Light-quark baryon spectroscopy from ANL-Osaka dynamical coupled-channels analysis

Hiroyuki Kamano  
(RCNP, Osaka U.)
Outline

1. N* and Δ* spectroscopy via ANL-Osaka Dynamical Coupled-Channels (DCC) analysis of πN, γN, and eN reactions
   ➔ HK, Nakamura, Lee, Sato, PRC88(2013)035209
   (See also talk by Toru Sato in NSTAR2013: http://ific.uv.es/nucth/nstar/talks/P1_Sato.pdf)

2. Λ* and Σ* spectroscopy via ANL-Osaka DCC analysis of K− p reactions
ANL-Osaka DCC approach to N* and Δ*


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

\[ a, b, c = ( γ^{(*)}N, πN, ηN, \{πΔ, σN, ρN\}, KΛ, KΣ, \cdots) \]

\[ ππN \]

✓ Summing up all possible transitions between reaction channels!!

(⇒ satisfies multichannel two- and three-body unitarity)

e.g.) πN scattering

✓ Momentum integral takes into account off-shell rescattering effects in the intermediate processes.
ANL-Osaka DCC approach to N* and Δ*


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

CC effect  off-shell 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

Construct by simultaneous analysis of

- πN SAID PW amps. (W < 2.3 GeV)
- ππp → ηN, KΛ, KΣ (W < 2.1 GeV)
- γp → πN, ηN, KΛ, KΣ (W < 2.1 GeV)
ANL-Osaka DCC approach to $N^*$ and $\Delta^*$

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

$\gamma p \rightarrow \pi^0 p$

$\frac{d\sigma}{d\Omega}$ for $W < 2.1$ GeV

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

$\frac{d\sigma}{d\Omega}$ for $W < 2.1$ GeV

$\pi p \rightarrow K^0\Sigma^0$

$\frac{d\sigma}{d\Omega}$ for $W < 2.1$ GeV

Red: minor updated ver.

Blue: PRC88(2013)035209
ANL-Osaka DCC approach to $N^*$ and $\Delta^*$

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

$\gamma p \rightarrow \pi^0 p$

$d\sigma/d\Omega$ for $W < 2.1$ GeV

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

$d\sigma/d\Omega$ for $W < 2.1$ GeV

$\pi p \rightarrow K^0 \Sigma^0$

$d\sigma/d\Omega$ for $W < 2.1$ GeV

Red: minor updated ver.
Blue: PRC88(2013)035209
Comparison of N* & Δ* spectrum between multichannel analyses

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

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

\[ M_R : \text{Resonance pole mass (complex)} \]

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

**“N” resonance (I=1/2)**

1/2+(P11) 3/2+(P13) 5/2+(F15) 7/2+(F17)

**“Δ” resonance (I=3/2)**

1/2+(P31) 3/2+(P33) 5/2+(F35) 7/2+(F37)

PDG: 4* & 3* states assigned by PDG2012
AO : ANL-Osaka

Juelich [EPJA49(2013)44]
Comparison of $N^*$ & $\Delta^*$ spectrum between multichannel analyses

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

Existence and mass spectrum are now well established for most low-lying resonances!!
(➔ Next task: establish high-mass resonances)

$N$ resonance ($I=1/2$)

$\Delta$ resonance ($I=3/2$)

PDG: $4^*$ & $3^*$ states assigned by PDG2012

AO: ANL-Osaka

J: Juelich [EPJA49(2013)44]

To establish the spectrum of high-mass resonances, inelastic reaction (particularly double pion production) data are highly desirable:

\[ \pi N, \gamma N \rightarrow \pi \pi N, K\Lambda, K\Sigma, \eta N, \eta' N, \omega N, \Phi N, \ldots \]

**Measurements of**

\[ \pi N \rightarrow \pi \pi N, \ldots : \]

**HADES**

[› Talk by W. Przygoda
27th(Wed.) Plenary 27-2]

**J-PARC E45**

[› Talk by K. Hosomi
27th(Wed.) ParallelA 27-2]
Necessity of inelastic reaction data for establishing high-mass $N^*$ and $\Delta^*$ spectrum

To establish the spectrum of high-mass resonances, inelastic reaction (particularly double pion production) data are highly desirable:

$$\pi N, \gamma N \to \pi \pi N, K\Lambda, K\Sigma, \eta N, \eta' N, \omega N, \Phi N, \ldots$$

![Graph showing partial decay widths of $N^*$ and $\Delta^*$](image)

**Measurements of**

$$\pi N \to \pi \pi N, \ldots$$:

**HADES**
- [Talk by W. Przygoda, 27th(Wed.) Plenary 27-2]

**J-PARC E45**
- [Talk by K. Hosomi, 27th(Wed.) ParallelA 27-2]
Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

N-N* e.m. transition form factors

\[ \gamma^* q (q^2 = -Q^2) \]

N \rightarrow N^*,\Delta^*

How effective d.o.f. of baryon constituents changes with Q^2?

Q^2: small \quad Q^2: large

CLAS database for 1π electroproductions (Q^2 < 6 GeV^2)

Meson electro-productions:

\[ e \rightarrow e' \]

N \rightarrow N^*,\Delta^*

+ K^+Λ, K^+ Σ^0 electro-production data
Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

\[ \sigma_T + \epsilon \sigma_L @ Q^2 = 2.42 \text{ (GeV/c)}^2 \]

Structure functions are provided by K. Joo and C. Smith.

Ep \rightarrow e\pi^0p \ (1.11 < W < 1.69 \text{ GeV})

Ep \rightarrow e\pi^+n \ (1.15 < W < 1.67 \text{ GeV})

cos\theta
Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

$$\sigma_T + \epsilon \sigma_L @ Q^2 = 2.42 \ \text{(GeV/c)}^2$$

Structure functions are provided by K. Joo and C. Smith.

$$G_M(Q^2) \text{ for } \gamma^*N \to \Delta(1^{st} P33) \text{ evaluated at pole}$$

PRELIMINARY

Red: 8ch model (current)
Black: 6ch model [$$Q^2 < 1.5 (\text{Gev/c})^2$$]
PRC80(2009)025207; 82(2010)045206
Blue: Extracted by experiment groups (Breit-Wigner)

$$\cos\theta$$

$$G_M^*/(3 G_D)$$
Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

\[ \sigma_T + \varepsilon_\sigma_L \ @ \ Q^2 = 2.42 \ (\text{GeV}/c)^2 \]

Structure functions are provided by K. Joo and C. Smith.

\[ e p \rightarrow e \eta^0 p \ (1.11 < W < 1.69 \ \text{GeV}) \]

\[ e p \rightarrow e \pi^+ n \ (1.15 < W < 1.67 \ \text{GeV}) \]

\[ G_M(Q^2) \ for \ \gamma^* N \rightarrow \Delta(1^{st}\ P33) \ \text{evaluated at pole} \]

- Red: 8ch model (current)
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Preliminary

Structure functions are provided by K. Joo and C. Smith.
Meson photoproductions off “neutron”

✓ Need for isospin decomposition of electromagnetic currents.
→ Necessary for applications to NEUTRINO reactions: S. Nakamura, 27th (Wed) ParallelA 27-1

γ ‘n’ → π⁺ p

dσ/dΩ for W < 2 GeV

Σ for 1.14 < W < 1.9 GeV
Meson photoproductions off “neutron”

✓ Need for isospin decomposition of electromagnetic currents.
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S. Nakamura, 27th (Wed) ParallelA 27-1

γ ‘n’ → π⁺ p
dσ/dΩ for W < 2 GeV

Σ for 1.14 < W < 1.9 GeV

Future work:
Analyze deuteron reaction data directly to extract single- & double-polarization observables for “neutron-target” reactions in a fully consistent way in our approach.
Y* ( = Λ*, Σ*) resonances are much less understood than N* and Δ*.

Comprehensive & systematic PWA to extract Y* defined by poles of scattering amplitudes has only recently been made:

- Kent State University (KSU) group (2013, “KSU parametrization” of S-matrix)
- Our group (2014-, dynamical approach)
Current situation for $Y^*$ spectroscopy

- $Y^*$ (= $\Lambda^*$, $\Sigma^*$) resonances are much less understood than $N^*$ and $\Delta^*$.
- Comprehensive & systematic PWA to extract $Y^*$ defined by poles of scattering amplitudes has only recently been made:
  - Kent State University (KSU) group (2013, “KSU parametrization” of S-matrix)
  - Our group (2014-, dynamical approach)

What we have done so far

- Formulation of DCC approach for $S = -1$ sector
  - contains $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$, $\pi\pi\Lambda(\pi\Sigma^*)$, $\pi\bar{K}N(\bar{K}^*N)$ channels

- Comprehensive analysis of all available data of $K^-p \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$ up to $W = 2.1$ GeV. [HK, Nakamura, Lee, Sato, PRC90(2014)065204]
  - Successfully determined the partial-wave amplitudes for S, P, D, and F waves !!

- Extraction of $\Lambda^*$ and $\Sigma^*$ resonance parameters defined by poles of scattering amplitudes. [HK, Nakamura, Lee, Sato, in preparation]
The K⁻p reaction data are far from “complete”!!

→ Need help of hadron beam facilities!!
Results of the fits

HK, Nakamura, Lee, Sato, PRC90(2014)065204

K^- p → MB total cross sections

“Incompleteness” of the current database allows us to have two parameter sets that give similar quality of the fit.
Results of the fits

$K^- p \rightarrow K^- p$ scattering

$\frac{d\sigma}{d\Omega} (1464 < W < 1831 \text{ MeV})$

$\frac{d\sigma}{d\Omega} (1832 < W < 2100 \text{ MeV})$

Red: Model A  Blue: Model B

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N$ scattering amplitudes

Red: Model A  
Blue: Model B  
Circles: KSU single-energy solution  
[PRC88(2013)035204]

$L_{1,2J}$ : $L = S, P, .. ; I =$ isospin; $J =$ Total angular mom.

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Predicted spin-rotation angle $\beta$

## NOTE:
$\beta$ is modulo $2\pi$

**Currently no data for spin-rotation angle $\beta**

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Analysis dependence is clearly seen!!

Measurement of $\beta$ will give strong constraints on $\gamma^*$ spectrum!!

Red: Model A
Blue: Model B
Black: KSU

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

## NOTE:
Comparison of $\Lambda^*$ spectrum between multichannel analyses

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

**JP(L_{12j})**

```
1/2^+ (P_{01})
3/2^+ (P_{03})
5/2^+ (F_{05})
7/2^+ (F_{07})
```

**“$\Lambda$” resonance (I=0)**


HK, Nakamura, Lee, Sato, in preparation
Comparison of $\Lambda^*$ spectrum between multichannel analyses

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

$$J^P(L_{12J}) \quad \text{“$\Lambda$” resonance (I=0)}$$

- $1/2^+ (P_{01})$
- $3/2^+ (P_{03})$
- $5/2^+ (F_{05})$
- $7/2^+ (F_{07})$

$M_R$ : (resonance pole mass (complex))

-2Im($M_R$) (“total width”)

$R(MR)$


HK, Nakamura, Lee, Sato, in preparation

PRELIMINARY
Comparison of Λ* spectrum between multichannel analyses

HK, Nakamura, Lee, Sato, in preparation

### Here only Y*s above KN threshold are presented.

#### J^P(L_{12j}) "Λ" resonance (I=0)

- **1/2^+ (P_{01})**
- **3/2^+ (P_{03})**
- **5/2^+ (F_{05})**
- **7/2^+ (F_{07})**

- **1/2^- (S_{01})**
- **3/2^- (D_{03})**


-2Im(M_R) ("total width")

M_R: (resonance pole mass)

**Re(M_R)**

**K^- p → η Λ**

Sharp peak near threshold require the existence of Λ(1/2-) resonance.

**π^- p → η n**

**N^*(1535)1/2^-**

π^- p → η n

N*(1535)1/2-

Comparison of $\Lambda^*$ spectrum between multichannel analyses

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

$\Lambda^*$ resonance ($l=0$)

<table>
<thead>
<tr>
<th>$J^P(L_{12j})$</th>
<th>“$\Lambda$” resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/2^+ (P_{01})$</td>
<td>Red: Model A</td>
</tr>
<tr>
<td>$3/2^+ (P_{03})$</td>
<td>Blue: Model B</td>
</tr>
<tr>
<td>$5/2^+ (F_{05})$</td>
<td>Green: KSU</td>
</tr>
<tr>
<td>$7/2^+ (F_{07})$</td>
<td>Black: PDG</td>
</tr>
</tbody>
</table>

$M_R$ : (resonance pole mass)

-2Im($M_R$) ("total width")


HK, Nakamura, Lee, Sato, in preparation
Comparison of $\Lambda^*$ spectrum between multichannel analyses

HK, Nakamura, Lee, Sato, in preparation

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

**$J^P(L_{123})$**

- $1/2^+ (P_0^1)$
- $3/2^+ (P_0^3)$
- $5/2^+ (F_0^5)$
- $7/2^+ (F_0^7)$

- $1/2^- (S_0^1)$

**“$\Lambda$” resonance ($I=0$)**

- $1671-15$ MeV

- $-2\text{Im}(M_R)$
  - “total width”

$M_R$ : (resonance pole mass (complex))

**Model A**

- Full $S01$

**Model B**

- Full $S01$

Comes from P03 resonance

**P03 resonance just above the $\eta\Lambda$ threshold**

\[ \frac{d\sigma}{d\Omega} \text{ of } K^- p \rightarrow \eta\Lambda @ W=1672 \text{ MeV (just 8 MeV above the threshold)} \]

- Even close to the threshold, the data show a clear angular dependence.

**Model A**

(S01 wave ~99%)

- Concave-up behavior not reproduced.

**Model B**

(S01 wave ~60%, P03 wave ~40%)

- Narrow P03 resonance responsible for the angular dependence !!
P03 resonance just above the ηΛ threshold

Even close to the threshold, the data show a clear angular dependence.

- Concave-up behavior not reproduced.
- Narrow P03 resonance responsible for the angular dependence!!
P03 resonance just above the $\eta\Lambda$ threshold

$\text{d}\sigma/\text{d}\Omega$ of $K^- p \rightarrow \eta\Lambda$ @ $W = 1672$ MeV (just 8 MeV above the threshold)

- Even close to the threshold, the data show a clear angular dependence.

Model A
(S01 wave ~99%)

- Concave-up behavior not reproduced.

Model B
(S01 wave ~60%, P03 wave ~40%)

- Narrow P03 resonance responsible for the angular dependence!!

HK, Nakamura, Sato, in preparation
Summary & ongoing/future works

**Summary**

- Comprehensive PWA to extract properties of light-quark baryons ($N^*$, $\Delta^*$, $\Lambda^*$, $\Sigma^*$) within Dynamical Coupled-Channels (DCC) approach.

- Visible analysis dependence in extracted resonance spectrum.
  - needs more extensive meson production data (including polarization observables) from electron, photon, and hadron beam facilities.

**Ongoing/future works**

- N-N* e.m. transition form factors to high Q2

- High-mass $N^*$ and $\Delta^*$ spectroscopy (extends channel space, inclusion of $\pi\pi N$ data)

- DCC approach to deuteron target reactions
  - Helicity amplitudes for $\gamma$-neutron $\to N^*$ (need for isospin separation)
  - $Y^*$ spectroscopy below $\bar{K}N$ threshold with $K^-d$ reactions (J-PARC E31)

- Applications to neutrino-induced reactions (input for neutrino-oscillation experiments)
  - Collaboration@J-PARC Branch of KEK Theory Center
    (http://j-parc-th.kek.jp/html/English/e-index.html)

- Applications to hypernuclei & kaonic nuclei productions
Back up
Comparison of $\Sigma^*$ spectrum between multichannel analyses

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

- $\Sigma$ resonance (I=1)
  
<table>
<thead>
<tr>
<th>$J^P(L_{12\ell})$</th>
<th>&quot;$\Sigma$&quot; resonance (I=1)</th>
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<td>$1/2^+ (P_{11})$</td>
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- $-2\text{Im}(M_R)$ ("total width")
  
  $M_R$ : Resonance pole mass (complex)

Comparison of $\Sigma^*$ spectrum between multichannel analyses

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

$J^P(L_{12j})$  

"$\Sigma$" resonance ($I=1$)

- $1/2^+ (P_{11})$
- $3/2^+ (P_{13})$
- $5/2^+ (F_{15})$
- $7/2^+ (F_{17})$

$M_R$ : Resonance pole mass (complex)

$-2\text{Im}(M_R)$ ("total width")

Comparison of $\Sigma^*$ spectrum between multichannel analyses

### Here only $Y^*$s above $\bar{K}N$ threshold are presented.

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<td></td>
<td>$7/2^+ (F_{17})$</td>
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-2$\text{Im}(M_R)$ (“total width”)

$M_R$ : Resonance pole mass (complex)

Low-lying $\Sigma^*$ resonances (PDG)

- $\Sigma(1193)$  $1/2^+$  ****
- $\Sigma(1385)$  $3/2^+$  ****
- $\Sigma(1480)$  *
- $\Sigma(1560)$  **
- $\Sigma(1580)$  $3/2^-$  *
- $\Sigma(1620)$  $1/2^-$  **
- $\Sigma(1660)$  $1/2^+$  ****
- $\Sigma(1670)$  $3/2^-$  ****

Extending analysis of N* production within ANL-Osaka DCC approach

\[ \pi^+ p \rightarrow \omega n \text{ DCS} \]

\[ \gamma p \rightarrow \omega p \text{ DCS} \]

Very preliminary

Combined analysis including \( \omega N \) data is in progress!!

Very preliminary
How we study the region below the $\bar{K}N$ threshold?

E.g.) $\gamma p \to K^+\pi\Sigma$ @CLAS

At the CLAS energy, many production processes contribute and sizably affect mass distributions as backgrounds.

Forward $p(\pi, K^*)X$ reactions with high-momentum pion beam (⇒ J-PARC E50)

- For forward $K^*$ (small $t$), the processes are dominated by diffractive $t$-channel exchange processes.
- We DO have fully unitarized $\bar{K}N \to MB$ and $K^*N \to MB$ half off-shell amplitudes !!
- 12 GeV JLab can do a similar measurement by replacing incident $\pi$ by high-energy photon.
- Useful also for determining low-lying $\Sigma^*$ resonances

Nakamura, Jido, PTEP(2014)023D01

Large model dependence from complicated production processes.

⇒ Makes unambiguous determination of $\Lambda(1405)$ difficult.

Low-lying $\Sigma^*$ resonances (PDG)

<table>
<thead>
<tr>
<th>Mass</th>
<th>Spin/Parity</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma(1193)$</td>
<td>1/2+</td>
<td>****</td>
</tr>
<tr>
<td>$\Sigma(1385)$</td>
<td>3/2+</td>
<td>****</td>
</tr>
<tr>
<td>$\Sigma(1480)$</td>
<td>*</td>
<td></td>
</tr>
<tr>
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<td>**</td>
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<td>$\Sigma(1580)$</td>
<td>3/2−</td>
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</tr>
<tr>
<td>$\Sigma(1620)$</td>
<td>1/2−</td>
<td>**</td>
</tr>
<tr>
<td>$\Sigma(1660)$</td>
<td>1/2+</td>
<td>****</td>
</tr>
<tr>
<td>$\Sigma(1670)$</td>
<td>3/2−</td>
<td>****</td>
</tr>
</tbody>
</table>

?
Branching ratios

HK, Nakamura, Lee, Sato, in preparation

Model A

PRELIMINARY

Branching ratio (%)
Branching ratios

Model B for Λ*

Resonances producing sharp peak in the K-p → ηΛ total cross section near the threshold

Large branching ratio to ηΛ !!

HK, Nakamura, Lee, Sato, in preparation
Reliable neutrino reaction model is necessary for **precise** determination of neutrino parameters from future neutrino-oscillation experiments (leptonic CP phase, neutrino mass hierarchy…).

Relevant kinematical region extends over **Quasi elastic, Resonance, and DIS regions.**

Collaboration@J-PARC Branch of KEK Theory Center [http://j-parc-th.kek.jp/html/English/e-index.html]

Y. Hayato (ICRR, U. of Tokyo), M. Hirai (Nippon Inst. Tech.)
H. Kamano (RCNP, Osaka U.), S. Kumano (KEK)
S. Nakamura (Osaka U.), K. Saito (Tokyo U. of Sci.)
M. Sakuda (Okayama U.), T. Sato (Osaka U.)

[**arXiv:1303.6032**]

**Talk by S. Nakamura**
27(Wed) Parallel-A:27-1
Application to neutrino-induced reactions

The **first-time** full coupled-channels calculation of $\nu$-nucleon reactions **beyond the $\Delta(1232)$ region**!!

- Single pion production:
  - $\nu_\mu p \rightarrow \mu^+ \pi^- p$
  - $\nu_\mu n \rightarrow \mu^+ \pi^0 p$
  - $\nu_\mu n \rightarrow \mu^+ \pi^- n$

- Double pion production:
  - $\nu_\mu p \rightarrow \mu^+ \pi^- \pi^0 p$
  - $\nu_\mu p \rightarrow \mu^+ \pi^+ \pi^- n$
  - $\nu_\mu n \rightarrow \mu^+ \pi^+ \pi^- p$

##NOTE: $Q^2$ dependence of all $N-N^*$ axial transition form factors are currently fixed with that of $N-\Delta(1232)$ transition.

## $\eta N$, $K\Lambda$, $K\Sigma$ productions can also be calculated.

Nakamura, HK, Sato, in preparation
Light-quark baryon ($N^*$, $\Delta^*$, $\Lambda^*$, $\Sigma^*$) spectroscopy:
Physics of broad & overlapping resonances

- Width: $O(10^1-10^2)$ MeV.
- Resonances are highly overlapping in energy except $\Delta(1232)$ and $\Lambda(1520)$
- To reliably extract baryon resonances, one must do comprehensive PWA of meson production reactions:
  - Taking account of various final states simultaneously.
  - Extending over the wide energy region.
- Analysis with a theoretical framework satisfying multichannel unitarity is essential.
- Employ a Dynamical Coupled-Channels (DCC) approach for meson production reactions
Why DCC approach??

- Given the lack of “complete” data, theoretical guidance as taken within DCC approaches (introducing model Hamiltonian etc.) will be effective for reducing experimental uncertainties in determining partial wave amplitude and extracting resonance parameters.

- If one wants to explore and understand the *physics* behind hadron resonances (dynamical origin and internal structure, etc.), one *needs a model* that appropriately describes the dynamics of reaction processes.

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Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato PRL104 065203 (2010)

Dynamical coupled-channels (DCC) model for Y* production reactions

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates)

Exchange potentials

Bare Y* states

\[
V_{a,b} = v_{a,b} + \sum_{Y^*} \frac{\Gamma_{Y^*,a}^{\dagger} \Gamma_{Y^*,b} Y^*}{E - M_{Y^*}}
\]

Exchange potentials

bare Y* states
Contribution of narrow P03 resonance to amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Extracted $\bar{K}N \to \pi\Sigma$ amplitudes

Extracted $\bar{K}N \to \eta\Lambda$ amplitudes

Red: Model A
Blue: Model B
Results of the fits

**K^- p \rightarrow K^0 n reaction**

\[ \frac{d\sigma}{d\Omega} (1466 < W < 1796 \text{ MeV}) \]

\[ \frac{d\sigma}{d\Omega} (1804 < W < 1992 \text{ MeV}) \]

Red: Model A  Blue: Model B

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Results of the fits

\( \frac{d\sigma}{d\Omega} \)

\[ \text{K}^{-}\text{p} \rightarrow \pi^{-}\Sigma^{+} \text{reaction} \]

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A Blue: Model B
Results of the fits

\[ \frac{d\sigma}{d\Omega} \]

**K^- p \rightarrow \pi^0 \Sigma^0 reaction**

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A Blue: Model B
Results of the fits

$K^- p \rightarrow \pi^+ \Sigma^-$ reaction

Red: Model A  Blue: Model B

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Results of the fits

$K^- p \rightarrow \pi^0 \Lambda$ reaction

Red: Model A  Blue: Model B

$\frac{d\sigma}{d\Omega}$ (1536 < $W$ < 1870 MeV)

$\frac{d\sigma}{d\Omega}$ (1875 < $W$ < 2088 MeV)

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Results of the fits

$K^- p \rightarrow \pi^0 \Lambda$ reaction (cont’d)

Red: Model A  Blue: Model B
Results of the fits

$K^- p \to \eta \Lambda$ reaction

$K^- p \to K^0 \Xi^0$ reaction

$K^- p \to K^+ \Xi^-$ reaction

Red: Model A  Blue: Model B
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \to \pi\Sigma$ amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1\,2j} : L = S, P, \ldots ; I = \text{isospin}; J = \text{Total angular mom.}$

Red : Model A
Blue: Model B
Circles: KSU single-energy solution
[PRC88(2013)035204]
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \rightarrow \pi\Lambda$ amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1,2j}$ : $L = S, P, \ldots$ ; $I = \text{isospin}$; $J = \text{Total angular mom.}$

Sizable analysis dependence seen in $S_{11}$ etc., even though the three analyses reproduce the available data equally well.
Comparison of extracted partial-wave amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1,2j}$ : $L = S, P, \ldots$ ; $I =$ isospin; $J =$ Total angular mom.

Red : Model A
Blue: Model B
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \rightarrow K\Xi$ amplitudes

Red: Model A
Blue: Model B

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1,2j}$ : $L = S,P,..$ ; $I$ = isospin; $J$ = Total angular mom.
### Scattering length and effective range

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th></th>
<th>Model B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I = 0$</td>
<td>$I = 1$</td>
<td>$I = 0$</td>
<td>$I = 1$</td>
</tr>
<tr>
<td>$a_{KN}$ (fm)</td>
<td>$-1.37 + i0.67$</td>
<td>$0.07 + i0.81$</td>
<td>$-1.62 + i1.02$</td>
<td>$0.33 + i0.49$</td>
</tr>
<tr>
<td>$a_{\eta\Lambda}$ (fm)</td>
<td>$1.35 + i0.36$</td>
<td>-</td>
<td>$0.97 + i0.51$</td>
<td>-</td>
</tr>
<tr>
<td>$a_{K\Xi}$ (fm)</td>
<td>$-0.81 + i0.14$</td>
<td>$-0.68 + i0.09$</td>
<td>$-0.89 + i0.13$</td>
<td>$-0.83 + i0.03$</td>
</tr>
<tr>
<td>$r_{KN}$ (fm)</td>
<td>$0.67 - i0.25$</td>
<td>$1.01 - i0.20$</td>
<td>$0.74 - i0.25$</td>
<td>$-1.03 + i0.19$</td>
</tr>
<tr>
<td>$r_{\eta\Lambda}$ (fm)</td>
<td>$-5.67 - i2.24$</td>
<td>-</td>
<td>$-5.82 - i3.32$</td>
<td>-</td>
</tr>
<tr>
<td>$r_{K\Xi}$ (fm)</td>
<td>$-0.01 - i0.33$</td>
<td>$-0.42 - i0.49$</td>
<td>$0.13 - i0.20$</td>
<td>$-0.22 - i0.11$</td>
</tr>
</tbody>
</table>

$a_{K-p} = -0.65 + i0.74$ fm (Model A)

$a_{K-p} = -0.65 + i0.76$ fm (Model B)
S-wave contributions in the threshold region

$K^- p \rightarrow MB$ total cross sections

Red: Model A
Blue: Model B

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