Non-strange baryons

1. The CLAS N* program
2. Photoproduction off the proton
3. Photoproduction off the neutron

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NSTAR2019, The 12th International Workshop on the Physics of Excited Nucleons,
Bonn University, June 10th to 14th, 2019
The status of the nucleon resonances (PDG 2018)

Improvements since 2016:

N(2060)5/2-
N(2100)1/2+
N(2060)5/2-
N(1900)3/2+
N(1895)1/2-
N(1900)1/2+

now 21 3☆, 4☆ N

Results from the CLAS collaboration contributed significantly to that progress.

Missing-resonance problem and relevant degrees of freedom

**Quark Models**

- **Constituent Quark Models** predict many more of excited states than have been observed; some of the states may only couple weakly to \( \pi N \).
- Quark-Diquark Models with a tightly bound diquark predict fewer states.
- Adding additional gluonic degrees of freedom increases number of bound states (hybrids).

Lattice QCD solutions consistent with CQM expectation of an extensive $N^*$ spectrum

LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6) x O(3) symmetry; **more states** than have been identified experimentally.

No signs of parity doubling of states.

Hadron spectrum collaboration
Two components of the experimental N* program

\[ Q^2 = 0: \text{Spectroscopy} \]

- search for new states and accounting for the complete excitation spectrum

\[ Q^2 > 0: \text{Electroproduction} \]

- study of the internal structure of a resonance with transition form factors

Electromagnetic Excitation of N*’s

Photon probes the dressed vertex ⇒ reaction models to separate reaction mechanisms from nucleon structure

⇒ \[ A_{1/2}(Q^2), A_{3/2}(Q^2), S_{1/2}(Q^2) \] helicity amplitudes

(Proton and neutron data needed to deduce isospin I=1/2 amplitudes)
Studied decay channels

Proton target

\[ \gamma p \rightarrow \pi^0 p, \pi^+ n \quad \text{present examples} \]
\[ \gamma p \rightarrow \eta p, \eta' p \]
\[ \gamma p \rightarrow \omega p, \rho p, \phi p \]
\[ \gamma p \rightarrow K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+ \]
\[ \gamma p \rightarrow \pi^+ \pi^- p \]
...  
  e.g. CLAS frozen spin target (FROST)

Neutron target

\[ \gamma n \rightarrow \pi^- p \]
\[ \gamma n \rightarrow K^0 \Sigma^0, K^0 \Lambda \]
\[ \gamma n \rightarrow \pi^+ \pi^- n \]
...  
  e.g. unpolarized deuterium target (g13),
  polarized HD-Ice target (g14)

Cross section and polarization observables

Unpolarized, circularly polarized, linearly polarized beam

Unpolarized, longitudinally polarized, transversally polarized target

Recoil polarization (asymmetry in the weak decay of the hyperon)
Polarized electron beam
Energies up to $E_e = 6$ GeV
(now up to 11 GeV)

Photon Tagger

$$E_\gamma = E_e - E_{e'}$$

CEBAF Large Acceptance Spectrometer (CLAS)

Target
unpolarized p or d,
polarized FROST, HDice

Polarized targets for CLAS

<table>
<thead>
<tr>
<th>Target</th>
<th>FROST</th>
<th>HD-ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>50 mm x 15 mm Ø</td>
<td>50 mm x 15 mm Ø</td>
</tr>
<tr>
<td>Polarization</td>
<td>P(p) = 82%; avg. g9a</td>
<td>P(D) = 25%; avg. g14</td>
</tr>
<tr>
<td>Spin relaxation</td>
<td>typ. 2800 h with beam</td>
<td>years</td>
</tr>
<tr>
<td>Repolarization</td>
<td>once per week</td>
<td></td>
</tr>
<tr>
<td>Dilution</td>
<td>10/74 (in analysis &gt; 0.5)</td>
<td>1/1 for n, 1/2 for p</td>
</tr>
</tbody>
</table>

Partial Wave Analyses

Good overall description after fit, however, not with identical results.

New evidence for a $\Delta(2200)^{7/2-}$ resonance

Parity partner of $\Delta(1950)^{7/2+}$ was poorly known.

$\Delta(1950)^{7/2+}$☆☆☆☆☆
$\Delta(2200)^{7/2-}$☆ (now: ☆☆☆☆)

Evidence found for $\Delta(2200)^{7/2-}$ in an analysis of the Bonn/Gatchina group.

$M(\Delta^{7/2-}) \approx 2180$ MeV

… and not $\approx 1950$ MeV. Chiral symmetry is not restored in high-mass hadrons.

Kaon-data-constrained Jülich-Bonn solutions describe new $\pi^0$ photoproduction data well

488 data points (T and F)
1.455 GeV < $W$ < 2.519 GeV

Examples: 3 out of 37 $W$-bins

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

g9b analysis by Hao Jiang (South Carolina); model: Deborah Rönchen (Bonn), private communication (2016)
Double-polarization Observable G

\[
\left( \frac{d\sigma}{d\Omega} \right) = \left( \frac{d\sigma}{d\Omega} \right)_0 \left\{ 1 + P_\gamma \Sigma \cos(2\alpha) + P_\gamma P_z G \sin(2\alpha) \right\}
\]

W = 1.4 – 2.3 GeV

PWA predictions of preliminary data:

- SAID MA19
- MAID
- GW-Jülich, EPJA 54, 110 (2018)
- Bonn-Gatchina, EPJA 51, 95 (2015), EPJA 52, 284 (2016)

Fair description at low energies.
Poor description at higher energies.

g9 analysis by N. Zachariou (2019, University of York)
- under collaboration review

Examples: 3 out of 23 W-bins
γp → π⁺n
Helicity asymmetry $E$ in eta photoproduction on the proton

$\gamma p \rightarrow \eta p$

eta photoproduction isolates $N^*(I=1/2)$ states in the resonance spectrum.

Narrow structure seen in MAMI $\gamma p \rightarrow \eta p$ cross section data.
[predicted in $\pi N$ PWA: Phys. Rev. C 69, 035208 (2004)]

Present CLAS E data do not demand the presence of a narrow resonance with a width of 40 MeV or less at about 1.7 GeV.

Observable Σ for η and η’ photoproduction

\[ \vec{\gamma} p \rightarrow \eta p, \quad W = 1700 - 2079 \text{ MeV} \]

\[ \vec{\gamma} p \rightarrow \eta' p, \quad W = 1900 - 2079 \text{ MeV} \]

Both new BnGa solutions indicate:

- N(1895)1/2− (2018: ☆☆☆☆) dominance near threshold,
- N(1900)3/2+ (2018: ☆☆☆☆) presence,
- N(2100)1/2+ (2018: ☆☆☆) presence,

g8b: P. Collins et al., PLB 771, 213 (2017)
A.V. Anisovich et al., PLB 772, 247 (2017)
A partial-wave analysis within the Bonn–Gatchina framework found dominant contributions from the $3/2^+$ partial wave near threshold, which is identified with the subthreshold $N(1720)3/2^+$ nucleon resonance.
Observables $\Sigma$ and $T$ in $\omega$ photoproduction

$s$-channel resonance production and $t$-channel exchange processes contribute to the reaction.

Data help to fix the magnitudes of the interference terms in the BnGa PWA.
Double-polarization observables \( F, P, \) and \( H \) in \( \omega \) photoproduction

\[
\gamma p \rightarrow \omega p
\]

The results reveal significant contributions from several nucleon (\( N^* \)) resonances.

Evidence was found for the poorly known states \( N(1880)^{1/2+} \), \( N(2000)^{5/2+} \), \( N(1895)^{1/2-} \), \( N(2120)^{3/2-} \),

Polarization Transfer Observables $C_x$, $C_z$

$C_x (●), C_z (○)$ for $K^+\Lambda$ channel

Bonn-Gatchina coupled-channel isobar model: $N(1900)3/2^+$ needed in PWA of Nikonov et al.

with $N(1900)3/2^+$

without $N(1900)3/2^+$

State confirmed in more recent analyses and is now a ★★★★★ resonance.

$N(1900)3/2^+$ found in qqq models, not expected in some quark-diquark models.

Strengthened evidence for set of $3/2^+$, $5/2^+$ resonances

ANL-Osaka coupled-channels calculations,
Bonn-Gatchina partial wave analysis (2014),
Bonn-Gatchina calculations after a refit including the present data, which include additional $N^*(3/2^+)$ and $N^*(5/2^+)$ resonances.

g8: C.A. Paterson et al. (CLAS Collaboration), PRC 93, 065201 (2016)
Double-pion photoproduction as a tool in the study of excited nucleons

$N\pi\pi$ is a dominant decay channel of highly excited nucleons.

Essential part in coupled-channel calculations.

Allows for the study of sequential decays, e.g.,

- $\gamma p \rightarrow N^* \rightarrow \pi\Delta$
- $\gamma p \rightarrow N^* \rightarrow \rho p$

Example:

$\gamma p \rightarrow \pi^+ \pi^- p$

Parity conservation yields to symmetry properties of observables

\[ M^{-\lambda_y}_{\lambda_N-\lambda_N'} (\theta, \theta_1, \phi_1) = (-1)^{\lambda_y-\lambda_N+\lambda_N'} M^{\lambda_y}_{\lambda_N\lambda_N'} (\theta, \theta_1, 2\pi - \phi_1) \]

**Example:**
circularly polarized photons - transversely polarized target

**odd observables:** do not exist in single meson final states.
**even observables:**
\( P_y \) and \( P_x^\odot \) correspond to \( T \) and \( F \), respectively.

\[ \gamma p \rightarrow \pi^+ \pi^- p \]
Preliminary results (g9b)

\[ \gamma p \rightarrow \pi^+ \pi^- p \]

Effective Lagrangian Model (A. Fix)

Exchange mesons, \( \pi, \rho, \sigma \), and resonances, \( \Delta(1232) \), \( N^*(1440) \), \( N^*(1520) \), \( N^*(1535) \), \( \Delta(1620) \), \( N^*(1675) \), \( N^*(1680) \), \( \Delta(1700) \), \( N^*(1720) \), Nucleon and Delta

Born terms; Resonance terms:

\[ W = 1600 \text{ MeV data binned in } \cos \theta_{\text{cm}}, \]


Preliminary FROST g9b data: Aneta Net (USC)
Intermediate $\Delta(1232)$ Resonance

Example of sequential decays

$$\gamma p \rightarrow N^* \rightarrow \pi \Delta$$

$\Delta(1232)$

$N(1520) \rightarrow \pi^- \Delta^{++} \rightarrow p \pi \pi$

$N(1520) \rightarrow \pi^+ \Delta^0 \rightarrow p \pi \pi$

Fourier coefficients of the angular distribution

$$I^\circ(\phi) = \sum_k a_k \sin(k\phi)$$

$N(1520) \rightarrow \pi^- \Delta^{++} \rightarrow p \pi \pi$

$N(1520) \rightarrow \pi^+ \Delta^0 \rightarrow p \pi \pi$

Extensive data set with over 8400 data points

\[ W \in [1.31, 2.37] \text{ GeV} \]
\[ \cos \theta^\text{c.m.} \in [-0.72, 0.92] \]

The data made possible

- the extraction of \( N^* \rightarrow \gamma n \) photodecay amplitudes (SAID),
- the first determination of the excited neutron multipoles for the \( N(1440)1/2^+, N(1535)1/2^-, N(1650)1/2^-, \) and \( N(1720)3/2^+ \) resonances.

These new precision \( \gamma n \rightarrow \pi^- p(p) \) data will provide important and necessary constraints to advance coupled-channel analysis fits.

\[ \gamma d \rightarrow \pi^- p(p) \]
Measurement of $\Sigma$ in $\pi^-$ photoproduction on the neutron from the g13b dataset

Examples of three out of 20 angular bins; 1200 data points in total

$1620 \text{ MeV} < W < 2360 \text{ MeV}$

\[ \gamma d \rightarrow \pi^- p(p) \]

-0.70 < $\cos \theta$ < -0.60

0.00 < $\cos \theta$ < 0.10

0.80 < $\cos \theta$ < 0.90

$\Sigma$

backward $\pi$

$W$ (MeV)

forward $\pi$

g13: Daria Sokhan (University of Glasgow) - finalized analysis
Significant revisions for several $\gamma nN^*$ resonance photocouplings

- Inclusion of these results in new PWA calculations has resulted in revised $\gamma nN^*$ couplings and, in the case of the $N(2190)7/2^-$, convergence among different PWA groups.
- Couplings are sensitive to the dynamical process of $N^*$ excitation; provide important guides to nucleon structure models.

\[ \gamma d \rightarrow \pi^- p(p) \]
Asymmetries with Linearly Polarized Beams and Longitudinally Polarized Targets

- Preliminary CLAS (HD-ice)
  - $W = 1820 - 2140$ MeV
- SAID (not yet fitted to the data)

- $\Sigma$ results (not shown) are in quite good agreement with the model prediction.

- $G$ results are generally very much smaller than the PWA values.

$\gamma d \rightarrow \pi^- p(p)$

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$W = 1860 \pm 40$ MeV
$W = 1940 \pm 40$ MeV
$W = 2020 \pm 40$ MeV
$W = 2100 \pm 40$ MeV

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Constraints for models describing nucleon resonances that couple strongly to the KY decay channels

\[ \gamma d \rightarrow K^0\Lambda(p) \]

The first differential and total cross-section measurements (○, □) of the reaction \( \gamma d \rightarrow K^0\Lambda(p) \) where the proton is a spectator.

N(1900)3/2+ couples strongly to KY decay channels.

\( \gamma d \rightarrow K^0\Lambda(p) \) has suppression of t-channel terms.

Interference of N(1900)3/2+ and t-channel background processes

Missing interference terms?

g10+g13 (deuterium): N. Compton et al. (CLAS Collaboration), PRC 96, 065201 (2017).
g11 (proton): M. E. McCracken et al. (CLAS Collaboration), PRC 81, 025201 (2010).
Beam-target helicity asymmetry $E$ in hyperon photoproduction on the neutron, $1.70 \text{ GeV} < W < 2.34 \text{ GeV}$

Analysis of clean $p\pi^+\pi^-\pi^-$ sample with intermediate hyperons; limited by small cross section.

$\gamma d \rightarrow K^0\Sigma^0(p)$

$\gamma d \rightarrow K^0\Lambda(p)$
First induced polarization, $P$, and polarization-transfer, $C_x$ and $C_z$, data in $K^0\Lambda$ photoproduction

$\gamma d \rightarrow K^0\Lambda(p)$

1.6 GeV < $W$ < 2.4 GeV

$C_z \approx 1$, for $E_\gamma < 1.4$ GeV and at forward angles for all $W$.

Preliminary

$\cos \theta_K$

ANL Osaka
Bonn-Gatchina
Bonn-Gatchina

Summary and outlook

CLAS polarized photoproduction data off

- polarized and unpolarized,
- proton and neutron targets

continue to contribute to complete or nearly complete experiments and help establishing new nucleon resonances.

Recent analyses of the data

- strengthened evidence of previously poorly known resonances,
- provided improved values for $\gamma pN^*$ and $\gamma nN^*$ couplings,
- clarified background and interference terms.

Large impact expected as data analyses are being finalized.