{35} )</td>
</tr>
<tr>
<td>( F_{15} )</td>
<td>( F_{35} )</td>
</tr>
<tr>
<td>( F_{17} )</td>
<td>( F_{37} )</td>
</tr>
<tr>
<td>( G_{17} )</td>
<td>( G_{37} )</td>
</tr>
<tr>
<td>( G_{19} )</td>
<td>( G_{39} )</td>
</tr>
<tr>
<td>( H_{19} )</td>
<td>( H_{39} )</td>
</tr>
</tbody>
</table>

| Sum          | 994          | 944          | 1938         |

- **first step:** \( W<1.4 \) mainly non-resonant interaction + \( \delta_{33} \)
- **second step:** \( W<2.3 \) mainly \( N^* \) parameters
• pi-eta differential cross section (J. Durand et al., PRC 78 025204(2008))

• Third step: start global fit

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### Number of data points of hadronic processes

<table>
<thead>
<tr>
<th>Process</th>
<th>$d\sigma/d\Omega$</th>
<th>$P$</th>
<th>$\beta$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^- p \rightarrow \eta p$</td>
<td>294</td>
<td>–</td>
<td>–</td>
<td>294</td>
</tr>
<tr>
<td>$\pi^- p \rightarrow K^0 \Lambda$</td>
<td>544</td>
<td>262</td>
<td>43</td>
<td>849</td>
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<tr>
<td>$\pi^- p \rightarrow K^0 \Sigma^0$</td>
<td>160</td>
<td>70</td>
<td>–</td>
<td>230</td>
</tr>
<tr>
<td>$\pi^+ p \rightarrow K^+ \Sigma^+$</td>
<td>552</td>
<td>312</td>
<td>7</td>
<td>871</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>1550</strong></td>
<td><strong>644</strong></td>
<td><strong>50</strong></td>
<td><strong>2244</strong></td>
</tr>
</tbody>
</table>
Number of data points of photoproduction processes

<table>
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<th>$\Sigma$</th>
<th>$T$</th>
<th>$P$</th>
<th>$\hat{E}$</th>
<th>$G$</th>
<th>$H$</th>
<th>$O_x'$</th>
<th>$O_{z'}$</th>
<th>$C_x$</th>
<th>$C_z$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p \rightarrow \pi^0 p$</td>
<td>4381</td>
<td>1128</td>
<td>380</td>
<td>589</td>
<td>140</td>
<td>125</td>
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<td>7</td>
<td>7</td>
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<td>6806</td>
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<td>$\gamma p \rightarrow \pi^+ n$</td>
<td>2315</td>
<td>747</td>
<td>678</td>
<td>222</td>
<td>231</td>
<td>86</td>
<td>128</td>
<td></td>
<td></td>
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<td></td>
<td>4407</td>
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<tr>
<td>$\gamma p \rightarrow \eta p$</td>
<td>3221</td>
<td>235</td>
<td>50</td>
<td></td>
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<td>800</td>
<td>86</td>
<td>66</td>
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<td></td>
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<td>66</td>
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<tr>
<td>$\gamma p \rightarrow K^+ \Sigma^0$</td>
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<td>169</td>
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<td>1069</td>
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<tr>
<td>$\gamma p \rightarrow K^0 \Sigma^+$</td>
<td>220</td>
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<td>Sum</td>
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<td>1881</td>
<td>371</td>
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<td>73</td>
<td>73</td>
<td>119</td>
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<td>18166</td>
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</table>

- Global fit of pion and photon induced reactions
- Loop: back to the first step
• Improvement for S31,P31,D35
• Direct comparison with obs. was done.
\[ \frac{d\sigma}{d\Omega} \]

\[ \pi^+ p \rightarrow K^+ + \Sigma^+ \]
• Extensive data of differential cross section can be fitted very well for $W<1.9\text{GeV}$.
• Not able to account forward peak $W>1.933\text{GeV}$
\[ \sum \text{ of } \gamma + p \rightarrow \pi^0 + p \]

- Extensive data of Sigma can be fitted well for \( W < 1.9 \text{GeV} \).
Polarization observables of $\gamma + p \rightarrow \pi^0 + p$

- Number of data points is much less than $d\sigma/d\Omega$, $\Sigma$

$\hat{E} = -\Delta_{31}/2$
\[ \gamma + p \rightarrow K^+ + \Sigma^0 \]

\[ \frac{d\sigma}{d\Omega} \]
Extraction of resonance poles and residues of scattering amplitudes
Extraction of resonance parameters

Resonance as a pole of S/T-matrix

Partial wave amplitude $\mathcal{F}(W)$

Analytic continuation

Resonance parameter

$< \beta | \mathcal{F}(W) | \alpha > \sim - \frac{R_{\beta,\alpha}}{W - M_{N^*}}$

mass and width $M_{N^*} = M - i\Gamma/2$

coupling constant residue $R_{\beta,\alpha}$
coupling constant helicity amplitude $R_{\beta,\alpha} = g_{\beta,N^*} g_{\alpha,N^*}$

$-\pi < \text{arg}(g_{\pi N,N^*}) \leq \pi$
resonance poles of ANL-Osaka analysis

\[
\begin{array}{c|cc|c|cc}
 & \text{I}=1/2 & & \text{I}=3/2 & & \\
 & \text{AO} & \text{JLMS} & & \text{AO} & \text{JLMS} \\
1/2^- & 2 & 2 & & 1^+1* & 1 \\
3/2^- & 1^+1* & 1 & & 2 & 1 \\
5/2^- & 1 & 1 & & 1 & 0 \\
1/2^+ & 2 & 2 & & 1 & 0 \\
3/2^+ & 2 & 0 & & 2 & 1 \\
5/2^+ & 1 & 1 & & 1 & 2 \\
7/2^+ & 0 & 0 & & 1 & 1 \\
\end{array}
\]

Re(M) < 2GeV, \quad \text{Im}(M) < 0.2GeV, \quad \text{at closest sheet}

JLMS: Suzuki et al. PRL104(2010)042302
Spectrum of nucleon resonances

Re(M) < 2GeV
Width < 0.4GeV, (AO only poles on the nearest sheet)

\[ I = 3/2 \]

\[ \begin{array}{cccc}
1/2+&(P31) & 3/2+&(P33) & 5/2+&(F35) & 7/2+&(F37) \\
1/2-(S31) & 3/2-(D33) & 5/2-(D35) \\
\end{array} \]

AO: Argonne-Osaka

2\textsuperscript{nd} S31(1702-193i)
2\textsuperscript{nd} D13(1702-141i)

PDG: 2012 3*, 4*

J: Julich (model A dynamical reaction model)
arXiv 1211.6998 D. Ronchen et al.

BG: Bonn-Gachina(K-matrix approach)
• AO agree with PDG for $W<2\text{GeV}(3^*,4^*)$ except no 3rd P33,D13, additional 2nd D33, 2nd S31

• Pole positions of AO, Julich, Bonn-Gachina agree well only for the first $N^*$
Three analyses for \( \pi N \) residue agree well for Delta(1232), for some states agree qualitatively. Similar situation for the photon helicity amplitudes. Residues are more sensitive to the analyses than pole positions.
Near future improvements on the description of meson production reactions N⁺ extraction

Resonances, photo coupling of higher energy resonances

Complete measurement of pseudo scalar meson production reaction


Understanding of pipiN dynamics

- large part of the meson production cross section
- large partial width of N⁺
- poor data for piN → pipiN reaction compared with photo-production data

Proposal for JPARC

Proposal for J-PARC 50 GeV Proton Synchrotron

3-Body Hadronic Reactions for New Aspects of Baryon Spectroscopy

K.H. Hicks (Ohio University), H. Sako (JAEA), spokespersons
Importance of $\pi N \rightarrow \pi\pi\pi N$ data

**VERY PRELIMINARY**

- Current model
- Refit F37 PWA keeping $N^* \rightarrow \pi\Delta$ off

Kamano at Tohoku 2012
Summary

- We have investigated within a dynamical coupled channel model of pi-N and gamma-N reactions up to 2GeV.

- The meson baryon channels included in calculations are
  \[ \gamma N, \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N \] (\( \pi\Delta, \rho N \) and \( \sigma N \)).

- Parameters for non-resonant interaction is mainly constrained by the fit to low energy region \( W < 1.4 \text{GeV} \) and \( N^* \) parameters are determined by the fit up to \( W < 2 \text{GeV} \).

- Pole positions and residues (coupling constants of \( N^* \)) are extracted by analytic continuation of the amplitudes.

- Recent analyses agree well only for the first \( N^* \) in each spin parity Isospin\((J,P,I)\).

- New hadronic data in particular piN \( \rightarrow \) pipiN are needed to improve analysis and hope the results will converge in near future.
Next step

- Continue combined fit including two pion and omega production data to improve fits around $W \sim 2\text{GeV}$. Combine information from new hyperon photo production data.

- Extract transition electromagnetic forms factor for major resonances

- Analysis on the nature of resonance poles

- Urgent needs to extend a model for neutrino induced reaction.

Collaboration at J-PARC Branch of KEK theory center

backup
Signal of weak resonances (Pi-N amplitude)

Second Delta33

Weak coupling with piN, sizable coupling with gamma N

First P33
Second P33

P11

ANL-Osaka

Julich
Estimation of resonance amplitude

\[ T_{\alpha,\beta}(W) = t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \Gamma_{\alpha,i}(W) \left[ \frac{1}{W - m_0 - \Sigma(W)} \right]_{ij} \Gamma_{\beta,j}(W) \]

\[ T_{res} = \frac{(\sum_i \Gamma_{\alpha,i}(W)c_i)(\sum_j \Gamma_{\beta,j}(W)c_j)}{W - M_{pole} + i\Gamma_{pole}/2} \]
Choice of phase (Residue -> coupling constant)

\[ R_{\pi N, \pi N} = g_{\pi N}^2 \quad R_{\pi N, \gamma N} = g_{\pi N} g_{\gamma N} \]