Modern dynamical coupled-channels calculations for extracting and understanding the nucleon spectrum

Hiroyuki Kamano
(KEK)
PART I:
Background & motivation for spectroscopic study of $\text{N}^*$ & $\Delta^*$ resonances

PART II:
Recent results from ANL-Osaka Dynamical Coupled-Channels (DCC) analysis
PART I
Background & motivation for spectroscopic study of $N^*$ & $\Delta^*$ resonances
Behavior of the $\pi^+ p$ & $\pi^- p$ cross sections implies the existence of a new baryon with isospin 3/2!!
# Introduction: $N^*$ & $\Delta^*$ spectroscopy

<table>
<thead>
<tr>
<th>$N^*$</th>
<th>$\Delta^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle</strong></td>
<td><strong>$J^P$</strong></td>
</tr>
<tr>
<td>$N$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$N(1440)$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$N(1520)$</td>
<td>3/2$^-$</td>
</tr>
<tr>
<td>$N(1535)$</td>
<td>1/2$^-$</td>
</tr>
<tr>
<td>$N(1650)$</td>
<td>1/2$^-$</td>
</tr>
<tr>
<td>$N(1675)$</td>
<td>5/2$^-$</td>
</tr>
<tr>
<td>$N(1680)$</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>$N(1700)$</td>
<td>3/2$^-$</td>
</tr>
<tr>
<td>$N(1710)$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$N(1720)$</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td>$N(1860)$</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>$N(1875)$</td>
<td>3/2$^-$</td>
</tr>
<tr>
<td>$N(1880)$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$N(1895)$</td>
<td>1/2$^-$</td>
</tr>
<tr>
<td>$N(1900)$</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td>$N(1990)$</td>
<td>7/2$^+$</td>
</tr>
<tr>
<td>$N(2000)$</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>$N(2040)$</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td>$N(2060)$</td>
<td>5/2$^-$</td>
</tr>
<tr>
<td>$N(2100)$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$N(2120)$</td>
<td>3/2$^-$</td>
</tr>
<tr>
<td>$N(2190)$</td>
<td>7/2$^-$</td>
</tr>
<tr>
<td>$N(2220)$</td>
<td>9/2$^+$</td>
</tr>
<tr>
<td>$N(2250)$</td>
<td>9/2$^-$</td>
</tr>
<tr>
<td>$N(2300)$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$N(2570)$</td>
<td>5/2$^-$</td>
</tr>
<tr>
<td>$N(2600)$</td>
<td>11/2$^-$</td>
</tr>
<tr>
<td>$N(2700)$</td>
<td>13/2$^+$</td>
</tr>
</tbody>
</table>

**PDG(2015):**

[http://pdg.lbl.gov](http://pdg.lbl.gov)
**Introduction: N* & Δ* spectroscopy**

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J^P$</th>
<th>overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>$1/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>(1440) $N$</td>
<td>$1/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>(1520) $N$</td>
<td>$3/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>(1535) $N$</td>
<td>$1/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>(1650) $N$</td>
<td>$1/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>(1675) $N$</td>
<td>$5/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>(1680) $N$</td>
<td>$5/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>(1700) $N$</td>
<td>$3/2^-$</td>
<td>***</td>
</tr>
<tr>
<td>(1710) $N$</td>
<td>$1/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>(1720) $N$</td>
<td>$3/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>(1860) $N$</td>
<td>$5/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>(1875) $N$</td>
<td>$3/2^-$</td>
<td>***</td>
</tr>
<tr>
<td>(1880) $N$</td>
<td>$1/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>(1895) $N$</td>
<td>$1/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>(1900) $N$</td>
<td>$3/2^+$</td>
<td>***</td>
</tr>
<tr>
<td>(1990) $N$</td>
<td>$7/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>(2000) $N$</td>
<td>$5/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>(2040) $N$</td>
<td>$3/2^+$</td>
<td>*</td>
</tr>
<tr>
<td>(2060) $N$</td>
<td>$5/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>(2100) $N$</td>
<td>$1/2^+$</td>
<td>*</td>
</tr>
<tr>
<td>(2120) $N$</td>
<td>$3/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>(2190) $N$</td>
<td>$7/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>(2220) $N$</td>
<td>$9/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>(2250) $N$</td>
<td>$9/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>(2300) $N$</td>
<td>$1/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>(2570) $N$</td>
<td>$5/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>(2600) $N$</td>
<td>$1/2^-$</td>
<td>***</td>
</tr>
<tr>
<td>(2700) $N$</td>
<td>$13/2^+$</td>
<td>**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J^P$</th>
<th>overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Δ(1232)$</td>
<td>$3/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>$Δ(1600)$</td>
<td>$3/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(1620)$</td>
<td>$1/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(1700)$</td>
<td>$3/2^-$</td>
<td>****</td>
</tr>
<tr>
<td>$Δ(1750)$</td>
<td>$1/2^+$</td>
<td>*</td>
</tr>
<tr>
<td>$Δ(1900)$</td>
<td>$1/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(1905)$</td>
<td>$5/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>$Δ(1910)$</td>
<td>$1/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>$Δ(1920)$</td>
<td>$3/2^+$</td>
<td>***</td>
</tr>
<tr>
<td>$Δ(1930)$</td>
<td>$5/2^-$</td>
<td>***</td>
</tr>
<tr>
<td>$Δ(1940)$</td>
<td>$3/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(1950)$</td>
<td>$7/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>$Δ(2000)$</td>
<td>$5/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(2150)$</td>
<td>$1/2^-$</td>
<td>*</td>
</tr>
<tr>
<td>$Δ(2200)$</td>
<td>$7/2^-$</td>
<td>*</td>
</tr>
<tr>
<td>$Δ(2300)$</td>
<td>$9/2^+$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(2350)$</td>
<td>$5/2^-$</td>
<td>*</td>
</tr>
<tr>
<td>$Δ(2390)$</td>
<td>$7/2^+$</td>
<td>*</td>
</tr>
<tr>
<td>$Δ(2400)$</td>
<td>$9/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(2420)$</td>
<td>$11/2^+$</td>
<td>****</td>
</tr>
<tr>
<td>$Δ(2750)$</td>
<td>$13/2^-$</td>
<td>**</td>
</tr>
<tr>
<td>$Δ(2950)$</td>
<td>$15/2^+$</td>
<td>**</td>
</tr>
</tbody>
</table>

All of these studies essentially agree on the existence and (most) properties of the 4-star states. For the 3-star and lower states, however, even a statement of existence is problematic.

— Arndt, Briscoe, Strakovsky, Workman PRC74(2006)045205

Introduction: $N^*$ & $\Delta^*$ spectroscopy


$N^*$ & $\Delta^*$ spectroscopy remains as central issue in the hadron physics!!

- Mass, width, spin, parity ...?
- quark-gluon structure (form factors)?
- How produced in reaction processes?
  ...

All of these studies essentially agree on the existence and (most) properties of the 4-star states. For the 3-star and lower states, however, even a statement of existence is problematic.

—— Arndt, Briscoe, Strakovsky, Workman PRC74(2006)045205
Various static hadron models have been proposed to calculate hadron spectrum and form factors.

- Constituent quark models, solitron models, Dyson-Schwinger Eq. approaches,
- Excited hadrons are treated as stable particles.

Various *static* hadron models have been proposed to calculate hadron spectrum and form factors.

- Constituent quark models, soliton models, Dyson-Schwinger Eq. approaches,…
- Excited hadrons are treated as *stable* particles.

In reality, excited hadrons are “unstable” and can exist only as resonance states in hadron reactions.
Static hadron models and reaction dynamics

✓ Various static hadron models have been proposed to calculate hadron spectrum and form factors.

- Constituent quark models, soliton models, Dyson-Schwinger Eq. approaches,...
- Excited hadrons are treated as stable particles.

✓ In reality, excited hadrons are “unstable” and can exist only as resonance states in hadron reactions.

What is the role of reaction dynamics in interpreting the hadron spectrum, structures, and dynamical origins??
Light-quark hadron spectroscopy:
Physics of broad & overlapping resonances

- Width: a few hundred MeV.
- Resonances are highly overlapping in energy except $\Delta(1232)$. 
Light-quark hadron spectroscopy: Physics of broad & overlapping resonances

- Width: a few hundred MeV.
- Resonances are highly overlapping in energy except $\Delta(1232)$. 

\[
\Delta (1232)
\]
Light-quark hadron spectroscopy:
Physics of broad & overlapping resonances

- Width: a few hundred MeV.
- Resonances are highly overlapping in energy except $\Delta(1232)$. 

$N^* : 1440, 1520, 1535, 1650, 1675, 1680, ...$

$\Delta : 1600, 1620, 1700, 1750, 1900, ...$
Light-quark hadron spectroscopy: Physics of broad & overlapping resonances

- $\Delta(1232)$:
  - Width: a few hundred MeV.
  - Resonances are highly overlapping in energy except $\Delta(1232)$.

- $N^*$: 1440, 1520, 1535, 1650, 1675, 1680, ...
- $\Delta$: 1600, 1620, 1700, 1750, 1900, ...

- Resonances width: $\sim$10 keV to tens of MeV
- Each resonance peak is clearly separated.

$R = \sigma(e^-e^+ \rightarrow \text{hadrons})/\sigma(e^-e^+ \rightarrow \mu^-\mu^+)$
Light-quark hadron spectroscopy: Physics of broad & overlapping resonances

- $\Delta (1232)$ width: a few hundred MeV.
- Resonances are highly overlapping in energy except $\Delta (1232)$.
- $N^*$: 1440, 1520, 1535, 1650, 1675, 1680, ...
- $\Delta$: 1600, 1620, 1700, 1750, 1900, ...
- Width: $\approx$10 keV to tens of MeV
- Each resonance peak is clearly separated.

Cooperative efforts between experiments and theoretical analyses are crucial for the light-quark baryon spectroscopy!!!
Cooperative efforts between experiments and theoretical analyses

Experiments

E.g.) Meson photoproductions

Since late 90s

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

Theoretical analyses with coupled-channels framework

ANL-Osaka
Argonne-Pittsburgh
Bonn-Gatchina
Carnegie-Mellon-Berkeley
Dubna-Mainz-Taipei
EBAC
Giessen
GWU/VPI
Juelich-Bonn
Karlsruhe-Helsinki
KSU
Zagreb
...

✓ Multichannel unitary condition:

\[ T_{ab}(E) - T_{ab}^+(E) = -2\pi i \sum_c T_{ac}^\dagger \delta(E - E_c) T_{cb}(E) \]
Why multichannel unitarity is so important??

\[ T_{ab}(E) - T_{ab}^\dagger(E) = -2\pi i \sum_c T_{ac}^\dagger \delta(E - E_c) T_{cb}(E) \]

1) Ensures **conservation of probabilities** in multichannel reaction processes

- **Key essential to**
  - **simultaneous analysis** of various inelastic reactions.
  - **increasing predictivity** of constructed reaction models

![Graph showing (exclusive) yp reaction total cross sections.](image)
Why multichannel unitarity is so important??

\[ T_{ab}(E) - T_{ab}^\dagger(E) = -2\pi i \sum_c T_{ac}^\dagger \delta(E - E_c) T_{cb}(E) \]

1) Ensures conservation of probabilities in multichannel reaction processes

Key essential to

- simultaneous analysis of various inelastic reactions.
- increasing predictivity of constructed reaction models

2) Defines proper analytic structure (branch points, cuts,…) of scattering amplitudes in the complex energy plane, as required by scattering theory

- Crucial for extracting resonances “correctly”, and avoiding \textit{WRONG} resonance signals!!
  [e.g., Ceci et al, PRC84(2011)015205]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{(exclusive) yp reaction total cross sections}
\end{figure}
Approaches for coupled-channels analysis

✓ Multichannel unitary condition:

\[ T_{ab}(E) - T_{ab}^\dagger(E) = -2\pi i \sum_c T_{ac}^\dagger \delta(E - E_c) T_{cb}(E) \]

✓ Heitler equation:

\[ T_{ab}(E) = K_{ab}(E) + \sum_c K_{ac}(E) [-i\pi \delta(E - E_c)] T_{cb}(E) \]

*K-matrix: must be hermitian for real E.*
Approaches for coupled-channels analysis

✓ Multichannel unitary condition:

\[ T_{ab}(E) - T_{ab}^\dagger(E) = -2\pi i \sum_c T_{ac}^\dagger \delta(E - E_c) T_{cb}(E) \]

✓ Heitler equation:

\[ T_{ab}(E) = K_{ab}(E) + \sum_c K_{ac}(E) \left[ -i\pi \delta(E - E_c) \right] T_{cb}(E) \]

➤ (on-shell) K-matrix approach:

\[ K_{ab}(E) \equiv (\text{Polynomials of } E) + (\text{Pole terms}) \]

Argonne-Pittsburgh, Bonn-Gatchina, Carnegie Mellon-Berkely, GWU/VPI, Karlsruhe-Helsinki, KSU, ...

✓ Heitler equation can be solved algebraically.

➤ Dynamical-model approach:

\[ K_{ab}(E) \equiv K_{ab}(\vec{p}_a, \vec{p}_b; E) = V_{ab}(\vec{p}_a, \vec{p}_b; E) + \sum_c \mathcal{P} \int d\vec{q} V_{ac}(\vec{p}_a, \vec{q}; E) \frac{1}{E - H_c^0 + i\varepsilon} K_{cb}(\vec{q}, \vec{p}_b; E) \]

off-shell rescattering effect

ANL-Osaka, Dubna-Mainz-Taipei, Juelich-Bonn, ...
### Why dynamical coupled-channels approach??

<table>
<thead>
<tr>
<th></th>
<th>(on-shell) K-matrix</th>
<th>Dynamical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Numerical cost</strong></td>
<td>Cheap</td>
<td>(Very) Expensive</td>
</tr>
<tr>
<td></td>
<td>- solve on-shell algebraic eq.</td>
<td>- solve off-shell integral eq.</td>
</tr>
<tr>
<td></td>
<td>(Analysis can be done quickly on PC.)</td>
<td>(Supercomputers are needed.)</td>
</tr>
<tr>
<td><strong>Data fitting</strong></td>
<td>Efficient</td>
<td>Not so efficient</td>
</tr>
<tr>
<td></td>
<td>- K(E) can be parametrized as one likes</td>
<td>- Form of ( V ) is severely constrained</td>
</tr>
<tr>
<td></td>
<td></td>
<td>by theoretical input (model Hamiltonian)</td>
</tr>
</tbody>
</table>
Why dynamical coupled-channels approach??

<table>
<thead>
<tr>
<th></th>
<th>(on-shell) K-matrix</th>
<th>Dynamical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Numerical cost</strong></td>
<td>Cheap</td>
<td>(Very) Expensive</td>
</tr>
<tr>
<td></td>
<td>- solve on-shell algebraic eq.</td>
<td>- solve off-shell integral eq.</td>
</tr>
<tr>
<td></td>
<td>(Analysis can be done quickly on PC.)</td>
<td>(Supercomputers are needed.)</td>
</tr>
<tr>
<td><strong>Data fitting</strong></td>
<td>Efficient</td>
<td>Not so efficient</td>
</tr>
<tr>
<td></td>
<td>- K(E) can be parametrized as one likes</td>
<td>- Form of V is severely constrained by theoretical input (model Hamiltonian)</td>
</tr>
</tbody>
</table>

To understand the **physics of reaction dynamics** behind formation, structure, etc. of hadron resonances, one needs:

- **Modeling reaction processes appropriately with a model Hamiltonian.** (not a simple “pole + polynomial” parametrization, etc.)

- **Solving proper quantum scattering equation (LS eq.)** in which off-shell rescattering effects are also appropriately contained.

This can be achieved only by using the dynamical-model approach !!
Dynamical origin of $P_{11} \, N^*$ resonances
(nontrivial feature of multichannel reaction dynamics)

Double-pole structure of the Roper resonance

Would be related to a baryon state in static hadron models excluding meson-baryon continuaums

Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato, PRL104 042302 (2010)
Dynamical origin of $P_{11} N^*$ resonances

(nontrivial feature of multichannel reaction dynamics)

Would be related to a baryon state in static hadron models excluding meson-baryon continuums

Double-pole structure of the Roper resonance

Corresponding to $N(1710)^{1/2+}$

Move of poles by "gradually" strengthening channel couplings

Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato, PRL104 042302 (2010)
PART II
Recent results from ANL-Osaka DCC analysis
Dynamical coupled-channels (DCC) model for meson production reactions

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

✓ Partial-wave (LSJ) amplitudes of a → b reaction:

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

Coupled-channels effect
Off-shell effect

✓ Reaction channels:

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

\[ \pi \pi N \]

✓ Transition Potentials:

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

Exchange potentials
Z-diagrams
Bare N* states
Partial-wave (LSJ) amplitudes of a $\rightarrow$ b reaction:

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

Coupled-channels effect

Off-shell effect

Meson-Baryon Green functions $G_{MB}$

$MB = \pi N, \eta N, K\Lambda, K\Sigma, \omega N$

Stable channels

$MB = \pi\Delta, \rho N, \sigma N$

Quasi 2-body channels


HK, Nakamura, Lee, Sato, PRC(2013)035209
Partial-wave (LSJ) amplitudes of a $\rightarrow$ b reaction:

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

Reaction channels:

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

Transition Potentials:

$$V_{a,b} = v_{a,b} + Z_{a,b} + \sum_{N^*} \frac{\Gamma_{N^*,a}^{\dagger} \Gamma_{N^*,b}}{E - M_{N^*}}$$

HK, Nakamura, Lee, Sato, PRC(2013)035209
Dynamical coupled-channels (DCC) model for meson production reactions

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

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

Exchange potentials  Z-diagrams  bare N* states
Dynamical coupled-channels (DCC) model for meson production reactions

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

Partial-wave (LSJ) amplitudes of $a \rightarrow b$ reaction:

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

Reaction channels:

$$a, b, c = (\gamma^{(*)} N^*)$$

Transition Potentials:

$$V_{a,b} = v_{a,b} + Z_{a,b} + \sum_{N^*} \frac{\Gamma_{N^*,a}^{\dagger} \Gamma_{N^*,b}}{E - M_{N^*}}$$

Would be related with hadron states of the static hadron models (quark models, DSE, etc.) excluding meson-baryon continuums.

Exchange potentials  Z-diagrams  bare $N^*$ states
Dynamical coupled-channels (DCC) model for meson production reactions

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

✓ Partial-wave (LSJ) amplitudes of a $\rightarrow$ b reaction:

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

Coupled-channels effect

Off-shell effect

✓ Reaction channels:

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

ππN

✓ Transition Potentials:

$$V_{a,b} = \nu_{a,b} + Z_{a,b} + \sum_{N^*} \frac{\Gamma^+_{N^*,a} \Gamma_{N^*,b}}{E - M_{N^*}}$$

Exchange potentials

Z-diagrams

Bare N* states
Strategy for N* and Δ* spectroscopy

1) Construct a model by making $\chi^2$-fit of the world data of meson production reactions.

- Latest published model (8-channel):

Made simultaneous analysis of
- $\pi N \rightarrow \pi N$ (SAID amp) ($W < 2.3$ GeV)
- $\pi p \rightarrow \eta N, K\Lambda, K\Sigma$ ($W < 2.1$ GeV)
- $\gamma p \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ ($W < 2.1$ GeV)
- $\gamma 'n' \rightarrow \pi N$ ($W < 2$ GeV)

~27,000 data points of both $d\sigma/d\Omega$ & spin-pol. obs.

Use supercomputers to accomplish coupled-channels analyses:
Strategy for N* and Δ* spectroscopy

1) Construct a model by making $\chi^2$-fit of the world data of meson production reactions.

Latest published model (8-channel):

Made simultaneous analysis of
- $\pi N \to \pi N$(SAID amp) ($W < 2.3$ GeV)
- $\pi p \to \eta N, K\Lambda, K\Sigma$ ($W < 2.1$ GeV)
- $\gamma p \to \pi N, \eta N, K\Lambda, K\Sigma$ ($W < 2.1$ GeV)
- $\gamma 'n' \to \pi N$ ($W < 2$ GeV)

$\Rightarrow$~27,000 data points of both $d\sigma/d\Omega$ & spin-pol. obs.

2) Search poles of scattering amplitudes by analytic continuation to a complex energy plane.

Pole position $\Rightarrow$ (complex) resonance mass
Residues $\Rightarrow$ coupling strengths between resonance and meson-baryon channel
1) Construct a model by making $\chi^2$-fit of the world data of meson production reactions.

- Latest published model (8-channel):

- Made simultaneous analysis of
  - $\pi p \rightarrow \eta N, K\Lambda, K\Sigma$ ($W < 2.1$ GeV)
  - $\gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ ($W < 2.1$ GeV)
  - $\gamma 'n' \rightarrow \pi N$ ($W < 2$ GeV)

- $\sim 27,000$ data points of both $d\sigma/d\Omega$ & spin-polar. obs.

2) Search poles of scattering amplitudes by analytic continuation to a complex energy plane.

3) Extract resonance parameters defined by poles.

**Mass spectrum**

**Partial decay widths**

**Region our model can cover**

- Use supercomputers to accomplish coupled-channels analyses:
  - NERSC
  - Argonne National Laboratory
ANL-Osaka DCC analysis

\[ \gamma p \rightarrow \pi^0 p \]

\[ \frac{d\sigma}{d\Omega} \text{ for } W < 2.1 \text{ GeV} \]

\[ \Sigma \text{ for } W < 2.1 \text{ GeV} \]


Red: Updated model [PRC94(2016)015201]
Blue: Original model [PRC88(2013)035209]
ANL-Osaka DCC analysis

γp → π⁰p
dσ/dΩ for W < 2.1 GeV

Σ for W < 2.1 GeV

Red: Updated model [PRC94(2016)015201]
Blue: Original model [PRC88(2013)035209]
Extracted $N^*$ & $\Delta^*$ mass spectrum (pole mass $M_R$)
Extracted $N^*$ & $\Delta^*$ mass spectrum (pole mass $M_R$)
Extracted $N^* \& \Delta^*$ mass spectrum (pole mass $M_R$)

- $N^* \& \Delta^*$ with $\text{Re}(M_R) < 1.7 \text{ GeV}$ have been established (with one exception).

![Graph showing mass spectrum with different models and data points indicating $N^* \& \Delta^*$ states.](graph.png)
Extracted $N^*$ & $\Delta^*$ mass spectrum (pole mass $M_R$)

- $\pi N \rightarrow \pi \pi N$ data would provide crucial information on establishing Roper-like state of $\Delta$!!

- J-PARC E45 experiment [Sako, Hicks et al.]

- $N^*$ & $\Delta^*$ with $\text{Re}(M_R) < 1.7 \text{ GeV}$ have been established (with one exception).
Electromagnetic transition form factors: quantitative understanding of $N^*$ & $\Delta^*$ structure

$\gamma(q^2 = -Q^2 <0)$

$Q^2$: corresponds to “resolution”

“dressed”-quark core obscured by dense meson clouds

How effective d.o.f.s of baryon constituents change with $Q^2$??

$Q^2$: small (low “resolution”)

$Q^2$: large (high “resolution”)

“Partons”
Role of reaction dynamics in form factors: Meson-cloud effect

Re\[G_M(Q^2)\] for $\gamma N \rightarrow \Delta (1232)$ M1 transition

N-N* e.m. transition form factor

virtual $\gamma$

$q^2 = -Q^2 < 0$

$Q^2$: corresponds to “resolution”

N, N*, $\Delta^*$

N-\Delta transition

$G_M^*/3G_D$

Full dressed

Bare

Meson cloud

Role of reaction dynamics in form factors: Meson-cloud effect

N-N* e.m. transition form factor

virtual $\gamma$

$q^2 = -Q^2 < 0$

$Q^2$: corresponds to “resolution”

N

N* $\Delta^*$

II

Bare

$\gamma$

Meson cloud

Most of the available static hadron models INDEED give $G_M(Q^2)$ close to the “Bare” form factor !!

Role of reaction dynamics in form factors: Meson-cloud effect

N-N* e.m. transition form factor

virtual $\gamma$

$q^2 = -Q^2 < 0$

$Q^2$: corresponds to “resolution”

N-N*, N*, $\Delta^*$

Meson cloud

“bare” state (core composed of “dressed” quarks)

$Q^2$ increases

Full dressed

Bare

Re[$G_M(Q^2)$] for $\gamma N \rightarrow \Delta (1232)$ M1 transition

Role of reaction dynamics in form factors: Meson-cloud effect

N-N\(^*\) e.m. transition form factor

virtual $\gamma \rightarrow q$  

$q^2 = -Q^2 < 0$

$Q^2$: corresponds to “resolution”

$N \rightarrow N^*\ Delta^*$

High $Q^2$ region ($5 < Q^2 < 12$ GeV\(^2\)) will be accessed by new measurements of $p(e,e'\pi)N$, $p(e,e'\pi\pi)N$, $p(e,e'K)Y$ at CLAS12@JLab (E12-09-003, E12-06-108A)

$G_M^*/3G_D$ vs $Q^2$ graph

Full dressed

Bare

“bare” state (core composed of “dressed” quarks)

meson cloud

Q\(^2\) increases
Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

- Meson electroproductions:

\[ e \rightarrow e' \gamma^* \rightarrow N \rightarrow N^*, \Delta^* \]

Database for 1π electroproduction@CLAS6
(Q^2 < 6 GeV^2)

(W,Q^2) region in the current analysis
(Q^2 < 6 GeV^2, W < 1.7 GeV)

(W,Q^2) region in the early analysis:
Julia-Diaz, HK, Lee, Matsuyama, Sato, Suzuki, PRC80(2009)025207

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

\[
\frac{d\sigma}{dE_e d\Omega_e d\Omega_{\pi^*}} = \Gamma \gamma \left[ \sigma_T + \epsilon \sigma_L + \sqrt{2\epsilon(1 + \epsilon)} \sigma_{LT} \cos \phi_{\pi^*} + \epsilon \sigma_{T\pi} \cos 2\phi_{\pi^*} + h_{e} \sqrt{2\epsilon(1 - \epsilon)} \sigma_{LT}, \sin \phi_{\pi^*} \right].
\]

\[\sigma_T + \epsilon \sigma_L \text{ for } ep \to e\pi^0p\]

Data for structure functions are obtained with the help of K. Joo and L. C. Smith.

\[\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos \theta_{\pi^*})\]
N → “1st P33(J^P=3/2^+) Δ” transition form factor A_{3/2}
[evaluated at Δ pole mass: M_R = 1210 –i 50 MeV]

- Current = πN, ππN, ηN, KΛ, KΣ; 2 bare states in P33
- JLMS = πN, ππN, ηN; 2 bare states in P33
- Sato-Lee = πN; 1 bare state in P33
Summary

✓ N* & Δ* spectroscopy as physics of broad & overlapping resonances

- Cooperative efforts between experiments and theoretical analyses with coupled-channels framework are indispensable to establishing the spectrum.

- Reaction dynamics is a crucial part of understanding the spectrum, dynamical origin, and structure, ... of N* & Δ*.

- Dynamical coupled-channels approach is a suitable one to study the role of reaction dynamics.
  - Multichannel reaction dynamics in the origin of P_{11} N* resonances.
  - Meson-cloud effect on the transition form factors.
Summary

✓ N* & Δ* spectroscopy as physics of broad & overlapping resonances

  ➢ Cooperative efforts between experiments and theoretical analyses with coupled-channels framework are indispensable to establishing the spectrum.

  ➢ Reaction dynamics is a crucial part of understanding the spectrum, dynamical origin, and structure, ... of N* & Δ*.

  ➢ Dynamical coupled-channels approach is a suitable one to study the role of reaction dynamics.

    ➢ Multichannel reaction dynamics in the origin of P_{11} N* resonances.
    ➢ Meson-cloud effect on the transition form factors.

✓ Major topics in N* & Δ* spectroscopy

  ➢ Establishing high-mass N* & Δ* resonances [Re(M_R) > 1.7 GeV]
    ➢ “(over-)complete” experiments for photoproduction reactions (CLAS6, ELSA, MAMI, ...)

  ➢ Determining Q^2 dependence of electromagnetic transition form factors for well-established low-lying N* & Δ* resonances.
    ➢ Measurements of electroproduction reactions over wide Q^2 range (CLAS6, CLAS12)
Summary

✓ N* & Δ* spectroscopy as physics of broad & overlapping resonances

- Cooperative efforts between experiments and theoretical analyses with coupled-channels framework are indispensable to establishing the spectrum.

- Reaction dynamics is a crucial part of understanding the spectrum, dynamical origin, and structure, ... of N* & Δ*.

- Dynamical coupled-channels approach is a suitable one to study the role of reaction dynamics.
  ➔ Multichannel reaction dynamics in the origin of P_{11} N* resonances.
  ➔ Meson-cloud effect on the transition form factors.

✓ Major topics in N* & Δ* spectroscopy

- Establishing high-mass N* & Δ* resonances [Re(M_R) > 1.7 GeV]
  ➔ “(over-)complete” experiments for photoproduction reactions (CLAS6, ELSA, MAMI,...)

- Determining Q^2 dependence of electromagnetic transition form factors for well-established low-lying N* & Δ* resonances.
  ➔ Measurements of electroproduction reactions over wide Q^2 range (CLAS6, CLAS12)

Electroproduction analysis & extension of our DCC model are underway !!
Back up
Applications of ANL-DCC approach

N* & Δ* spectroscopy
- Early analyses of πN & γN reactions:
  PRL104(2010)042302
- Latest analysis of πN & γN reactions:
- Electroproduction analysis & Form factor extraction:
  PRC80(2009)025207; 82(2010)045206

Λ* & Σ* spectroscopy
- Λ*, Σ* resonance extractions via analysis of Kp reactions:
  PRC90(2014)065204; 92(2015)025205

Meson spectroscopy
- Formulation of 3-body unitary model for decays of mesons:
  PRD84(2011)114019
- Application to γp → M*N → (3π)N:
  PRD86(2012)114012

Neutrino reactions
- Calculation in Q^2 = 0 limit:
  PRD86(2012)097503
- Full DCC-model calculation up to W = 2 GeV, Q^2 = 3 GeV^2:
  PRD92(2015)074024

ANL-Osaka DCC approach

Collaboration@J-PARC Branch,
KEK Theory Center [arXiv:1303.6032]
Substructure of N* & Δ*

“dressed”-quark core obscured by dense meson clouds

Meson clouds become small; “dressed”-quark core dominates

Q^2: small
(low “resolution”)

“constituent” quark

Running dressed quark mass

Q^2: large
(high “resolution”)

“current” quark

Will be accessed by CLAS12@JLab (E12-09-003, E12-06-108A)

http://www.ectstar.eu/node/1227

“Partons”

“dressed”-quark with “running” mass

Curves: a model based on Dyson-Schwinger equations (Landau gauge)

Points: Lattice QCD

e.g.) Cloet, Roberts, Prog.Part.Nucl.Phys.77(2014)1

Running dressed quark mass

Rapid acquisition of mass is effect of gluon cloud

m = 0 (Chiral limit)
m = 30 MeV
m = 70 MeV
Baryon resonances as poles of scattering amplitudes

PROPER definition of

✓ Hadron resonance masses (complex)  \(\Rightarrow\) Pole positions of scattering amplitudes in the lower-half of complex-W plane

✓ Transition amplitudes between resonance and scattering states  \(\Rightarrow\) ~ Residues\(^{1/2}\) at the pole

Extracting poles of amplitudes from analyzing reaction data is nothing but obtaining “exact” energy eigenvalues of QCD !!!
Baryon resonances as poles of scattering amplitudes

**PROPER definition of**

- **Hadron resonance masses** (complex) \(\rightarrow\) **Pole positions of scattering amplitudes** in the lower-half of complex-W plane
- **Transition amplitudes** between resonance and scattering states \(\rightarrow\) \(\sim\) **Residues}^{1/2} at the pole**

**Resonance theory based on Gamow vectors:**

[G. Gamow (1928), R. E. Peierls (1959), …]

“Quantum resonance state is an (complex-)energy eigenstate of the **FULL** Hamiltonian of the **underlying theory** under the Purely Outgoing Boundary Condition (POBC).”

**Energy eigenvalue** = **pole energy**

**Transition matrix elements** between resonance and scattering states \(\sim\) **Residues}^{1/2} at the pole**

Extracting poles of amplitudes from analyzing reaction data is nothing but obtaining “exact” energy eigenvalues of QCD !!!
Baryon resonances as poles of scattering amplitudes

PROPER definition of

✓ Hadron resonance masses (complex)

✓ Transition amplitudes between resonance and scattering states

Resonance theory based on Gamow vectors [G. Gamow (1928), R. E. Peierls]

“Quantum resonance state is an exact energy eigenstate of the FULL Hamiltonian of the underlying theory under the Purely Outgoing Boundary Condition.”

Energy eigenvalue

Transition matrix elements between resonance and scattering states

Residues$^{1/2}$ at the pole

Extracting poles of amplitudes from analyzing reaction data is nothing but obtaining “exact” energy eigenvalues of QCD !!!

There are attempts to link real energy spectrum of QCD in the finite volume to resonance pole masses.

Dudek et al, PRL113(2014)182001