Review of light baryon spectroscopy with CLAS at JLAB

S. Diehl[1,2], K. Joo[2] for the CLAS collaboration

[1]2nd Physics Institute, Justus Liebig University Giessen, 35410 Giessen, Germany
[2]Department of Physics, University of Connecticut, Storrs, CT 06269, USA
[1]E-mail: stefan.diehl@exp2.physik.uni-giessen.de
[2]E-mail: kyungseon.joo@uconn.edu

Baryon spectroscopy and structure studies are the key to a deeper understanding of the processes which happened during the first few microseconds of the universe. The understanding of the fundamental degrees of freedom inside a proton or a neutron and how they change with varying quark masses can help us to obtain a deeper understanding on the origin of confinement and its connection to chiral symmetry breaking. While photoproduction experiments are have established as a very effective tool to search and identify new resonances, a hard scale, provided by electroproduction is needed to probe the internal structure of the N* states and to reveal their true nature. The paper will give an overview on the spectroscopy of light baryon states, with a special focus on recent progress in hadron structure studies with CLAS at JLAB. The CLAS spectrometer offers a unique dataset to determine the electrocouplings of N* and Δ resonances using both single and double pion electroproduction. As an outlook, an overview of the planed baryon resonance studies with CLAS12 at the recently upgraded 12 GeV CEBAF electron accelerator will be presented.

Keywords: Baryon Spectroscopy, Electromagnetic Interactions, Form Factors, Nucleon Structure, Excited Nucleon States, CLAS

1. Introduction

The study of the baryon spectrum can help us to obtain a more complete understanding of the processes which happened within the first microseconds of the universe. Up to 10^{-8} s after the big bang the universe consisted of a quark gluon plasma. A short time later after ~ 10^{-6} s confinement emerges, the chiral symmetry is broken, light quarks acquire mass and form the first baryon resonances. Only ~ 10^{-4} s later all these resonances already decayed and only protons and neutrons remained, which finally formed the first nuclei after ~ 100s. The interaction of electromagnetic probes in the energy region of a few GeV with baryons can give us access to the processes which took place during this early era of the universe only 10^{-6} s after the big bang and help us to understand the underlying mechanisms, like the origin of confinement and its connection to chiral symmetry breaking. The study of excited baryons can especially help us to investigation of the fundamental degrees of freedom inside a proton or a neutron and how they change with varying quark masses.

Experimentally, the N* program can be divided in two parts. On the one side the spectroscopy, which is mainly driven by real photon scattering and on the other side the study of the structure of excited baryons, which is mainly driven by electron scattering. While the spectroscopy search for unobserved or so-called missing resonances to provide a more complete and more precise picture of the N* spectrum, the structure measurements study resonance from factors and their Q^2 dependence to investigate the underlying symmetries of the hadron system and to provide information on the confining /effective forces of the 3-quark system.

2. Experimental facilities

Around the world there are several experiments, which contribute to the exploration of the excited baryon spectrum. Besides others, the most important are the CB-ELSA and BGO-OD experiment in Bonn (Germany), the CLAS and the new CLAS12 spectrometer as well as the GlueX experiment at JLAB (USA), the crystal ball experiment in Mainz (Germany) and the BESIII experiment in Beijing (China).

This review will focus on the results obtained with CLAS at JLAB during the recent years, since many detailed studies of resonance electroexcitations in exclusive meson electroproduction off nucleons became possible only after dedicated experiments were carried out with the CLAS detector [1] in Hall B at Jefferson Lab (see Fig. 1).

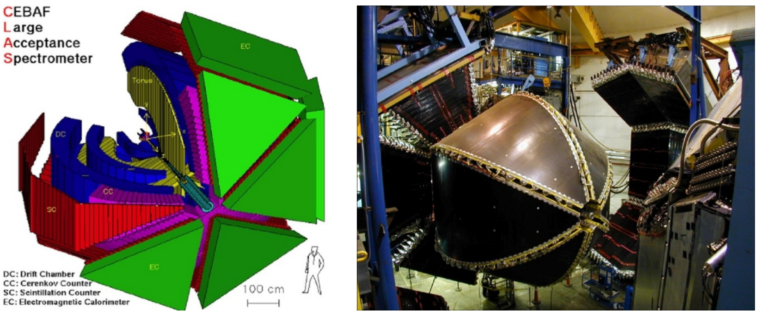

Fig. 1. A schematic drawing of the CLAS spectrometer (left). The torid magnet divides the detector in six sectors, Each equipped with series of drift chambers, a cherkenkov counter, a scintillation counter an an electromagnetic calorimeter. The picture on the right shows the CLAS detector in an open maintenance position exposing the large drift chambers covering nearly the full polar angle range. The time-of-flight scintillator bars and the forward electromagnetic calorimeters are also visible.

3. Search for new excited baryon states

To analyze high precision data of the hadron spectrum, accurate analysis procedures have to be established. A close interplay between the underlying QCD with predictions based on lattice QCD, Dyson-Schwinger equations and relativistic quantum mechanics and the parameters extracted from experimental data based on an amplitude analysis in combination with dispersion relations from reaction theory has to take place.

Over the recent years, the combination of different experimental observables besides the cross section, like the beam asymmetry, the recoil polarisation, the transverse target asymmetry as well as other polarization observables has led to more and more precise fits of the data. Based on the most recent data, several new states could be discovered and previously poorly known states could be fully established (see Tab. 1).

Table 1. Newly discovered and fully established states in PDG 2018 compared to 2012 [2]. **** - existence is certain *** - existence is likely ** - evidence of existence is fair * - evidence of existence is poor

State N((mass)J^P	PDG pre 2012	PDG 2018 evidence	Mass (Pole)	State N((mass)J^P	PDG pre 2012	PDG 2018 evidence	Mass (Pole)
N(1710)1/2$^+$	***	****	1700	N(1875)3/2$^-$		***	1900
N(1880)1/2$^+$		***	1860	N(2120)3/2$^-$		***	2100
N(2100)1/2$^+$	*	***	2100	N(2060)5/2$^-$		***	2070
N(1895)1/2$^-$		****	1910	Δ(2200)7/2$^-$	*	***	2150
N(1900)3/2$^+$	**	****	1920				

If we ignore the absolute mass scale, the newly discovered states nicely agree with the quantum numbers J^P predicted by lattice QCD in Ref. [3]. However, the absolute mass values are several hundred MeV too high, since a too high pion mass has to be used for the calculations to overcome mathematical constraints in the calculation.

4. Structure of excited baryon states

While the photoproduction of N* states is very effective for the search and identification of new resonances, a hard scale is needed to probe the internal structure and relevant degrees of freedom versus distance scale to finally reveal the true nature of the discovered states. Such a hard scale can be provided by electroproduction experiments, which can study the structure of the nucleon resonances in the domain where dressed quarks are the major active degree of freedom and explore the dynamics of the non-perturbative strong interaction behind the resonance formation [4, 5]. Nucleon resonance electroexcitation amplitudes of the $\gamma_v pN^*$ electrocouplings have been turned out to be an excellent source of information on many facets of non-perturbative strong interactions in the generation of the excited proton states from quarks and gluons.

The major part of the available world data on all meson electroproduction channels off the nucleon in the resonance region for Q^2 up to 5.0 GeV^2 has been produced by CLAS and can be found in the CLAS physics database [6]. Within the framework of phenomenological reaction models information on electrocouplings of most excited nucleon states in the mass range up to 1.8 GeV could be extracted from this data set [7]. The data base provides detailed information on the Q^2-evolution of the $\gamma_v pN^*$ electrocouplings of the excited nucleon states in the resonance region. The $\gamma_v pN^*$ electrocouplings of these resonances were determined from independent studies of $N\pi$ [8, 9], $N\eta$ [10] and $\pi^+\pi^- p$ [11-13] electroproduction off protons. Further results on $g_v pN^*$ electrocouplings from the exclusive meson electroproduction with CLAS are stored in the web databases listed in Ref. [14, 15].

The extracted electrocoupling values for the resonances from the dominant $N\pi$ and $\pi^+\pi^- p$ exclusive channels are fully consistent, even the channels show completely different non-resonant mechanisms, which can be seen as a strong evidence for a reliable nearly model independent extraction of these fundamental quantities and demonstrates the capability of the developed reaction models. Several $\gamma_v pN^*$ electrocouplings for different nucleon resonances determined from the CLAS can be found in the recent PDG edition [16]. Analyses of the CLAS results on $\gamma_v pN^*$ electrocouplings within the framework of continuum QCD Dyson-Schwinger equation approach and quark models showed, that the N* structure is a complex interplay between the inner core of three dressed quarks and the external meson-baryon cloud. In combination with theoretical models, CLAS results for nucleon resonance electrocouplings can help to obtain a better understanding of active degrees of freedom in the N* structure at different distances and the strong QCD dynamics underlying the generation of excited nucleon states. However, to obtain a more complete understanding, the full spectrum of excited nucleon states within a larger range of photon virtualities as to be studied. Exploring all prominent resonances will provide a deeper understanding of the diversity of qq-correlations in the structure of the excited nucleons of different quantum numbers as well as into dynamical chiral symmetry breaking through analyses of the results on the electroexcitation amplitudes of the pairs of resonances which are the chiral parity partners.

4.1 The current status of experimental measurements with CLAS

Based on the already available data of $N\pi$ and $\pi^+\pi^- p$ electroproduction off protons from CLAS, the JLab-Moscow (JM) model has been developed to extract resonance electrocouplings as well as $\pi\Delta$ and ρp hadronic decay widths. Examples for extracted structure functions of $p\pi^0$ are shown in Fig. 2 in comparison with predictions based on resonance electrocouplings and hadronic decay parameters from previous CLAS based analyses [8, 12, 13] and resonant contributions calculated from the JM model.

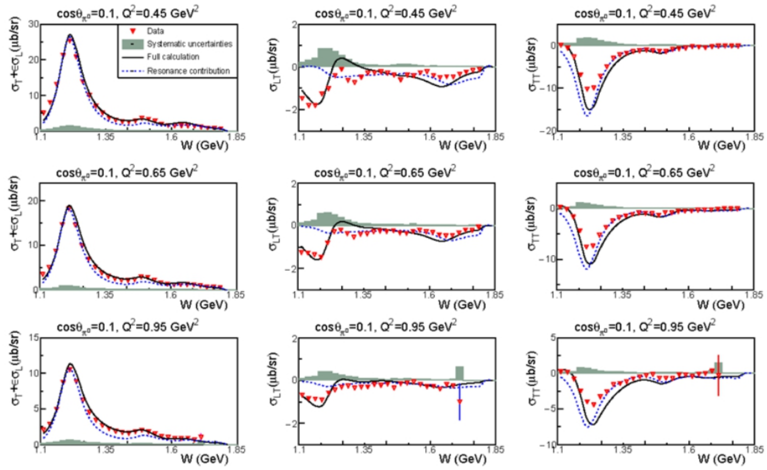

Fig. 2. W dependencies of the exclusive structure functions $\sigma_T + \varepsilon\sigma_L$, σ_{LT}, and σ_{TT} for a fixed cosθ oϕ 0.1 and different bins of Q^2. For comparison, the exclusive structure function within the framework of the JM model and with the resonance parameters determined from the CLAS exclusive meson electroproduction data [8, 12, 13] are shown (solid lines), while the blue dashed lines show the resonant contributions.

All relevant reaction mechanisms in the final-state resonance region are included into the model, including the $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, ρ^0p, π^+N(1520) $3/2^-$ and π^+N(1685) $5/2^+$ meson-baryon channels, as well as the direct production of the $\pi^+\pi^-$p final state without considering the formation of intermediate unstable hadrons. The contributions from the well-established N* states in the mass range up to 2.0 GeV were included into the amplitudes of the $\pi\Delta$ and ρp meson-baryon channels using a unitarized version of the Breit-Wigner ansatz. The comparison with experimental data shows, that the JM model provides a good description of the CLAS measurements at W < 2.0 GeV and 0.2 GeV^2 < Q^2 < 5.0 GeV^2. Considering only statistical uncertainties a χ^2/d.o.f. < 3.0 can be achieved.

Fig. 3 shows experimental results for the fully integrated $\pi^+\pi^-$p electroproduction cross sections in comparison to the predicted values and the contributions from the meson-baryon mechanisms of the JM model. The determined resonant/non-resonant contributions are located within well-defined ranges. Employing the unitarized Breit-Wigner ansatz [12], which fully accounts for the unitarity restrictions on the resonant amplitudes, it becomes possible to determine the resonance photo-electrocouplings along with the $\pi\Delta$ and ρN decay widths, based on the isolation of the resonant contributions. The obtained results can be used as a valuable input for global multi-channel analyses in the resonance excitation region within advanced coupled channel approaches for their extensions towards the extraction of γ_VpN* electrocouplings from exclusive meson electroproduction off nucleon data.

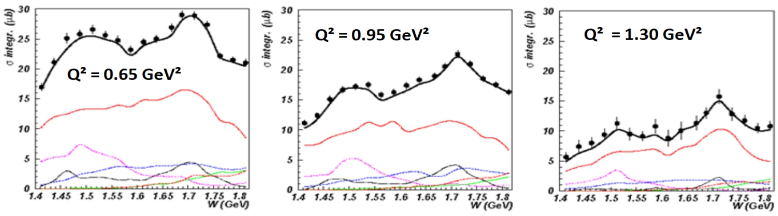

Fig. 3. Fully integrated $\pi^+\pi^-$p electroproduction cross section in comparison to calculations achieved within the framework of the JM model. In addition, the cross sections for the various contributing mechanisms are shown: full cross section (black solid), $\pi^-\Delta^{++}$ (red thin solid), ρ^0p (green thin solid), $\pi^+\Delta^0$ (blue thin dashed), π^+N(1520) 3/2$^-$ (black dotted), direct 2π mechanisms (magenta thin dot-dashed), and π^+N(1685) 5/2$^+$ (red thin dashed).

4.2 Resonance parameters from the exclusive πN and $\pi^+\pi^-$p channels

The results for the γ_VpN* electrocouplings of the N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances, determined in independent analyses of the dominant meson electroproduction channels πN and $\pi^+\pi^-$p are shown in Fig. 4.

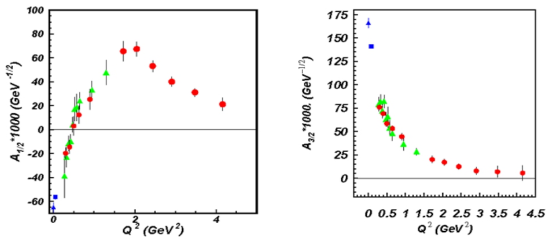

Fig. 4. $A_{1/2}$ γ_vpN* electrocouplings of the N(1440)1/2$^+$ (left), $A_{3/2}$ γ_vpN* electrocouplings of the N(1520)3/2$^-$ (right) from analyses of the CLAS electroproduction data off protons in the πN (red circles) and $\pi^+\pi^-$p channels [12, 13] (green triangles). The photocouplings were taken from the RPP [17] (blue filled triangles) and the CLAS data analysis [18] of πN photoproduction (blue filled squares).

The overlap of the results from the different channels / analyses demonstrates the quality and reliability of the extraction method for these quantities.

For low lying excited nucleon states in the mass range up to 1.6 GeV for which the dominant decay is into a πN final states, the extraction of resonance electrocouplings is mainly driven by the data on single-pion exclusive electroproduction. The CLAS data for the $\pi^+\pi^-$p channel plays a critical role in the extraction of the γ_vpN* electrocouplings of excited nucleon states in the mass range above 1.60 GeV, which decay preferentially to πN final states, for example Δ(1620)1/2$^-$, Δ(1700)1/2$^-$, N(1720)3/2$^+$, and the not fully established N'(1720)3/2$^+$ state. Based on the presently available data, the electrocouplings of these states can only be determined from the data in the $\pi^+\pi^-$p exclusive electroproduction channel off protons, while the πN channels do not show enough sensitivity.

The information on the excited nucleon state photocouplings could be extended recently based on CLAS photoprduction measurements to the photocouplings of most nucleon resonances with masses above 1.6 GeV from the exclusive πN and $\pi^+\pi^-p$ photoproduction off protons. Many of the investigated resonances decay preferentially to the ππN final states. The cross sections of $\pi^+\pi^-p$ photoproduction off protons dominates the ππN photoproduction off proton channels. A total of 400 million $\pi^+\pi^-p$ events were collected exceeding the statistics of previous experiments by a factor of ~ 50. Within the framework of the JM meson-baryon reaction model a good description of the new data could be achieved ($1.15 < \chi^2$/d.o.f. < 1.3). The resonance photocouplings extracted from this work are listed in Tab. 1. A comparison with the resonance photocoupling ranges and the results of the multichannel analysis included in the PDG2018 is given in the table.

Table 2. Resonance photocouplings determined from analysis of the $\pi^+\pi^-p$ photoproduction data from this work in comparison with the previous results from the PDG average and from multichannel analysis.

resonances	$A_{1/2} \times 10^3$ from $\pi^+\pi^-p$ $\mathrm{GeV}^{-1/2}$	$A_{1/2} \times 10^3$ PDG ranges $\mathrm{GeV}^{-1/2}$	$A_{1/2} \times 10^3$ multi-channel Analysis $\mathrm{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ from $\pi^+\pi^-p$ $\mathrm{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ PDG ranges $\mathrm{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ multi-channel analysis $\mathrm{GeV}^{-1/2}$
Δ(1620) 1/2⁻	29.0 ± 6.2	30 – 60	55 ± 7			
N(1650) 1/2⁻	60.5 ± 7.7	35 – 55	32 ± 6			
***N*(1680) 5/2⁺**	-27.8 ± 3.6	-18 – -5	-15 ± 2	128 ± 11	130 – 140	136 ± 5
***N*(1720) 3/2⁺**	80.9 ± 11.5	80 – 120	115 ± 45	-34.0 ± 7.6	-48 – 135	135 ± 40
Δ(1700) 3/2⁻	87.2 ± 18.9	100 – 160	165 ± 20	87.2 ± 16.4	90 – 170	170 ± 25
Δ(1905) 5/2⁺	19.0 ± 7.6	17 – 27	25 ± 5	-43.2 ± 17.3	-55 – -35	-50 ± 5
Δ(1950) 7/2⁺	-69.8 ± 14.1	-75 – −65	-67 ± 5	-118.1 ± 19.3	-100 − 80	-94 ± 4

A good agreement in the magnitude and sign of the photocouplings with the photocoupling ranges in the PDG listings can be observed. However, for several resonances, the photocouplings determined from the multichannel analysis are different. Implementing the new $\pi^+\pi^-p$ photoproduction data from CLAS into the global multichannel analyses will improve our knowledge on the photocouplings and hadronic decay parameters of the resonances in the mass range up to a W of 1.6 GeV significantly. The analysis shows, that for a complete description of the $\pi^+\pi^-p$ photo- and electroproduction measured with CLAS based on Q^2-independent resonance hadronic decay parameters, the new baryon states $N(1720)3/2^+$ is needed.

5. Outlook

The upgraded CLAS12 spectrometer started data taking in the beginning of 2018. Based on the already obtained high quality and high statistics data, the exploration of the structure of excited nucleon states in exclusive πN, KY, and

$\pi^+\pi^-p$ electroproduction off protons with photon virtualities Q^2 up to 12.0 GeV^2 has already started. The new data will significantly extend the accessible Q^2 range and improve the statistics in the already accessible range. The distance scale accessible at high Q^2 correspond to the still unexplored regime for N* electroexcitations where the resonance structure is dominated by the quark core with almost negligible meson-baryon cloud contributions providing access to the properties of dressed quarks inside N* states of different quantum numbers. The extraction of the dressed quark mass function from the data on the $\gamma_v pN^*$ electrocouplings of the resonances with different structure, such as radial excitations, spin-isospin flip, and orbital excitations, will the study of the fundamental assumptions of strong QCD with experimental data. The new data will provide access to the dressed quark mass function in the range of quark momenta up to 1.5 GeV for the first time. In this regime the transition from quark-gluon confinement to pQCD takes full effect, which will allow us to address several open problems of the Standard Model, like the nature of the hadron mass and quark-gluon confinement.

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