Baryon Resonances in a Coupled Analysis of Meson and Photon induced Reactions

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Introduction: Baryon spectrum in experiment and theory

- above 1.8 GeV much more states are predicted than observed, “Missing resonance problem”

Lattice calculation (single hadron approximation):

- only about half of the states have **** or *** status
- PDG listing: major part of the information from \( \pi N \) elastic
  (Exception: BnGa multi-channel PWA)

\[ N^* \text{ spectrum in a relativistic quark model:} \]


⇒ large coupling to inelastic channels?
Experimental studies of hadronic reactions: *major progress in recent years*

**Photoproduction:** e.g. from JLab, ELSA, MAMI, GRAAL, SPring-8

- enlarged data base with high quality for different final states
- (double) polarization observables
  → alternative source of information besides $\pi N \rightarrow X$
  → towards a complete experiment: unambiguous determination of the amplitude (up to an overall phase)

**Electroproduction:** e.g. from JLab, MAMI, MIT/Bates

- electroproduction of $\pi N$, $\eta N$, $KY$, $\pi\pi N$
- access the $Q^2$ dependence of the amplitude, information on the internal structure of resonances
Complete Experiment


\[ \hat{M} = iF_1 \vec{\sigma} \cdot \vec{\epsilon} + F_2 \vec{\sigma} \cdot \hat{q} \vec{\sigma} \cdot (\hat{k} \times \vec{\epsilon}) + iF_3 \vec{\sigma} \cdot \hat{k} \hat{q} \cdot \vec{\epsilon} + iF_4 \vec{\sigma} \cdot \hat{q} \hat{q} \cdot \vec{\epsilon} \]

- Electroproduction: e.g. Berends, Donnachie, Weaver NPB4,1 (1967)

\[ \hat{M} = iF_1 \vec{\sigma} \cdot \vec{\epsilon} + F_2 \vec{\sigma} \cdot \hat{q} \vec{\sigma} \cdot (\hat{k} \times \vec{\epsilon}) + iF_3 \vec{\sigma} \cdot \hat{k} \hat{q} \cdot \vec{\epsilon} + iF_4 \vec{\sigma} \cdot \hat{q} \hat{q} \cdot \vec{\epsilon} + iF_5 \vec{\sigma} \hat{k} \cdot \vec{\epsilon} + iF_6 \vec{\sigma} \hat{q} \hat{k} \cdot \vec{\epsilon} \]

\[ F_i = F_i(W, \theta, Q^2), \text{ multipoles } E_{L \pm}, M_{L \pm}, L_{L \pm} \text{ (or } E_{L \pm}, M_{L \pm}, S_{L \pm}) \]

\[ \Rightarrow \] 16 polarization observables:
- asymmetries composed of beam, target and/or recoil polarization measurements

\[ \Rightarrow \text{Complete Experiment: unambiguous determination of the amplitude} \]

8 carefully selected observables Chiang and Tabakin, PRC 55, 2054 (1997)
- e.g. \{\sigma, \Sigma, T, P, E, G, C_x, C_z\}

\[ \hat{q}: \text{ meson} \]
\[ \hat{k} (\vec{\epsilon}): \text{ photon (polarization)} \]
Different analyses frameworks: a few examples

- **GWU/SAID approach**: PWA based on Chew-Mandelstam $K$-matrix parameterization

- **unitary isobar models**: unitary amplitudes + Breit-Wigner resonances
  - MAID, Yerevan/JLab, KSU

- **multi-channel $K$-matrix**: BnGa (mostly phenomenological Bgd, N/D approach), Gießen (microscopic Bgd)

- **dynamical coupled-channel (DCC)**: 3-dim scattering eq., off-shell intermediate states
  - ANL-Osaka (EBAC), Dubna-Mainz-Taipeh, Jülich-Bonn

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The Jülich-Bonn DCC approach
Dynamical coupled-channels (DCC): ** simultaneous analysis of different reactions **

The scattering equation in partial-wave basis

\[
\langle L'S'p'|T^{ij}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{ij}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''} \int_{0}^{\infty} dq \ q^2 \ \langle L'S'p'|V^{ij}_{\mu\gamma}|L''S''q\rangle \frac{1}{E - E_{\gamma}(q) + i\epsilon} \langle L''S''q|T^{ij}_{\gamma\nu}|LSp\rangle
\]

- potentials \( V \) constructed from effective \( \mathcal{L} \)
- \( s \)-channel diagrams: \( T^P \)
- genuine resonance states
- \( t \)- and \( u \)-channel: \( T^{NP} \)
- dynamical generation of poles
- partial waves strongly correlated
Dynamical coupled-channels (DCC): simultaneous analysis of different reactions

The scattering equation in partial-wave basis

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\]

- free parameters fitted to data:

**s-channel:** resonances \((T^P)\)

\[
m_{bare} + f_{\pi NN^*}
\]

**t- and u-channel exchange:** "background" \((T^{NP})\)

cut offs \(\Lambda\) in form factors \(\left( \frac{\Lambda^2 - m_{ex}^2}{\Lambda^2 + q^2} \right)^n\)

(couplings fixed from SU(3))
The Jülich-Bonn DCC approach

Resonance states: Poles in the $T$-matrix on the 2nd Riemann sheet

- pole position $E_0$ is the same in all channels
- residues → branching ratios

$\text{Re}(E_0) =$ “mass”, $-2\text{Im}(E_0) =$ “width”

- (2-body) unitarity and analyticity respected
- 3-body $\pi\pi N$ channel:
  - parameterized effectively as $\pi\Delta$, $\sigma N$, $\rho N$
  - $\pi N / \pi\pi$ subsystems fit the respective phase shifts
  $\downarrow$ branch points move into complex plane
Multipole amplitude

\[ M_{\mu \gamma}^{IJ} = V_{\mu \gamma}^{IJ} + \sum_{\kappa} T_{\mu \kappa}^{IJ} G_{\kappa} V_{\kappa \gamma}^{IJ} \]

(partial wave basis)

\[ m = \pi, \eta, B = N, \Delta \]

\( T_{\mu \kappa} \): Jülich hadronic \( T \)-matrix \quad \rightarrow \text{Watson’s theorem fulfilled by construction}

\( \rightarrow \text{analyticity of} \ T \): extraction of resonance parameters

Photoproduction potential: approximated by energy-dependent polynomials

\[ V_{\mu \gamma}(E, q) = \tilde{\gamma}_\mu^a (q) \frac{P_{NP}^{\mu}(E)}{m_N} \gamma_{\mu;i}^{a}(q) P_i^P(E) + \sum_i \gamma_{\mu;i}^{a}(q) P_i^P(E) \]

\( \tilde{\gamma}_\mu^a, \gamma_{\mu;i}^{a} \): hadronic vertices \rightarrow correct threshold behaviour, cancellation of singularity at \( E = m_i^b \)

\( \rightarrow \gamma_{\mu;i}^{a} \) affects pion- and photon-induced production of final state \( mB \)

\( i \): resonance number per multipole; \( \mu \): channels \( \pi N, \eta N, \pi \Delta, KY \)
Data analysis and fit results
Combined analysis of pion- and photon-induced reactions

Fit parameters:

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

$\Rightarrow 128$ free parameters
  - $11 N^*$ resonances $\times (1 \text{ } m_{\text{bare}} + \text{ couplings to } \pi N, \rho N, \eta N, \pi \Delta, K \Lambda, K \Sigma)$
  - $+ 10 \Delta$ resonances $\times (1 \text{ } m_{\text{bare}} + \text{ couplings to } \pi N, \rho N, \pi \Delta, K \Sigma)$

- $\gamma p \rightarrow \pi^0 p, \pi^+ n, \eta p, K^+ \Lambda$

$\Rightarrow \sim 500$ free parameters
  - couplings of the polynomials

- $\sim 40,000$ data points

calculations on the JURECA supercomputer: parallelization in energy ($\sim 300 - 400$ processes)
Preliminary: $K^+\Lambda$ photoproduction in the JüBo model
simultaneous fit of $\gamma p \rightarrow \pi^0 p$, $\pi^+ n$, $\eta p$, $K^+\Lambda$ and $\pi N \rightarrow \pi N$, $\eta N$, $K\Lambda$, $K\Sigma$

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

- **Differential cross section**

- **Recoil polarization**

- **Beam asymmetry**

- **Target asymmetry**


LL09: Lleres EPJA 39 (2009)
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$\gamma p \rightarrow K^+\Lambda$:

- $C_x$
  - BR07: Bradford PRC 75 (2007)
  - 1838 MeV
  - 2169 MeV

- $O_x$
  - LL09: Lleres EPJA 39 (2009)
  - 1649 MeV
  - 1883 MeV

- $C_z$
  - BR07: Bradford PRC 75 (2007)
  - 1987 MeV
  - 2169 MeV

- $O_z$
  - LL09: Lleres EPJA 39 (2009)
  - 1728 MeV
  - 1808 MeV
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Impact of new polarization data
Recent new data on $\gamma p \rightarrow \pi N$:

- $E, G, H, P, T$ in $\gamma p \rightarrow \pi^0 p$ from ELSA Thiel et al. PRL 109, 102001 (2012); Gottschall et al. PRL 112, 012003 (2014); Hartmann et al. PLB 748, 212 (2015); Thiel et al. arXiv:1604.02922
- $\Sigma$ in $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \pi^+ n$ from JLab Dugger et al. PRC 88, 065203 (2013) 89, 029901(E) (2014)
- $\Sigma$ in $\gamma p \rightarrow \pi^0 p$ from MAMI Hornidge et al. PRL 111, 062004 (2013)

⇒ included in the SAID, BnGa, JüBo fits

- compare multipoles before and after the inclusion of the new data
- conversion to a common solution?
The SAID, BnGa and JüBo approaches

All three approaches:

- coupled channel effects
- unitarity (2 body)
- amplitudes are analytic functions of the invariant mass

### SAID PWA

based on Chew-Mandelstam $K$-matrix

- $K$-matrix elements parameterized as energy-dependent polynomials
- resonance poles are dynamically generated (except for the $\Delta(1232)$)
- masses, width and hadronic couplings from fits to pion-induced $\pi N$ and $\eta N$ production

### Bonn-Gatchina (BnGa) PWA

Multi-channel PWA based on $K$-matrix (N/D)

- mostly phenomenological model
- resonances added by hand
- resonance parameters determined from large experimental data base:
  pion-, photon-induced reactions, 3-body final states

### Jülich-Bonn (JüBo) DCC model

based on a Lippmann-Schwinger equation formulated in TOPT

- hadronic potential from effective Lagrangians
- photoproduction parameterized by energy-dependent polynomials
- resonances as $s$-channel states (dynamical generation possible)
- resonance parameters determined from pion- and photon-induced data
Selected new data and predictions

Fig. 1. Selected data and the predictions from the four different PWAs: black solid line: BnGa2011-02, blue dashed: JüBo2015B, green dotted: MAID2007, red dash-dotted: SAID CM12. The predictions are based on fits which did not yet use these new data. The new data are shown for the beam asymmetry $\Xi$ for $\gamma p \rightarrow \Lambda n$ [81] (1st row), for the beam asymmetry $\Xi$ in the low-energy region [80] and at higher energies (2nd row) for $\gamma p \rightarrow \Lambda_0 p$, (2nd and 3rd row). The next three rows show $T$, $G$ [38,83], and $E$ [37,84] for $\gamma p \rightarrow \Lambda_0 p$. Note that the data from refs. [80] and [81] are included in the fits of JüBo2015 B and SAID CM12.

covers also KAON MAID [98]. Data on $\pi N$ and $\Phi p$ (and $K^+ \Psi$) are fitted independently.

Particle properties. The SAID and MAID PWA groups use photoproduction reactions to determine the dynamics of the reaction and to determine the helicity amplitudes of contributing resonances while $M_i$, $\Gamma_i$, and $|B R_N|^2$ are imposed from the fits to $\pi N$ elastic scattering and charge exchange reactions (SAID) or directly from the Review of Particle Properties, RPP, (MAID). The BnGa and JüBo groups use pion and photo-induced reactions and determine the properties of the contributing resonances in global fits to all included data.

New data. To study the impact of the new data from Bonn, JLab, and Mainz on the photoproduction multipoles, the PWA groups agreed to perform new fits incorporating the new data. In the fits called predictions below, the new data are shown for the beam asymmetry $\Xi$ for $\gamma p \rightarrow \Lambda n$ [81] (1st row), for the beam asymmetry $\Xi$ in the low-energy region [80] and at higher energies (2nd row) for $\gamma p \rightarrow \Lambda_0 p$, (2nd and 3rd row). The next three rows show $T$, $G$ [38,83], and $E$ [37,84] for $\gamma p \rightarrow \Lambda_0 p$. Note that the data from refs. [80] and [81] are included in the fits of JüBo2015 B and SAID CM12.


Predictions: black solid lines: BnGa, red dash-dotted: SAID, blue dashed: JüBo, green dotted: MAID
Fig. 2. The new fit results of the different PWAs in comparison with the new data: black solid line: BnGa, blue dashed: JüBo, red dash-dotted: SAID. New data are shown for the beam asymmetry $\Xi$ for $\gamma p \rightarrow \Lambda + n$ [81] (1st row), for the beam asymmetry $\Xi$ in the low-energy region [80] and at higher energies (2nd row) for $\gamma p \rightarrow \Lambda_0 p$, (2nd and 3rd row). The next three rows show $T$, $G$ [38,83], and $E$ [37,84] for $\gamma p \rightarrow \Lambda_0 p$. The BnGa fit did not yet use the data on the beam asymmetry $\Xi$ for $\gamma p \rightarrow \Lambda_0 p$ in the low-energy region [80]. Nevertheless, the new fit is fully consistent with the new data.

The $M_1^-$ multipole (fig. 3(c), (d)) drives the excitation of the $J^P = 1/2^+$ partial wave containing the Roper $N(1440)1/2^+$ resonance, the three-star $N(1710)1/2^+$ resonance, the one-star $\Sigma(1750)1/2^+$, and the four-star $\Sigma(1910)1/2^+$. The imaginary part of the $M_1^-$ multipole evidences clearly $N(1440)1/2^+$, the contributions from the higher-mass resonances are small. The new data lead to a small improvement of the consistency of the results for the imaginary part of the multipole. In the real part a significant improvement can be observed.


Fits: black solid lines: BnGa, red dash-dotted: SAID, blue dashed: JüBo
Comparison of multipoles before & after including the new data: Selected examples

black solid lines: BnGa, red dash-dotted: SAID, blue dashed: JüBo, green dotted: MAID
Consistency of the results

- Pairwise variances between two PWAs:

\[ \text{var}(1, 2) = \frac{1}{2} \sum_{i=1}^{16} (M_1(i) - M_2(i)) (M_1^*(i) - M_2^*(i)) \]

- beyond 1.7 GeV: BnGa, SAID, JüBo multipoles now in closer agreement
- 1.5 to 1.7 GeV:
  - BnGa agrees well with SAID and with JüBo
  - larger discrepancies between SAID and JüBo
Summary

- Progress in experimental and theoretical study of the baryon spectrum

- Jülich-Bonn model:
  - DCC approach that respects analyticity and (2 body) unitarity
  - simultaneous analysis of pion- and photon-induced reactions
  - preliminary results for $K^+ \Lambda$ photoproduction

- Impact of new polarization data for pion photoproduction from ELSA, CLAS, MAMI:
  - joint analysis of the BnGa, SAID and JüBo groups
  - comparison of the multipoles before and after the inclusion of the new data

→ agreement between the three analyses is improved!
Thank you for your attention!