Light quark baryons from photoproduction and electroproduction experiments

U. Thoma replacing J. Hartmann, Bonn

Contents:
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- Experimental Data
- Results (PWA)
- Summary
Baryon Spectroscopy

Aim: Good understanding of the spectrum and the properties of baryon resonances ↔ bound states of strong QCD

- What are the relevant degrees of freedom?
- Effective forces between them?

e.g.: or ?

Symmetric quark models:
→ many more resonances expected than observed yet

non-strange N*-resonances

U. Loering, B. Metsch, H. Petry et al. (2001)
relativistic quark model
Constituent quarks, confinement potential + residual interaction

\(|\vec{J}| = |\vec{L} + \vec{S}_{qqq}|\)

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Baryon Spectroscopy

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- What are the relevant degrees of freedom?
- Effective forces between them?

Symmetric quark models:
→ many more resonances expected than observed yet
   (certain configurations completely missing)

• Certain configurations not realised by QCD? Why?
• Experimentally not found yet
   (resonances might decouple from $\pi N$)
Baryon Spectroscopy

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- What are the relevant degrees of freedom?
- Effective forces between them?

\[ e.g.: \quad \text{or} \quad ? \]

Symmetric quark models:
- many more resonances expected than observed yet
  (certain configurations completely missing)
- Certain configurations not realised by QCD? Why?
- Experimentally not found yet
  (resonances might decouple from $\pi N$)

\[ \text{e.g.:} \quad \text{L}=1 \quad \text{L}^{\text{tot}}=1 \quad \ldots \text{seems to be missing} \]

Or does the quark model just use the wrong degrees of freedom?

↔ Mesons-Baryon degrees of freedom?

U. Thoma replacing J. Hartmann, Bonn: - Light quark baryons from photoproduction and electroproduction experiments
Excited baryons from Lattice QCD:

Exhibits the broad features expected from SU(6)⊗O(3)-symmetry

→ Counting of levels consistent with non-rel. quark model
→ no parity doubling

Of course there are also approximations made by lattice QCD (e.g. $m_\pi = 396$ MeV)
Baryon Spectroscopy

⇒ Good understanding of the spectrum and properties of baryon resonances

Experimentally:
Broad and strongly overlapping resonances

Important:
→ Investigation of different final states
→ Investigation of different production processes: $\pi N$, $\gamma N$, $\gamma^* N$, $\Psi$, $\Psi'$-decays, ...
→ Measurement of polarization observables (unambiguous PWA)

Recently: a lot of progress from photoproduction experiments:

CLAS (JLab), CBELSA/TAPS (ELSA), CBALL (MAMI), LEPS (Spring-8), ...
⇔ polarized beam, polarized target
Circularly polarized photons, longitudinally polarized target

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

PWAs:

SAID (SN11, CM12), MAID

BnGa (2011-2)

↔ describe the so far existing photoproduction data, but ...

large deviations → observed

Differences even at low energies where everything was thought to be well understood ...

⇒ Sensitivity on high mass resonances!


U. Thoma replacing J. Hartmann, Bonn: - Light quark baryons from photoproduction and electroproduction experiments
Circularly polarized photons, longitudinally polarized target:

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

(only every second bin shown)

\[ E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \]

PWAs predictions:

– MAID,
– SAID \textsuperscript{(CM12)},
– BnGa \textsuperscript{(2011.2)}

Fit:

– BnGa

Predictions (–, –, –):

⇒ Large deviations observed:

High sensitivity of the data on the contributing amplitudes

\[ \gamma p \rightarrow p\pi^0 \] - Impact of the new data on \( E, G, T, P, H \)

**Resulting multipoles - BnGa-PWA**

Re \( \pi^0p \) [mfm]  |  \( E_0^+ \)  |  \( M_1^- \)  |  \( E_1^+ \)  |  \( M_1^+ \)  |  \( E_2^- \)  |  \( M_2^- \)  |  \( E_2^+ \)  |  \( M_2^+ \)  |  \( E_3^- \)  |  \( M_3^- \)  |  \( E_3^+ \)  |  \( M_3^+ \)
---|---|---|---|---|---|---|---|---|---|---|---|---
1/2−  |  \( 1/2^- \)  |  \( 3/2^+ \)  |  \( 3/2^- \)  |  \( 5/2^- \)  |  \( 5/2^+ \)

BnGa-PWA without → with the new data on: 

\( E, G, T, P, H \)

J. Hartmann et al. 

PLB 748 (2015) 212
\( \gamma p \rightarrow p\pi^0 \) - Impact of the new data on E, G, T, P, H

Resulting multipoles - BnGa-PWA

\[
\begin{array}{c}
\text{Re \( \pi^0 p \text{[mfm]} \)}
\end{array}
\]

\[
\begin{array}{c}
\text{Im \( \pi^0 p \text{[mfm]} \)}
\end{array}
\]

The next step:

⇔ Inclusion of new data also in the other analyses

JüBo and SAID analyses

= recent work

(A.V. Anisovich et al., EPJ A52 (2016) 284)

⇒ Different analyses converge toward similar multipoles!
Photoproduction $\gamma p \rightarrow p\pi$

- Isospin selective: only $N^*$ ($I=1/2$) contribute
- Investigation of resonances with small $\pi N$-coupling

\[ S_{11}(1535) \]

A few differential cross section bins:

Differential cross sections, beam asymmetries included in the different PWAs
\[ \gamma \vec{p} \rightarrow p \eta \] — Selected polarization observables —

circ. pol. photons, long. pol. target

\begin{align*}
&\text{1660 MeV} < W < 1716 \text{ MeV} \\
&1650 \text{ MeV} < W < 1700 \text{ MeV} \\
&1769 \text{ MeV} < W < 1822 \text{ MeV} \\
&1750 \text{ MeV} < W < 1800 \text{ MeV} \\
&2017 \text{ MeV} < W < 2108 \text{ MeV} \\
&2195 \text{ MeV} < W < 2279 \text{ MeV} \\
&2050 \text{ MeV} < W < 2100 \text{ MeV}
\end{align*}

\[ \Rightarrow \text{Large sensitivity! (also true for } G \text{ (CBEELSA/TAPS) and } F \text{ (MAMI)}) \]

\[ \Rightarrow \text{data approaches the high mass region} \]

linear pol. photons, transv. pol. target

\begin{align*}
&1514 \text{ MeV} \\
&1558 \text{ MeV} \\
&1617 \text{ MeV} \\
&1796 \text{ MeV} \\
&1993 \text{ MeV} \\
&2290 \text{ MeV}
\end{align*}

Predictions : — Maid, — Said, — JüBo, — BnGa

— new BnGa-fit: Determination of precise \( p\eta \)-branching ratios for resonances
indications for a new resonance (no PDG entry) at 2200 MeV
\( \vec{\gamma} \vec{p} \rightarrow p\eta \) - Results including new data on \( E, G, T, P, H \)

Determination of \( p\eta \)-branching ratios for various resonances, e.g.:

<table>
<thead>
<tr>
<th>( N(1535)1/2^- )</th>
<th>( N(1650)1/2^- )</th>
<th>( N(1710)1/2^+ )</th>
<th>( N(1720)3/2^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BnGa</td>
<td>0.42( \pm )0.04</td>
<td>0.32( \pm )0.04</td>
<td>0.27( \pm )0.09</td>
</tr>
<tr>
<td>PDG</td>
<td>0.42( \pm )0.10</td>
<td>0.05 - 0.15</td>
<td>0.10 - 0.30</td>
</tr>
</tbody>
</table>

Large and heavily discussed difference in the \( p\eta \)-branching ratio of \( N(1535)1/2^- \) and \( N(1650)1/2^- \) now significantly reduced

⇒ Hints for a new resonance around 2200 MeV with \( J^P=5/2^- \)

Higher statistics data on \( E \) and \( T \) and data of \( F \) could further clarify the situation
⇔ Proof of the \( N(2200)5/2^- \)
The Spectrum of Baryon Resonances

Multi-channel Bonn-Gatchina PWA:

⇒ Confirmation known resonances, better determination of their properties
⇒ New resonances observed

<table>
<thead>
<tr>
<th>Resonance</th>
<th>RPP 2010</th>
<th>our analyses</th>
<th>RPP</th>
<th>GWU’06 (SAID)</th>
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<tr>
<td>N(1700)3/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>no evidence</td>
</tr>
<tr>
<td>N(1710)1/2&lt;sup&gt;+&lt;/sup&gt;</td>
<td>***</td>
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<td>***</td>
<td>no evidence</td>
</tr>
<tr>
<td>N(1860)5/2&lt;sup&gt;+&lt;/sup&gt;</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>no evidence</td>
</tr>
<tr>
<td>N(1875)3/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>no evidence</td>
</tr>
<tr>
<td>N(1880)1/2&lt;sup&gt;+&lt;/sup&gt;</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>no evidence</td>
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<tr>
<td>N(1895)1/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>**</td>
<td>**</td>
<td>**</td>
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<tr>
<td>N(1900)3/2&lt;sup&gt;+&lt;/sup&gt;</td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>no evidence</td>
</tr>
<tr>
<td>N(1990)7/2&lt;sup&gt;+&lt;/sup&gt;</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>no evidence</td>
</tr>
<tr>
<td>N(2000)5/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>**</td>
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<td>N(2060)5/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>***</td>
<td>**</td>
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</tr>
<tr>
<td>N(2150)3/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>no evidence</td>
</tr>
<tr>
<td>Δ(1900)1/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>no evidence</td>
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<tr>
<td>Δ(1920)3/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>no evidence</td>
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<tr>
<td>Δ(1940)3/2&lt;sup&gt;-&lt;/sup&gt;</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>no evidence</td>
</tr>
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from 2000-2010 not one new baryon resonance was considered by the PDG

↔ Results from photoproduction do now enter the PDG and determine the properties of baryon resonances!

(before: almost entirely πN-scattering and some π-photoproduction)

Photoproduction provides access to the “inelastic channels”
⇒ better determination of resonance properties

A.V. Anisovich et al. (BnGa-PWA), EPJA 48 (2012) 15
Multi-channel Bonn-Gatchina PWA:
⇒ Confirmation known resonances, better determination of their properties
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Interesting new MAMI-data:
\[ \gamma p \rightarrow \eta p \]

(V.L.Kashevarov et al., PRL 118 (2017) 212001)
⇒ cusp effect \( \eta'p \)-threshold observed

MAID-analysis of \( \gamma p \rightarrow \eta p \),
\( \gamma p \rightarrow \eta'p \) confirms \( N(1895)1/2^- \)
coupling to \( p\eta \), \( p\eta' \)

A.V. Anisovich et al. (BnGa-PWA), EPJA 48 (2012) 15
Strangeness Photoproduction: $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$

Beam-Recoil polarization:

**without $P_{13}(1900)$**

**with $P_{13}(1900)$**

- **Cx, Cz**
  - 1889, 1939
  - 2035, 2081
  - 2169, 2212

- **cos $\theta_K$$C_x, C_z**
  - 0.5 0 0.5 0 -0.5 0.5

---

R. K. Bradford et al. (CLAS), PRC75, 035205 (2007)

V. Nikonov et al. (BnGa-PWA), PLB662, 245 (2008)

**Fit within the Bonn-Gatchina multi-channel PWA:** Favours the existence of the $P_{13}(1900)$

(confirmed by O. V. Maxwell, PRC85, 034611 (2012), T. Mart, M. Kholili, PRC86, 022201 (2012))

$\Leftrightarrow$ **Evidence against the quark-diquark model**

U. Thoma replacing J. Hartmann, Bonn: - Light quark baryons from photoproduction and electroproduction experiments
Parity doublets occur:

- Mass (pole position) found within the BnGa–PWA

... but: Do parity doublets exist for all high mass states?

Not expected by:
- present lattice QCD calculations or constituent quark-models

⇔ QCD not yet understood!
Search for parity doublets

Do ALL high mass states have parity partners?

$\Delta(1910)_{1/2}^+ \; \Delta(1920)_{3/2}^+ \; \Delta(1905)_{5/2}^+ \; \Delta(1950)_{7/2}^+$
$\Delta(1900)_{1/2}^- \; \Delta(1940)_{3/2}^- \; \Delta(1930)_{5/2}^- \; ??? \ 7/2^-$

Search for the parity partner of the well known $\Delta(1950)_{7/2}^+ \ (4^*)$

$J^P = 7/2^-$-state found at a significantly higher mass: $m = 2200 \text{ MeV}$

( $7/2^- (2200) - (1^*)$-resonance (PDG) confirmed )

No parity-partner found

Certain states have parity partners, others not

Not yet understood!

V. Anisovich et al. (BnGa-PWA), arXiv:1503.05774
Precise measurements of polarisation observables

CBELSA/TAPS, CLAS-data (only few of the measured bins / data sets shown:)

Results from the multi-channel BnGa-PWA:

— : fit with \( \Delta(2200)^7/2^- \)
- - - : fit without \( \Delta(2200)^7/2^- \)

J. Hartmann et al. (CBELSA/TAPS), PLB 748, 212 (2015)
The nature of states: Roper resonance - \( N(1440)1/2^+ \)

Electroproduction data from CLAS: \( Q^2 \)-dependence of helicity amplitudes

In 2002 Roper was still consistent with a hybrid state

\[ \Rightarrow \text{the new data:} \]

\[ \text{LF RQM describes helicity amplitudes at } Q^2 > 1.5-2.5 \text{ GeV}^2 \]

Interpretation: Meson-baryon contributions dominate low \( Q^2 \)-behaviour

CLAS results: Identify Roper resonance as first radial excitation of the proton

The 1st radial excitation of the 3q-core emerges as the probe penetrates the MB cloud
The nature of states: $N(1440)1/2^+, N(1535)1/2^-$

Electroproduction data from CLAS: $Q^2$-dependence of helicity amplitudes

$N(1440)1/2^+$

$N(1535)1/2^-$

LF RQM describes helicity amplitudes at $Q^2 > 1.5$-2.5 $\text{GeV}^2$

Interpretation: Meson-baryon contributions dominate low $Q^2$-behaviour

Understanding the nature of the states further: qqq, meson-baryon, hybrid via measurement of the $Q^2$-dependence of the helicity amplitudes

⇒ Further data to come from CLAS12
Summary

- Based on the new data, our knowledge of the spectrum and the properties of baryons is steadily increasing!

↔ Important contributions from photoproduction experiments (single and double polarisation experiments (many final states))

⇒ Observation of new resonances

⇒ Confirmation of known states, determination of their properties
e.g.: - puzzling difference between $p\eta$-BR of $N(1535)1/2^-$ and $N(1650)1/2^-$ now very much reduced
  - multi-meson-decays of baryon resonances

⇒ much more interesting data to come

⇒ Many interesting results on the spectrum and the properties of baryon resonances

↔ Quark models/first lattice calculations do not yet provide the expected systematics in the spectrum
  Experiment: - no alternating pattern of positive and negative parity states
  - parity doublets observed (not for all states (?) )
  - Baryons fall on Regge-trajectories, Why?

↓

Bound states of QCD are not yet understood!