## Advances in the Studies of the Nucleon Resonance Spectrum in Experiments with Electromagnetic Probes







#### Talk Outline:

- N\* spectrum and strong QCD emergence
- Studies of the N\* spectrum in exclusive meson photoproduction off protons
- Evidence for new N'(1720)3/2+ baryon state
- New opportunities in the exploration of the N\* spectrum with CLAS12



### 5<sup>th</sup> Joint APS/JPS Meeting, October 23-27, Waikoloa, Hawaii







ellerson (

Dramatic events occur in the microsecond old universe during the transition from the deconfined quark and gluon phase to hadron phase.



V.I. Mokeev, 5th Joint APS/JPS Meeting, October 23-27, 2018, Waikoloa Hawaii

## SU(6)xO(3) Spin-Flavor Symmetry and ``Missing" Resonances



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 LQCD exploratory results on the N\*-spectrum.

#### **Exclusive Photoproduction in the Nucleon Resonance Region**

#### Common effort at ELSA, JLab and MAMI.

Combination of continuous electron beams and detectors of  $\sim 4\pi$  acceptance allow us to determine types of all final particles and their 4-momenta in each reaction.

Most exclusive photoproduction channels in the resonance region were studied.



## **Polarization Observables in Meson-Baryon Photoproduction Channels**

[SHKL, J Phys G38 (11) 053001]

Photon beam		Target			Recoi	l		Target - Recoil								
					<i>x'</i>	у'	z'	<i>x'</i>	<i>x'</i>	<i>x'</i>	у'	у'	у'	z'	z'	Ζ'
		x	У	Ζ				x	У	Ζ	x	У	Z	x	У	Ζ
unpolarized	σ <sub>0</sub>		T			Р		$T_{x'}$	. * 1987 1987 1987 1987 1987 1987 1987	$L_{x}$ ,		$\sum$		<i>T<sub>z</sub></i> ,		$L_z$ ,
$P_L^{\gamma} sin(2\phi_{\gamma})$		Н		G	<i>O</i> <sub><i>x</i></sub> ,		<b>O</b> z',		<i>C</i> <sub>z</sub> ,		E		F		$-C_{x'}$	
$P_L^{\gamma} \cos(2\phi_{\gamma})$	-Σ		- <b>P</b>			- <i>T</i>		- <b>L</b> <sub>z</sub> ,		<b>T</b> <sub>z</sub> ,		$-\sigma_0$		$L_{x'}$		$-T_{x'}$
circular $P_c^{\gamma}$		F		- <b>E</b>	$C_{x'}$		$C_{z}$ ,		- <b>O</b> z'		G		-H		<b>O</b> <sub>x'</sub>	



#### 16 different observables

- They are described by different bi-• linear combinations of amplitudes
- *Combined fit of all observables* • offers rigorous constraints on the reaction amplitude at the real energy axis

#### 2-Body Photoproduction off Protons: Data and Analysis Approaches

 $\checkmark$  - data acquired  $\checkmark$  - analyzed/published

Observable	σ	Σ	т	Р	E	F	G	н	T <sub>x</sub>	T <sub>z</sub>	L <sub>x</sub>	Lz	0 <sub>x</sub>	0 <sub>z</sub>	C <sub>x</sub>	C <sub>z</sub>
ρπ⁰	1	✓	✓		✓	✓	√	~								
nπ⁺	1	✓	~		1	✓	✓	~				C				
рղ	1	~	~		1	✓	✓	~					n, rada wordraara da	BARANDER.		
<b>թղ</b> '	1	~	~		✓	✓	✓	~			үр	→X				
K⁺Λ	1	✓	1	1	<b>√</b>	✓	√	<b>√</b>	<b>√</b>	✓	✓	✓	1	1	1	<ul> <li>Image: A set of the set of the</li></ul>
K <sup>+</sup> Σ <sup>0</sup>	1	<b>√</b>	1	1	✓	✓	~	~	<b>√</b>	~	~	✓	1	1	<b>√</b>	1
К⁺*Л	1			1					SDME							
K <sup>0*</sup> Σ+	1	✓									✓	√		SD	ME	

Coupled-channel approaches for N\* parameter extraction from exclusive meson photoproduction data off the proton

Bonn-Gatchina A.V. Anisovich et al., Eur. Phys. J. A53, 242 (2017). A.V. Anisovich et al., Eur. Phys. J. A50, 129 (2014). A.V. Anisovich et al., Eur. Phys. J. A48, 15 (2012).

Argonne-Osaka H. Kamano et al., Phys. Rev. C94, 015201 (2016). H. Kamano et al., Phys. Rev. C88, 035209 (2013).

GWU-Julich D. Rönchen et al., Eur. Phys. J. A51, 70 (2015). D. Rönchen et al., Eur. Phys. J. A50, 101 (2014).



#### **Connecting Nucleon Resonance Properties to the Photoproduction Observables**



- Constrain exclusive photoproduction amplitudes by fitting them to the differential cross sections and polarization asymmetries.
- Incorporate the FSI effects→ Global multi-channel analyses of all exclusive photo-/hadroproduction channels.
- · Make analytical continuation of reaction amplitudes into the complex energy plane and:

a) locate poles Resonance masses ( $M_{N^*}$ ) and total widths ( $\Gamma_{N^*}$ );

b) determine residues Resonance photocouplings and partial hadronic decay widths.



# **Establishing the N\* Spectrum**

### Hyperon photoproduction $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$ from CLAS

#### ANL-Osaka 8 coupled-channel analysis





## **Establishing the N\* Spectrum, cont'd**

#### Hyperon photoproduction $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$ from CLAS

Bonn-Gatchina multichannel analysis: 9 new resonances were included







Several **new nucleon resonances** were established in a global multi-channel analysis of exclusive photoproduction data



#### Nucleon resonances listed in Particle Data Group (PDG) tables

State N(mass)J <sup>₽</sup>	PDG pre 2012	PDG 2018*
N(1710)1/2+	***	****
N(1880)1/2+		***
N(1895)1/2 <sup>-</sup>		****
N(1900)3/2+	**	****
N(1875)3/2 <sup>-</sup>		***
N(2100)1/2⁺	*	***
N(2120)3/2 <sup>-</sup>		***
N(2000)5/2+	*	**
N(2060)5/2 <sup>-</sup>		***
<b>∆(1600)3/2</b> +	***	****
∆ <b>(</b> 1900)1/2 <sup>.</sup>	**	***
∆(2200)7/2 <sup>-</sup>	*	***

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 $\pi^+\pi^-p$ photo-/electroproduction off proton CLAS data revealed evidence for the existence of a new N'(1720)3/2<sup>+</sup> baryon state in addition to those listed above.



### First Interpretation of the Structure at W~1.7 GeV in $\pi^+\pi^-p$ Electroproduction

M.Ripani et al., CLAS Collaboration Phys. Rev. Lett. 91, 022002 (2003).

*conventional states only, consistent with PDG 02* 

<u>Two equally successful ways for the data description:</u> different than in PDG 02' N(1720)3/2<sup>+</sup> N $\pi\pi$ hadronic decay widths:

	$\Gamma_{tot,}MeV$	BF(π∆) %	BF(ρp) %
N(1720)3/2 <sup>+</sup> decays fit to the CLAS Nππ data	126±14 420±80 (BoGa)	64-100 47-89 (BoGa)	<5 1-2 (BoGa)
N(1720)3/2+ PDG 02'	150-300	<20	70-85

new N'(1720)3/2<sup>+</sup> state and consistent with PDG 02' N $\pi\pi$  hadronic decays of the regular N(1720)3/2<sup>+</sup>:

	$\Gamma_{tot,}MeV$	BF(π∆) %	<b>BF(</b> ρ <b>p)</b> %
N'(1720)3/2+ New	119±6	47-64	3-10.
N(1720)3/2⁺ Regular	112±8	39-55	23-49

lefferson Pab

implementing N'(1720)3/2<sup>+</sup> candidate or conventional states only with different N(1720)3/2<sup>+</sup> N $\pi\pi$  decays than in PDG 02



V.I. Mokeev, 5th Joint APS/JPS Meeting, October 23-2, 2018, Waikoloa Hawaii



• Fit of  $\theta_{\pi-}$ ,  $\theta_{\pi+}$ ,  $\theta_p$  angular distributions requires essential contribution(s) from the resonance(s) of  $J^{\pi}=3/2^+$ .

• 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 distributions.

lefferson Pab

JM Model for Analysis of  $\pi^+\pi^-p$  Photo-/Electroproduction

Major objectives: extraction of  $\gamma_{r,v}$  pN\* photo-/electrocouplings and  $\pi\Delta$ ,  $\rho$ p decay widths



five channels with unstable intermediate meson/baryon and direct  $\pi^+\pi^-p$  production:

N<sup>\*</sup> contribute to  $\pi\Delta$ and op channels only;

unitarized Breit-Wigner ansatz for resonant amplitudes;

phenomenological parameterization of the other meson-baryon channel amplitudes (see **Ref. 2)** 

- V.I. Mokeev, V.D. Burkert et al., (CLAS Collaboration) Phys. Rev. C86, 035203 (2012). 1.
- V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009). 2.

efferson Pab

Good description of  $\pi^+\pi^-p$  photo-/electroproduction off protons cross sections at 1.4 GeV<W<2.0 GeV and 0.2 GeV<sup>2</sup><Q<sup>2</sup><5.0 GeV<sup>2</sup>

# Description of the CLAS $\pi^+\pi^-p$ Photoproduction off Protons Data with/without the New State N'(1720)3/2+



Almost the same quality of the photoproduction data fit was achieved with and without N'(1720)3/2<sup>+</sup> new state:

N(1720)3/2<sup>+</sup> and N'(1720)3/2<sup>+</sup>  $\longrightarrow$  1.19 <  $\chi^2$ /dp. < 1.28 N(1720)3/2<sup>+</sup> only  $1.08 < \chi^2$ /dp. < 1.26

efferson

Val

Would it be possible to describe photo- and electroproduction data with Q<sup>2</sup>-independent resonance masses, the total and partial hadron decay width?

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

	BF(π∆), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

The contradictory BF values for N(1720)3/2<sup>+</sup> 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.

ellerson C

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

Resonance	BF(π∆), %	<b>BF(</b> ρ <b>p)</b> , %
N'(1720)3/2+ electroproduction photoproduction	47-64 46-62	3-10 4-13
N(1720)3/2+ electroproduction photoproduction	39-55 38-53	23-49 31-46
∆(1700)3/2 <sup>-</sup> electroproduction photoproduction	77-95 78-93	3-5 3-6

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

### The Parameters of N'(1720)3/2<sup>+</sup> New State from the CLAS Data Fit

The photo-/electrocouplings of N'(1720)3/2<sup>+</sup> and conventional N(1720)3/2<sup>+</sup> states:



Jefferson Pab

### Accessing the Nature of N'(1720)3/2<sup>+</sup> New State

- In the mass range of W<1.8 GeV all N\* states expected from quark models were already established suggesting peculiar features for the structure of the new N'(1720)3/2<sup>+</sup> state.
- N'(1720)3/2<sup>+</sup> is the only candidate state for which the results on Q<sup>2</sup>-evolution of transition electrocouplings have become available offering the insight to the structure of the new baryon state.



- Promising prospect to improve knowledge on Q<sup>2</sup>-evolution of N'(1720)3/2<sup>+</sup> electrocouplings from the recent CLAS π<sup>+</sup>π<sup>-</sup>p electroproduction off proton data obtained with minimal bin size over Q<sup>2</sup> ever achieved ΔQ<sup>2</sup>= 0.05 GeV<sup>2</sup> in the range of 0.4 GeV<sup>2</sup> < Q<sup>2</sup>< 0.8 GeV<sup>2</sup>.
- Theory analyses of the results on electrocouplings of N'(1720)3/2<sup>+</sup> state are needed in order to get insight to its peculiar structural features.

'ellerson C

### **12 GeV Era with the CLAS12 Detector**





CLAS12 kinematic coverage from the first inclusive electron scattering events with a 10.6 GeV electron beam incident on a liquidhydrogen target

V.I. Mokeev, 5<sup>th</sup> Joint APS/JPS Meeting, October 23-27, 2018, Waikoloa Hawaii 18

Hybrid Baryons E12-16-010	Search for hybrid baryons (qqqg) focusing on 0.05 GeV <sup>2</sup> < $Q^2 < 2.0$ GeV <sup>2</sup> in mass range from 1.8 to 3 GeV in KA, N $\pi\pi$ , N $\pi$ ( <i>A. D'Angelo et al.</i> )
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 <sup>2</sup> evolution of electrocoupling amplitudes at $Q^2 < 7.0 \text{ GeV}^2$ (D.S. Carman et al.)

## **Approved by PAC44**

Run Group conditions:

 $E_{b} = 6.6 \text{ GeV}, 50 \text{ days}$ 

 $E_{b} = 8.8 \text{ GeV}, 50 \text{ days}$ 

- •Polarized electrons, unpolarized LH<sub>2</sub> target
- L =  $1x10^{35}$  cm<sup>-2</sup>s<sup>-1</sup>



# Hunting for Glue in Excited Baryons with CLAS12

## Can glue be a structural component to generate hybrid q<sup>3</sup>g baryon states?

Predictions of the N\* spectrum from QCD show both regular q<sup>3</sup> <u>and</u> hybrid q<sup>3</sup>g states



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

LQCD, Continuum QCD, and QM predictions on Q<sup>2</sup> evolution of the hybrid-baryon electroexcitation amplitudes are critical in order to establish the nature of a baryon state



V.I. Mokeev, 5th Joint APS/JPS Meeting, October 23-27, 2018, Waikoloa Hawaii

- The knowledge of the spectrum of excited nucleons was extended considerably from the studies of the CLAS data on exclusive meson photo- and electroproduction.
- The new N(1895)1/2<sup>-</sup> and N(1900)3/2<sup>+</sup> resonances with the four star PDG ratings were established in the global multi-channel analysis of the exclusive photo- and hadroproduction channels with a major impact from the CLAS KΛ, KΣ photoproduction data. The knowledge on the spectrum of high-lying resonances was improved considerably.
- Combined studies of exclusive π<sup>+</sup>π<sup>-</sup>p photo-/electroproduction off proton data revealed convincing evidence for existence of new N'(1720)3/2<sup>+</sup> resonance and offer insight on the state structure from the data on the resonance electroexcitation amplitudes in a wide range of photon virtualities.
- Evaluation of the resonance spectrum in the partial wave J<sup>P</sup>=3/2<sup>+</sup> and the resonance electroexcitation amplitudes within continuum QCD approaches will elucidate the emergence of new baryon states from QCD.
- Experiments with the CLAS12 detector will allow us to complete studies of the N\* spectrum in the mass range up to 3.0 GeV and to perform the search for new states of baryon matter with the glue as active structural component, the so-called hybrid baryons.

