New Baryon States in Exclusive Meson Photo-/Electroproduction with CLAS

Talk outline:
- Hadron spectra and emergence of the strong QCD regime
- N* spectrum from photoproduction data
- New N'(1720)3/2⁺ state from analysis of π⁺π⁻p photoproduction/electroproduction data
- Validating new baryon state existence
- Insight into "missing" resonance structure
Dramatic events occurred in the micro-second old universe during the transition from the deconfined quark and gluon phase to the hadron phase.

- Quark-gluon confinement emerges
- Chiral symmetry of QCD is broken
- Quarks and gluons acquire mass
- Baryon resonances form

This transition was shaped by the full meson and baryon spectra.
Studies of the N*-spectrum were driven by a guess for the ``missing” baryon states expected from underlying SU(6)xO(3) symmetry and supported by continuum lattice QCD results on the N*-spectrum.
Several new nucleon resonances were established in a global multi-channel analysis of exclusive photoproduction data.

**N*/Δ* Spectrum 2020**

Description of the exclusive electroproduction data off the proton with the same masses and hadronic decay widths as in photoproduction will validate the existence of new baryon states.

Combined studies of the CLAS \( \pi^+\pi^-p \) photo-/electroproduction off proton data allow us to observe a new \( N'(1720)3/2^+ \) baryon state in addition to those listed above.
Interpretation of the Structure at $W\sim$1.7 GeV in $\pi^+\pi^-p$ Electroproduction

Two equally successful ways for the data description:

No new states, different than in PDG 02'

N(1720)3/2+ Nππ hadronic decay widths:

| $\Gamma_{\text{tot}}, \text{MeV}$ | BF($\pi\Delta$) % | BF(ρp) % |
|-----------------|-----------------|---------|
| N(1720)3/2+ decays fit to the CLAS Nππ data | 126±14 | 64-100 | <5 |
| N(1720)3/2+ PDG 02' | 150-300 | <20 | 70-85 |

new N'(1720)3/2+ and regular N(1720)3/2+:

| $\Gamma_{\text{tot}}, \text{MeV}$ | BF($\pi\Delta$) % | BF(ρp) % |
|-----------------|-----------------|---------|
| N'(1720)3/2+ New | 119±6 | 47-64 | 3-10 |
| N(1720)3/2+ Conventional | 112±8 | 39-55 | 23-49 |
Analysis of the $e^-\pi^+\pi^-p$ CLAS data at $W\sim1.7$ GeV in the JM model

Conventional $N^*$-states with $\pi\Delta$, $\rho p$ couplings fit to the data

$2.85<\chi^2/d.p.<3.03$ (1.66 GeV<$W<$1.76 GeV)

$W=1.71$ GeV, $Q^2=0.65$ GeV$^2$

- Fit of $\theta_{\pi^-}$, $\theta_{\pi^+}$, $\theta_p$ angular distributions requires essential contribution(s) from $J^\pi=3/2^+$ resonance(s).
- Single state of $J^\pi=3/2^+$ should have major $\pi\Delta$ (>60%) and minor $\rho p$ (<5%) decays in order to reproduce pronounced $\Delta$-peaks in $\pi^+p$ and to avoid $\rho$-peak formation in the $\pi^+\pi^-$ mass distribution.

$N'(1720)3/2^+$ candidate state is included in the fit

$2.56<\chi^2/d.p.<2.80$ (1.66 GeV<$W<$1.76 GeV)

$W=1.71$ GeV, $Q^2=0.65$ GeV$^2$
Almost the same quality of the photoproduction data description was achieved with and without the new N'(1720)3/2⁺ state:

\[
\begin{align*}
\text{N(1720)3/2⁺ and N'(1720)3/2⁺} &\quad 1.19 < \chi^2/d.p. < 1.28 \\
\text{N(1720)3/2⁺ only} &\quad 1.08 < \chi^2/d.p. < 1.26 
\end{align*}
\]

Would it be possible to describe photo- and electroproduction data with Q²-independent resonance masses and total and partial hadron decay widths?
Evidence for the Existence of the New State $N'(1720)3/2^+$ from Combined $\pi^+\pi^-p$ Analyses in both Photo- and Electroproduction

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)

N$(1720)3/2^+$ hadronic decays from the CLAS data fit with conventional resonances only

| Resonance                  | BF$(\pi\Delta)$, % | BF$(\rho p)$, % |
|----------------------------|---------------------|-----------------|
| electroproduction          | 64-100              | <5              |
| photoproduction            | 14-60               | 19-69           |

The contradictory BF values for N$(1720)3/2^+$ decays to the $\pi\Delta$ and $\rho p$ final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.

N$^*$ hadronic decays from the data fit that incorporates the new N$'(1720)3/2^+$ state

| Resonance                  | BF$(\pi\Delta)$, % | BF$(\rho p)$, % |
|----------------------------|---------------------|-----------------|
| N$'(1720)3/2^+$ electroproduction photoproduction | 47-64               | 3-10            |
|                            | 46-62               | 4-13            |
| N$(1720)3/2^+$ electroproduction photoproduction | 39-55               | 23-49           |
|                            | 38-53               | 31-46           |
| $\Delta(1700)3/2^-$ electroproduction photoproduction | 77-95               | 3-5             |
|                            | 78-93               | 3-6             |

The successful description of the $\pi^+\pi^-p$ photo- and electroproduction data achieved by implementing new N$'(1720)3/2^+$ state with $Q^2$-independent hadronic decay widths of all resonances contributing at $W \sim 1.7$ GeV provides strong evidence for the existence of the new N$'(1720)3/2^+$ state.
Newly Discovered $N'(1720)\ 3/2^+$

Evidence of a new $N'(1720)\ 3/2^+$ resonance in the photo- and electroproduction of the $\pi^+\pi^-p$ channel

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)
The Parameters of the New N’(1720)3/2+ State from the CLAS Data Fit

The photo-/electrocouplings of the N’(1720)3/2+ and conventional N(1720)3/2+ states

| Resonance       | Mass, GeV   | Total width, MeV |
|-----------------|-------------|------------------|
| N’(1720)3/2+    | 1.715-1.735 | 120±6            |
| N(1720)3/2+     | 1.743-1.753 | 112±8            |

- N’(1720)3/2+ is the only new resonance for which data on electroexcitation amplitudes have become available.
- Gaining insight into the ``missing” resonance structure will shed light on their peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD.
Description of the $\pi^+\pi^-p$ Differential Cross Sections at $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$

with the Contribution from $N'(1720)3/2^+$

- Nine 1-fold differential $\pi^+\pi^-p$ cross sections have been successfully described for $Q^2$ from 2 - 5 GeV$^2$ with $Q^2$-independent mass, $\pi\Delta$ and $\rho p$ decay widths of $N'(1720)3/2^+$, solidifying evidence for existence of this new resonance.

- Extraction of $N'(1720)3/2^+$ electrocouplings is in progress.
SU(6)-Assignment for N'(1720)3/2+ and N(1720)3/2+

New resonances discovered from exclusive meson photoproduction data revealed the following pattern of the high-lying resonance spectrum under approximate SU(6)xO(3) symmetry

\[ [70,2^+] \] multiplet

\[ S_q=3/2 \quad \begin{array}{lllll} N(1880)1/2^+ & N(1900)3/2^+ & N(2000)5/2^+ & N(2000)7/2^+ \end{array} \]

\[ M_{\text{avg}}(S_q=3/2) = 1.96 \text{ GeV} \quad \Delta M(S_q=3/2) = 0.075 \text{ GeV} \]

\[ S_q=1/2 \quad \begin{array}{lll} N'(1720)3/2^+ & N(1860)5/2^+ \end{array} \]

\[ \Delta M(S_q=3/2-S_q=1/2)[70,2^+] = \Delta M(S_q=3/2-S_q=1/2)[70,1^-] = 0.16 \text{ GeV} \]

\[ M_{\text{avg}}(S_q=1/2) = M_{\text{avg}}(S_q=3/2) - \Delta M(S_q=3/2-S_q=1/2)[70,2^+] = 1.96-0.16 = 1.80 \text{ GeV} \]

\[ M(N'(1720)3/2^+) = M_{\text{avg}}(S_q=1/2) - \Delta M(S_q=3/2) = 1.80-0.075 = 1.73 \text{ GeV} \text{ consistent with the mass of } N'(1720)3/2^+ \text{ inferred from the } \pi^+\pi^-p \text{ photo-/electroproduction data} \]

\[ N'(1720)3/2^+ \quad \text{three constituent quarks of total spin } S_q=1/2 \text{ and orbital momentum } L=2 \text{ in } [70,2^+] \text{ multiplet, double orbital excitation} \]

\[ N(1720)3/2^+ \quad \text{three constituent quarks of total spin } S_q=1/2 \text{ and orbital momentum } L=2 \text{ in } [56,2^+] \text{ multiplet} \]

Quark model evaluation of \( \gamma_vpN^* \) electrocouplings under the aforementioned assignments for \( N(1720)3/2^+ \) and \( N'(1720)3/2^+ \) states will shed light on peculiar features in \( N'(1720)3/2^+ \) structure
Insight into the Structure of the New N'(1720)3/2⁺

Soft-wall Ads/CFT, V.E. Lyubovitskij and I. Schmidt, e-Print:2009.07115 [hep--ph]

Leading/sub-leading contributions to N'(1720)3/2⁺ and N(1720)3/2⁺ come from the same/different AdS fields

| N → N(1720) | $g_{35}^A = -11.58, \ g_{46}^A = 34.50, \ g_{57}^A = -22.60, \ g_{35}^B = 79.15, \ g_{46}^B = 67.11, \ g_{57}^B = 29.95, \ g_{1C} = -36.53, \ g_{1C} = 105.65, \ g_{1C} = -58.59, \ g_{1D} = 0.16, \ g_{46} = -0.47, \ g_{57} = 0.31, \ g_{2E}^A = 12.14, \ g_{2E}^E = 10.29, \ g_{2E}^E = 4.59, \ g_{2E}^E = 5.56, \ g_{2F}^E = -16.07, \ g_{2F}^E = 8.91 |
| N → N'(1720) | $g_{35}^A = 30.18, \ g_{46}^A = -54.02, \ g_{57}^A = 24.82, \ g_{35}^B = -1.15, \ g_{46}^B = 6.41, \ g_{57}^B = -2.87, \ g_{1C} = -17.77, \ g_{1C} = 107.19, \ g_{1C} = -62.71, \ g_{35}^D = 8.48, \ g_{46}^D = -15.18, \ g_{57}^D = 6.97, \ g_{35}^E = -0.60, \ g_{46}^E = 3.37, \ g_{57}^E = -1.51, \ g_{35}^E = -3.57, \ g_{46}^E = 21.56, \ g_{57}^E = -12.61 |

- Checking [70,2⁺] and [56,2⁺] assignments for N'(1720)3/2⁺ and N(1720)3/2⁺, respectively (R. Bijker et al., PRD 94, 074040 (2016), G. Ramalho, FBS 59, 92 (2018)) from the results on $\gamma_v {\mathbf p} N^*$ electrocouplings. If confirmed, discovery of N'(1720)3/2⁺ represents the first observation of the resonance with two non-zero orbital momenta $l_\lambda$ and $l_\rho$ in three quark system.
- Alternative assignment of N'(1720)3/2⁺ as a member of 27-SU(3) baryon multiplet of chiral soliton model (G.-S. Yang and H.-C. Kim, PTEP, 093D01 (2019))
Conclusions and Outlook

• Several long-time awaited new, so-called "missing" nucleon resonances, have been discovered from global analyses of exclusive meson photo- and hadroproduction data with decisive impact from KY photoproduction channels measured with CLAS.

• New N'(1720)3/2\textsuperscript{+} resonance has been observed in combined studies of π\textsuperscript{+}π\textsuperscript{-}p photo- and electroproduction data. A successful description of π\textsuperscript{+}π\textsuperscript{-}p electroproduction data at 2.0<Q\textsuperscript{2}<5.0 GeV\textsuperscript{2} achieved accounting for contribution from N'(1720)3/2\textsuperscript{+} with Q\textsuperscript{2}-independent masses and decay widths into πΔ and ρp final states supports the new resonance existence.

• New N'(1720)3/2\textsuperscript{+} state is the only "missing" resonance for which the results on Q\textsuperscript{2}-evolution of γpN\textsuperscript{*} electrocouplings have become available. In the future, the information on the N'(1720)3/2\textsuperscript{+} electrocouplings from the CLAS data will be extended towards Q\textsuperscript{2} up to 5.0 GeV\textsuperscript{2}.

• Analyses of the results on the new resonance electrocouplings in collaborative efforts with hadron structure theory will shed light on particular features of the "missing" resonance structure which have made them so elusive for detection.

• Experiments with CLAS12 detector are expected to provide the ultimate information on the spectrum of excited nucleon states, including exotic hybrid baryons, and shed light on approximate symmetries of the strong interaction relevant for the generation of the N\textsuperscript{*}-spectrum.
Back Up
Physics run started successfully in February 2018
### Hybrid Baryons

**E12-16-010**

Search for hybrid baryons (qqqqg) focusing on $0.05 \text{ GeV}^2 < Q^2 < 2.0 \text{ GeV}^2$ in mass range from 1.8 to 3 GeV in KΛ, Nπππ, Nπ (A. D’Angelo, et al.)

### KY Electroproduction

**E12-16-010A**

Study N* structure for states that couple to KY through measurements of cross sections and polarization observables that will yield $Q^2$ evolution of electrocoupling amplitudes at $Q^2 < 7.0 \text{ GeV}^2$ (D. Carman, et al.)

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**Approved by PAC44**

Run Group conditions:

| $E_b$ | Condition |
|-------|------------|
| 6.6 GeV | 50 days |
| 8.8 GeV | 50 days |

- Polarized electrons, unpolarized LH$_2$ target
- $L = 1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
Hunting for Glue in Excited Baryons with CLAS12

Can glue be a structural component to generate hybrid $q^3g$ baryon states?

Predictions of the $N^*$ spectrum from QCD show both regular $q^3$ and hybrid $q^3g$ states.

Search for hybrid baryons with CLAS12 in exclusive KY and $\pi^+\pi^-p$ electroproduction.

LQCD and/or QM predictions on $Q^2$ evolution of the hybrid-baryon electroexcitation amplitudes are critical in order to establish the nature of a baryon state.

JLab LQCD group results
Expected outcome: The first results on the $\gamma pN^*$ electrocouplings of most $N^*$ states from data in the range $W < 3.0$ GeV and $Q^2 > 5.0$ GeV$^2$ for exclusive reaction channels: $\pi N$, $\pi\pi N$, $KY$, $K^*Y$, $KY^*$

Collecting data will extend the $Q^2$ range of the $\gamma pN^*$ electrocouplings to 8-10 GeV$^2$ for each of these channels.