Excited Nucleon Spectrum and Structure Studies with CLAS and CLAS12

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Abstract. The study of the spectrum and structure of excited nucleon states employing the electroproduction of exclusive reactions is an important avenue for exploring the nature of the non-perturbative strong interaction. The CLAS detector in Hall B has provided the dominant part of the available world data on most relevant meson electroproduction channels off the nucleon in the resonance region for Q^2 up to 5 GeV². Analyses of CLAS data for the exclusive channels πN , ηN , and $\pi^+\pi^- p$ on a proton target have provided the only results available on the Q^2 evolution of the electro-excitation amplitudes for the transitions from the initial photon-proton to the final N^* states in the mass range up to W=1.8 GeV. These electrocouplings allow for exploration of the internal structure of the produced excited nucleon states. This work has made it clear that consistent results from independent analyses of several exclusive channels with different resonance hadronic decay parameters and non-resonant backgrounds but the same N^* electro-excitation amplitudes, is essential to have confidence in the extracted results. Starting in early 2018, a program to study the spectrum and structure of N^* states in various exclusive electroproduction channels using the new CLAS12 spectrometer commenced. These studies will probe the structure of N^* states in the mass range up to W=3 GeV and for Q^2 as low as 0.05 GeV² and as high as 10-12 GeV², thus providing a means to access N^* structure information spanning a broad range of distance scales. Quasi-real photoproduction studies are also planned to search for additional N^* states, the so-called hybrid baryons, for which the glue serves as an active structural component. In this talk the N^* programs from both CLAS and CLAS12 will be reviewed.

HALL B N* PROGRAM - OVERVIEW AND GOALS

The study of the spectrum and structure of excited nucleon states in Hall B, referred to as the N^* program, represents one of the cornerstones of the physics program at Jefferson Laboratory (JLab). The experimental program was carried out for ~15 years using the large acceptance CLAS spectrometer [1]. This system was decommissioned in 2012 and replaced with the new large acceptance CLAS12 spectrometer [2] as part of the JLab 12 GeV upgrade project. The program of CLAS12 includes a number of experiments as part of the continuing N^* program in Hall B. The experiments will collect data over an unprecedented kinematic range for the study of nucleon excited states. Data will be acquired in the range of Q^2 from 0.05 to 12 GeV², spanning the full center-of-mass angular range of the decay final states. See Ref. [3] for more details on the overall CLAS12 physics program.

Both the CLAS N^* program with electron and photon beams with energies up to 6 GeV (for Ref. [4] for a summary) and the CLAS12 N^* program with electron beams up to 11 GeV were designed to measure cross sections and spin observables over a broad kinematic range for a host of different reaction channels. The main part of the N^* program is based on electroproduction experiments of various exclusive reactions employing an unpolarized liquid-hydrogen target. The central goals of this focused program include:

- Unravel the spectrum of contributing excited nucleon states in a manner complementary to photoproduction data and confirm evidence for new baryon states with electroproduction data;
- Explore the interplay between meson-baryon and dressed quark degrees of freedom in the structure of excited nucleon states via studies of the Q^2 evolution of the electro-excitation amplitudes;
- Probe the momentum dependence of the dressed quark mass function from independent studies of the electroexcitation amplitudes of different excited nucleon states to shed light on the generation of >98% of hadron mass;

- Map out the momentum dependence of the dressed quark mass function at distances where the transition from the regime of quark-gluon confinement to pQCD is expected;
- Understand the effect of non-point-like diquark correlations in explaining the structure of excited nucleon states of different quantum numbers via the electro-excitation amplitudes as a function of Q^2 ;
- Search for predicted hybrid baryon states where glue is an active structural component.

The CLAS spectrometer was used to provide a significant fraction of the available world data for the study of excited nucleon states with electron beams. To date nearly 50 papers have been published to detail the measurement results specifically relevant for the N^* program. The data include differential cross section and various spin and polarization observables for the exclusive electroproduction reactions $\gamma_{\nu}p \rightarrow \pi^+\pi^-p$, π^0p , π^+n , ηp , $K^+\Lambda$, $K^+\Sigma^0$, ωp , $\rho^0 p$, and ϕp . All data from CLAS are included in the CLAS Physics Database [5]. The analysis of data acquired from CLAS continues and additional analyses are currently in progress [6].

EXTRACTION OF ELECTRO-EXCITATION AMPLITUDES

The structure of excited nucleon states is more complex than what can be described accounting only for quark degrees of freedom. At lower Q^2 ($\leq 2 \text{ GeV}^2$), the structure of states is well described by adding an external meson-baryon cloud to the underlying quark core. However, at higher Q^2 ($\geq 3 \text{ GeV}^2$), the quark core is already the largest contributor to baryon structure. For $Q^2 > 5 \text{ GeV}^2$ we can probe the transition from the regime of confinement to perturbative Quantum Chromodynamics (QCD). The detailed structure of the excited nucleon states is probed by the $\gamma_v NN^*$ electro-excitation amplitudes as a function of Q^2 . As the virtual photon has both longitudinal and transverse polarization, these electro-excitation amplitudes (also called helicity amplitudes or transition form factors) include both longitudinal (S_{1/2}) and transverse ($A_{1/2}$ and $A_{3/2}$ - where the subscripts refer to the helicity of the $\gamma_{\nu}p$ system) amplitudes. These amplitudes directly reflect the underlying charge and current densities of these strongly interacting systems and elucidate the relevant degrees of freedom of the excited nucleon states and their evolution with distance scale Q^2 . As Q^2 increases it is expected that these amplitudes will probe the coupling to the elementary quarks as opposed to the dressed constituent quarks at lower Q^2 . Such measurements hold promise to establish the connection to QCD approaches in the strong interaction domain. Indeed, they represent our only source of information on many facets of the non-perturbative strong interaction in the generation of N^* states of different quantum numbers from quarks and gluons. The data from CLAS with electron beam energies up to 6 GeV, spanned a range of Q^2 up to ~5 GeV². With the coming data from CLAS12 with beam energies up to 11 GeV, the Q^2 range of the data will extend to ~12 GeV².

The extraction of the electrocouplings for most states up to $W \sim 1.8$ GeV has been completed from CLAS data based on exclusive analysis of the $\pi^0 p$, $\pi^+ n$, ηp , and $\pi^+ \pi^- p$ reaction channels. Table 1 shows details on the different states for which the electrocouplings have been extracted and the associated Q^2 range of the measurements [7]. To complete these extractions different analysis approaches have been employed. For the πN and ηN channels the electrocouplings have been extracted using either a unitary isobar model approach or via fixed-*t* dispersion relations. For the $\pi^+\pi^-p$ channel, the data-driven JLab-Moscow State University model (JM) has been employed. Ref. [8] contains a discussion of these different approaches.

Reaction Channel	N^*, Δ^* States	Q^2 Ranges of Electrocouplings (GeV ²)
$\pi^0 p, \pi^+ n$	$\Delta(1232)3/2^+$ N(1440)1/2 ⁺ , N(1520)3/2 ⁻ , N(1535)1/2 ⁻	0.16 - 6.0 0.30-4.16
$\pi^+ n$	N(1675)5/2 ⁻ , N(1680)5/2 ⁺ , N(1710)1/2 ⁺	1.6 - 4.5
ηp	N(1535)1/2 ⁻	0.2 - 2.9
$\pi^+\pi^-p$	$\begin{array}{c} N(1440)1/2^+, N(1520)3/2^-\\ \Delta(1620)1/2^-, N(1650)1/2^-, N(1680)5/2^+\\ \Delta(1700)3/2^-, N(1720)3/2^+, N'(1720)3/2^+ \end{array}$	0.25 - 1.5 0.5 - 1.5

TABLE 1. Excited nucleon states for which CLAS data have been used to extract the electroexcitation amplitudes. The table shows the reaction channel, the states, and the Q^2 range of the data. See Ref. [7] for the electrocouplings and the associated references.

Over the past several years calculations of form factors and electro-excitation amplitudes with the Dyson-Schwinger equation framework have shown that these fundamental quantities directly determined from experimental data are intimately connected with the underlying momentum dependence of the dressed quark mass function [6, 9]. Combining the data already produced by CLAS and the data expected with the increased Q^2 reach of CLAS12 up to 12 GeV², a very broad range of quark momenta will be spanned to further probe the dressed quark mass function moving from the regime of fully dressed constituent quarks in the confinement regime toward the regime of only "lightly" dressed bare quarks. In this manner, the data from the N^* program in Hall B can address critical and fundamental questions on the nature of confinement and how the overwhelming majority of the visible mass in the universe (i.e. the mass of the hadrons) is generated.

IMPORTANCE OF K+Y FINAL STATES

The majority of the advancements in understanding the spectrum and structure of excited nucleon states have been provided by advanced analyses of the πN , $\pi \eta$, and $\pi^+ \pi^- p$ channels [10]. However, with the publication of the high statistics photoproduction $K^+\Lambda$ and $K^+\Sigma^0$ data from CLAS, the potential and importance of the hyperon channels has been appreciated. In fact, the spectrum of excited nucleon states listed in the recent edition of the Particle Data Group (PDG) [11] has been radically altered by the CLAS K^+Y data, including not only the cross sections, but also the available polarization observables. Table 2 shows a comparison of the PDG evidence for a dozen N^* and Δ^* states (based on the PDG "*" rating) compared to just a decade ago. For most of these states the K^+Y data were a crucial input.

TABLE 2. The evolution of our understanding of the excited nucleon spectrum. This table shows 12 states whose PDG "assurance" rating has increased over the past decade and the initial and/or final states where this evidence has come from. The *KY* channels have been a critical aspect of this evolution for a number of states.

State	PDG	PDG	πN	KΛ	KΣ	γN
N(mass)J ^r	pre-2010	2018				
$N(1710)1/2^+$	***	****	****	**	*	****
N(1875)3/2 ⁻		***	**	*	*	**
$N(1880)1/2^+$		***	*	**	**	**
N(1895)1/2-		****	*	**	**	****
$N(1900)3/2^+$	**	****	**	**	**	****
$N(2000)5/2^+$	*	**	*			**
$N(2100)1/2^+$	*	***	***	*		**
N(2120)3/2-		***	**	**	*	***
N(2060)5/2-		***	**	*	*	***
$\Delta(1600)3/2^+$	***	****	***			****
$\Delta(1900)1/2^{-}$	**	***	***		**	***
$\Delta(2200)7/2^{-}$	*	***	**		**	***

It is also important to appreciate that the CLAS detector has provided the lion's share of the $K^+\Lambda$ and $K^+\Sigma^0$ world data for electroproduction in the nucleon resonance region (*W* up to 2.5 GeV, Q^2 from 0.3 to 5.4 GeV²) [12]. These data are available over a broad kinematic range and have comparable or smaller uncertainties than for the oftenused $\pi^+\pi^-p$ electroproduction data from CLAS. The available *KY* data from CLAS include differential cross sections, separated structure functions, and both recoil and beam-recoil transferred polarization. These *KY* electroproduction data can be used to confirm the signals of new baryon states observed in photoproduction in a complementary fashion. Within each bin of Q^2 , the determined states must have the same mass and decay widths. In such an analysis, the electroproduction data can be used to verify the findings for the states shown in Table 2. In order to extract the electrocouplings from the *KY* data to gain insight and access into the structure of the excited nucleon states, a suitable model of the reaction must be developed that accurately describes the available data. Such an extraction model has not been sufficiently developed to employ in this regard. However, there has been some recent advancement of a possible candidate isobar model that has been fit to the available K^+Y photo- and electroproduction data from CLAS and elsewhere [13]. Another important factor to consider is the fact that for higher-lying excited nucleon states where the decay strength to πN is much reduced compared to the dominant $\pi \pi N$ cross sections, the *KY* channels will be critical to provide an independent extraction of the electrocouplings for higher-lying excited nucleon states (that have decay strength to both final states). Such comparisons are essential to provide confidence in the reliability of the results.

CLAS12 N* PROGRAM OVERVIEW

The CLAS12 spectrometer in Hall B was conceived, designed, and built as part of the recent JLab 12 GeV upgrade project. The maximum beam energy in Hall B is limited to 11 GeV. The nominal beam-target luminosity for experiments with CLAS12 is 1×10^{35} cm⁻²s⁻¹, a 10 times increase above the original CLAS spectrometer. This is required in order to measure cross sections to higher Q^2 . CLAS12 was installed in Hall B in the period from 2012-2017. At the end of 2017 the detector system was commissioned during an Engineering Run. The physics program officially began with data taking in Feb. 2018. Experiments with a longitudinally polarized electron beam on both unpolarized liquid-hydrogen and liquid-deuterium targets have collected significant amounts of data with more running planned on these targets in upcoming years. The N* program experiments with CLAS12 include:

- Nucleon Resonance Studies with CLAS12 Studies of N^* , Δ^* spectrum and structure with a beam energy of 11 GeV focusing primarily on πN , ηN , and $\pi^+\pi^- p$ final states.
- *KY* Electroproduction with CLAS12 Studies of N^* , Δ^* spectrum and structure with a beam energy of 11 GeV focusing primarily on $K^+\Lambda$ and $K^+\Sigma^0$ final states.
- N^* Studies via KY Electroproduction at 6.6 and 8.8 GeV Extension of experiment at 11 GeV at lower beam energies to provide precision data at Q^2 overlapping existing data from CLAS.
- A Search for Hybrid Baryons in Hall B with CLAS12 A search for baryon states with glue as an active structure component predicted by lattice QCD calculations. This experiment will use beam energies of 6.6 and 8.8 GeV and focus on measurements of electrocouplings at $Q^2 < 0.5 \text{ GeV}^2$ where the amplitudes are predicted to have a significantly different Q^2 dependence compared to three quark baryons.

At the current time the CLAS Collaboration is gearing up to begin analysis of the significant amount of data already collected with CLAS12. To date this amounts to ~400 mC of collected charge and ~3 PB of data to tape storage after roughly of year of data taking. In order to be ready for physics analysis, a significant level of effort has been being geared toward optimizing detector alignment in both the Forward and Central Detectors of CLAS12 using data collected at zero field, quantifying our knowledge of tracking efficiency and improving algorithms to maximize this efficiency, understanding the momentum distortions to enable effective corrections to the reconstructions to optimize missing mass resolutions for identification of exclusive final states and minimizing backgrounds, and developing all corrections necessary to enable optimal timing resolution to enable the best possible charged particle identification versus momentum.

The initial analyses and publications based on data collected with CLAS12 will involve yield ratios from extractions of various beam spin asymmetries where a detailed understanding of detector acceptance and efficiencies are not essential. The important tasks that lie ahead are understanding the systematics of yield normalization for cross section extractions, to develop accurate kinematic corrections to optimize momentum and missing mass resolutions due to undesired effects due to limitations of our knowledge of magnetic field, detector geometry, alignment, and reconstruction biases. A key part of our efforts to extract cross sections from CLAS12 will also involve development of accurate radiative correction models to account for important bin migration effects over our full kinematic phase space for our inclusive, semi-inclusive, and exclusive reactions.

CONCLUDING REMARKS

The study of the spectrum and structure of excited nucleon states in Hall B at Jefferson Laboratory, referred to as the N^* program, is based on three different but equally essential aspects. The *first* is providing experimental data of high

quality and broad kinematic coverage for a number of different exclusive reaction channels. The observables are in the form of differential cross sections, separated structure functions, beam spin asymmetries, and polarization observables span invariant energies up to 4 GeV, four-momentum transfers Q^2 based on data from CLAS up to 5 GeV² with electron beams up to 6 GeV and on data from CLAS12 up to Q^2 of 12 GeV². With the large acceptance CLAS and CLAS12 spectrometers, these data span the full angular phase space in the center-of-mass system for the final state reaction products. To date, the data from CLAS in the nucleon resonance region for both photoproduction and electroproduction experiments dominate the world database. In the coming years the data measurements from CLAS12 will significantly overlap and extend these data.

The *second* essential aspect of the Hall B N^* program is to facilitate the development of reaction models that accurately describe the available experimental data. Such models are essential tools in order to be able to extract the electrocouplings of the contributing N^* and Δ^* states. The *third* essential aspect is the development of the QCD-rooted approaches in order to connect the data to theory to make progress in understanding strong interaction dynamics of dressed quarks and their confinement in baryons over a broad range of Q^2 . High quality experimental data are essential to address the most challenging problems of the Standard Model of fundamental particles and interactions on the nature of hadron mass, confinement, and the emergence of excited nucleon states of different quantum numbers from QCD.

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