N* and Y* baryon spectroscopy using high momentum pion beam (+ kaon beam)

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Outline

1. Brief description of ANL-Osaka Dynamical Coupled-Channels (DCC) approach & N* spectroscopy from the analysis of πN and γN reactions
   (HK, Nakamura, Lee, Sato, PRC88(2013)035209)

2. Y* (= Λ*, Σ*) spectroscopy using Kaon beam

3. Applications of ANL-Osaka DCC approach to forward p(π, ρ or K*)X with high-momentum pion beam
   (HK in preparation)
Brief description of ANL-Osaka DCC approach & N* spectroscopy from the analysis of πN and γN reactions
(1 of 3)
Introductory remarks

“Light-quark baryon spectroscopy”

= “Physics of very broad and highly overlapping resonances”

- Resonances are strongly correlated with each other in the reaction processes over the wide energy region.
- Resonances appear in the cross sections as rather complicated interference.

To disentangle the above complications and establish resonance mass spectrum, the followings must be accomplished:

- Simultaneous partial-wave analysis of various meson-production reactions over the wide energy range within multichannel reaction framework.
- Careful investigation of the analysis results in an comprehensive manner.

This requires extensive and accurate data of various meson production reactions that covers:

- wide energy and kinematical (angles, Q2,...) regions.
- both unpolarized and polarized observables.
Introductory remarks

Experimental and theoretical efforts for N* spectroscopy

Experiments
- JLab, ELSA, MAMI, GRAAL, SPring-8, ELPH, ...

Theoretical analyses
with multichannel framework
- ANL-Osaka/EBAC-JLab
- Bonn-Gatchina
- Carnegie-Mellon-Berkeley
- Dubna-Mainz-Taipei
- Giessen
- GWU/VPI
- Juelich
- Karlsruhe-Helsinki
- ...

✓ Multichannel unitary condition:

$$T_{ab}(E) - T_{ab}^+(E) = -2\pi i \sum_c T_{ac}^\delta(E-E_c)T_{cb}(E)$$

$$a,b,c = (\gamma^{(*)}N, \pi N, \eta N, \pi\pi N, K\Lambda, K\Sigma, \omega N \cdots)$$
Summing up all possible transitions between reaction channels !!
(\(\Rightarrow\) satisfies \textit{two- and three-body unitarity})

e.g.) \(\pi N\) scattering

\(\pi\pi N\)

\(\checkmark\) \textbf{Momentum integral} takes into account \textit{off-shell effects} in the intermediate processes.
**ANL-Osaka DCC approach to N**


\[
T_{a,b}^{(LSJ)}(p_a, p_b; E) = V_{a,b}^{(LSJ)}(p_a, p_b; E) + \sum_c \int_0^\infty q^2 dq V_{a,c}^{(LSJ)}(p_a, q; E) G_c(q; E) T_{c,b}^{(LSJ)}(q, p_b; E)
\]

**Coupled-channels effect**

\[a, b, c = (\gamma^{(*)}N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N, K\Lambda, K\Sigma, \cdots)\]

**Region our model can cover**

**Latest published model:**

HK, Nakamura, Lee, Sato, PRC88(2013)035209

**Constructed by simultaneous analysis of**

- \(\pi N\) scattering \((W < 2.3\) GeV\)
- \(\pi\rho \rightarrow \eta N, K\Lambda, K\Sigma\) \((W < 2.1\) GeV\)
- \(\gamma\rho \rightarrow \pi N, \eta N, K\Lambda, K\Sigma\) \((W < 2.1\) GeV\)

**yp reaction total cross sections in N** region
\( \gamma p \rightarrow K^+ \Sigma^0 \) reaction

DCS

At present, NO data are available for the other 11 observables (as of 2013): T, E, F, G, H, Ox', Oz', Lx', Lz', Tx', Tz'

8ch DCC-analysis

[HK, Nakamura, Lee, Sato, PRC88 (2013) 035209]
\[ \gamma p \rightarrow K^+ \Sigma^0 \] reaction

8ch DCC-analysis
[HK, Nakamura, Lee, Sato, PRC88 (2013) 035209]

At present, NO data are available for the other 11 observables (as of 2013):

“(Over-) complete” experiments has been accomplished by CLAS
(& complemental data from ELSA, MAMI,..)
for \( K\Lambda \) and \( K\Sigma \) photo-productions !!!

[See e.g., A. M. Sandorfi, S. Hoblit, HK, T.-S. H. Lee, JPG38(2011)053001]
**Comparison of N* spectrum with other multichannel analyses**

HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

### “N” resonances (I=1/2)

<table>
<thead>
<tr>
<th>J^P(L_2 I_2 J)</th>
<th>PDG</th>
<th>AO</th>
<th>J</th>
<th>BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2+(P11)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3/2+(P13)</td>
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<tr>
<td>5/2+(F15)</td>
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<tr>
<td>7/2+(F17)</td>
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</table>

**NOTE:**
- Plot only N*s with Re(M_R) < 2 GeV
- -2Im(M_R) < 0.4 GeV

**PDG:** 4* & 3* states assigned by PDG2012
**AO:** ANL-Osaka
**J:** Juelich [EPJA49(2013)44, Model A]
**BG:** Bonn-Gatchina [EPJA48(2012)5]
Comparison of N* spectrum with other multichannel analyses

HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

“N” resonances (I=1/2)

Re(M_R) - 2Im(M_R) (“width”)

M_R : Resonance pole mass (complex)

NOTE:
Plot only N*s with Re(M_R) < 2 GeV - 2Im(M_R) < 0.4 GeV

1st J^P=1/2^- N* resonance
6ch DCC 8ch DCC
width: 382 MeV 196 MeV

Due to inclusion of ηN production data into the analysis !!

PDG: 4* & 3* states assigned by PDG2012
AO : ANL-Osaka
J : Juelich [EPJA49(2013)44, Model A]
Comparison of N* spectrum with other multichannel analyses

HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

"Δ" resonances (I=3/2)

\[ \text{Re}(M_R) - 2\text{Im}(M_R) \]

(MR: Resonance pole mass (complex))

NOTE:
Plot only N*s with \( \text{Re}(M_R) < 2 \text{ GeV} \)
\( -2\text{Im}(M_R) < 0.4 \text{ GeV} \)

\[ J^P(L_{2I2J}) \]

1/2+(P31) 3/2+(P33) 5/2+(F35) 7/2+(F37)
1/2-(S31) 3/2-(D33) 5/2-(D35)

PDG: 4* & 3* states assigned by PDG2012
AO : ANL-Osaka
J : Juelich [EPJA49(2013)44, Model A]
Comparison of N* spectrum with other multichannel analyses

"Δ" resonances (I=3/2)

$\text{Re}(M) - 2\text{Im}(M)$ ("width")

$M_R$: Resonance pole mass (complex)

NOTE: Plot only N*s with $\text{Re}(M) < 2$ GeV - $2\text{Im}(M) < 0.4$ GeV

$J^P(L_{2I_2J})$

PDG: 4* & 3* states assigned by PDG2012

AO: ANL - Osaka

Juelich [EPJA49(2013)44, Model A]


$\pi N \rightarrow \pi N$ P33 (I=3/2, $J^P=3/2^+$) amp.

HK, Nakamura, Lee, Sato, PRC88 (2013) 035209
Comparison of N* spectrum with other multichannel analyses

HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

J-PARC E45 experiment (measurement of πN → ππN) would be a key to resolving the issue of Roper-like state of Δ!!
Short summary and remarks (1/3)

Main interests in N* in the near future (in my view):

✔ Establishing the spectrum for high-mass N*s (1.7 < M < 2.5 GeV)
  ➢ LEPS2 can play a key role !!
    (with their polarized photons; hopefully also polarized targets and recoil particles)

✔ Quantitative study of quark-gluon substructure of N* via the $Q^2$ dependence of N-N* e.m. transition form factors.
  ➢ Form factors are extracted from meson electro-productions.
  ➢ This is a main N* program at CLAS12. 
    (R. Gothe et al., JLab E12-09-003; D. Carman et al., a new proposal in preparation)

![Diagram showing N-N* e.m. transition form factors, quark-gluon substructure, and various particles like πN, ηN, ππN, KY, ωN, ...]
Y* (= Λ*, Σ*) spectroscopy using Kaon beam
(2 of 3)
Current status of $Y^*$ spectroscopy (some points may be missed):

- Much less understood than $N^*$ and $\Delta^*$ baryons.
- PDG lists only $Y^*$ mass spectrum defined by the “highly model-dependent” Breit-Wigner mass and width.
- Systematic partial-wave analysis to extract $Y^*$ defined as poles of scattering amplitudes was first performed by the KSU group (2013, on-shell K-matrix approach), and then by our group (2014, dynamical approach).
Applications of ANL-Osaka DCC approach to $Y^*$ spectroscopy

✓ $Y^*$ spectroscopy using anti-Kaon beams

➢ The simplest reactions for studying $Y^*$.

➢ Deuteron reactions allow direct access to $\Lambda(1405)$ region and study of $YN$ and $YY$ interactions.

Most importantly, J-PARC can measure all of these reactions!!
Applications of ANL-Osaka DCC approach to Y* spectroscopy

What we have done so far:

✓ Formulation of coupled-channels equations with $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $K\Xi$, $\pi\Sigma^*(\pi\pi\Lambda)$, $\bar{K}^*N(\pi\bar{K}N)$ channels

✓ Simultaneous analysis of available polarized and unpolarized data of $K^-p \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $K\Xi$ from the threshold up to $W = 2.1$ GeV. ($\sim 17,000$ data to fit) ($HK$, Nakamura, Lee, Sato, arXiv:1407.6839)

✓ Extraction of $\Lambda^*$ and $\Sigma^*$ mass spectrum defined by poles of scattering amplitudes. ($HK$, Nakamura, Lee, Sato, in preparation)
Applications of ANL-Osaka DCC approach to Y* spectroscopy


<table>
<thead>
<tr>
<th>Reactions</th>
<th>Observables</th>
<th>Number of data</th>
<th>$\chi^2$/data</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Model A</td>
</tr>
<tr>
<td>$K^- p \rightarrow K^- p$</td>
<td>$d\sigma/d\Omega$</td>
<td>3962</td>
<td>4.26</td>
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<tr>
<td></td>
<td>$P$</td>
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<td></td>
<td>$\sigma$</td>
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<td>$P$</td>
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<td>$P \times d\sigma/d\Omega$</td>
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<td>$K^- p \rightarrow K^0 \Xi^0$</td>
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<tr>
<td>$K^- p \rightarrow K^+ \Xi^-$</td>
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<td><strong>Total</strong></td>
<td></td>
<td><strong>16548</strong></td>
<td><strong>3.67</strong></td>
</tr>
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</table>

Database (mostly comes from 60-70’s)

Kinematical region covered (up to $W < 2.1$ GeV):

- $d\sigma/d\Omega : 1465 \text{ MeV} < W$
- $P : 1730 \text{ MeV} < W$
- $\beta, R, A: \text{ No data}$

- $d\sigma/d\Omega : 1465 \text{ MeV} < W$
- $P : \text{ No data}$
- $\beta, R, A: \text{ No data}$

- $d\sigma/d\Omega : 1535 \text{ MeV} < W$
- $P : 1535 \text{ MeV} < W < 1967 \text{ MeV}$
- $\beta, R, A: \text{ No data}$

- $d\sigma/d\Omega : 1535 \text{ MeV} < W < 1763 \text{ MeV}$
- $P : 1535 \text{ MeV} < W < 1696 \text{ MeV}$
- $\beta, R, A: \text{ No data}$

- $d\sigma/d\Omega : 1536 \text{ MeV} < W$
- $P : \text{ No data}$
- $\beta, R, A: \text{ No data}$

- $d\sigma/d\Omega : 1535 \text{ MeV} < W$
- $P : 1535 \text{ MeV} < W$
- $\beta, R, A: \text{ No data}$

No data for $d\sigma/d\Omega, P, \beta, R, A$
Applications of ANL-Osaka DCC approach to $Y^*$ spectroscopy

Results of the fit

DCS for $K^-p \rightarrow K^-p$

Red: Model A
Blue: Model B

Applications of ANL-Osaka DCC approach to Y* spectroscopy

Extracted S = -1 Y* mass spectrum
(Here only Y*s above KN threshold are presented.)

Predicted spin-rotation angle $\beta$

$K^- p \rightarrow K^- p$
$K^- p \rightarrow K^0 n$
$K^- p \rightarrow \pi^- \Sigma^+$
$K^- p \rightarrow \pi^0 \Sigma^0$
$K^- p \rightarrow \pi^+ \Sigma^-$
$K^- p \rightarrow \pi^0 \Lambda$

Red: Model A
Blue: Model B
Black: KSU

The KSU results are computed by us using their amplitudes in PRC88(2013)035204.

## NOTE:
$\beta$ is modulo $2\pi$
Systematic partial wave analyses to extract $Y^*$ defined by poles have been done recently by KSU and our groups.

The $K$- $p$ reaction data are still far from “complete”.
(Limitation of kinematical coverage, no spin-rotation parameters,...)

- Extracted $Y^*$ mass spectrum still contains sizable ambiguities !!

To eliminate the ambiguities, one needs:

- **Polarization observables**
  ($P$ in wider kinematical region, spin-rotations $\beta$, $R$, or $A$)

- **Data near the $\bar{K}N$ threshold**
  (Almost no differential cross section data below $W = 1.5$ GeV)

- **Data for inelastic reactions**: $K$- $p \rightarrow \eta\Lambda$, $K\Xi$, $\pi\bar{K}N$, $\pi\pi\Lambda$,...
Applications of ANL-Osaka DCC approach to $p(\pi, \rho \text{ or } K^*)X$ with high-momentum pion beam (3 of 3)
Applications of ANL-Osaka DCC approach to forward $p(\pi, V)X$ reactions

✓ Forward $p(\pi, \rho)X$ & $p(\pi, K^*)X$ reactions with high-momentum pions
   (Ishikawa-san’s talk at RCNP May 1st, 2012)

➢ New opportunity of light-quark baryon spectroscopy using diffractive processes
   (another useful source for addressing the $\bar{K}N$ subthreshold region!!)

➢ May be able to be used for determining $N-N^*$ and $N-Y^*$ transition form factors by axial currents (from virtual-$\pi NN^*$, virtual-$\bar{K}NY^*$ vertices + PCAC).

\[
\begin{align*}
\text{high-} & \rho \pi \quad \rho \text{ (forward)} \\
\text{virtual } & \pi \\
\text{p} \quad & N^* \\
\text{Off-shell amplitudes from our DCC model}
\end{align*}
\]

\[
\begin{align*}
\text{high-} & \rho \pi \quad K^* \text{ (forward)} \\
\text{virtual } & \bar{K}, \bar{K}^* \\
\text{p} \quad & Y^*
\end{align*}
\]
Applications of ANL-Osaka DCC approach to forward p(\(\pi, V\))X reactions

**Formulation:**

\[ \rho \rho \pi \pi \text{ vertex function:} \]

\[ \mathcal{X} = \pi N, \eta N, \pi \pi N, \eta N, \ldots \]

\[ \frac{d\sigma}{dtdW^2} = \frac{\sqrt{\lambda(W^2, m^2_N, t)}}{32\pi^2 \lambda(s, m^2_N, m^2_\pi)} |D_{\pi \text{ex}}|^2 \]

\[ \times \left( \sum_{S^z_\rho} |F_{\rho \pi \text{ex}, \pi}(t)|^2 \right) (I_{\rho} I^z_{\rho}, I_{\pi \text{ex}} I^z_{\pi} - I^z_{\rho} I^z_{\pi})^2 \]

\[ \times \sigma_{X, \pi \text{ex} N}. \]

Cross section for (half-off-shell) \(\pi \text{ex} N \rightarrow X\) reaction

**\(\rho \pi \pi \pi\) vertex function:**

\[ \sum_{S^z_\rho} |F_{\rho \pi \text{ex}, \pi}(t)|^2 = 2g_{\rho \pi \pi}^2 \left( m^2_\rho - 2(t + m^2_\pi) + \frac{(t - m^2_\pi)^2}{M^2_\rho} \right) [F(t)]^2. \]

\[ F(t) = \left( \frac{\Lambda^2_{\rho \pi \pi} - m^2_\pi}{\Lambda^2_{\rho \pi \pi} - t} \right) \]

\[ g_{\rho \pi \pi} = 6.04 \text{ (from } \rho \rightarrow \pi \pi \text{ decay)} \]

\[ \Lambda_{\rho \pi \pi} = 900 \text{ MeV [PRC24(1981)2611]} \]

**\(\pi\) propagator (Reggeized) [e.g., Guidal et al, NPA627(1997)645]:**

\[ D_{\text{ex}} = \left( \frac{s}{s_0} \right)^{\alpha(t)} \frac{\pi \alpha'}{\sin(\pi \alpha(t))} \frac{S + e^{-i\pi \alpha(t)}}{2} \frac{1}{\Gamma(1 + \alpha(t))} \]
Applications of ANL-Osaka DCC approach to forward $p(\pi,V)X$ reactions

\[ \frac{d\sigma}{dW^2} \equiv \int_{-t_{\min}}^{-t_{\max}=0.1\text{GeV}^2} d(-t) \frac{d\sigma}{d(-t)dW^2} \]

$\pi^- p \rightarrow \rho^0 X$

Contributions of $X = \eta N, K\Lambda, K\Sigma$ are much smaller than $X = \pi N, \pi\pi N$.  

HK, in preparation
Applications of ANL-Osaka DCC approach to forward \( p(\pi,V)X \) reactions

Angular distribution for \( \pi^+ p \rightarrow \rho^0 X \) with \( X = \pi^+ p \)

\( p_{\text{Lab}} = 10 \text{ GeV/c}, \ t = -0.1 \text{ GeV}^2, \ W = 1.232 \text{ GeV} \)

DCS of \( \pi^+ p \) scattering at \( W = 1.232 \text{ GeV} \)

[HK, Nakamura, Lee, Sato PRC88(2013)035209]

VERY PRELIMINARY

HK, in preparation
An attempt to using forward \( p(\pi, \rho)X \) for light-quark baryon spectroscopy is underway within our DCC model.

Application to \( p(\pi, K^*)X \) will also be possible using our DCC model for \( K^- p \) reactions!!