Studies of Excited Nucleons in Exclusive Electroproduction

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1 Executive Summary

- With the advent of the new generation of electron-scattering facilities, such as CEBAF at JLab, the Mainz Microtron, and MIT/Bates [1], enormous progress has been made in uncovering the underlying structure of excited nucleon states. Using a proton target, a large body of data in the nucleon resonance region relating to the crucial exclusive channels ($\pi^+ n$, $\pi^0 p$, ηp, KY, $\pi^+\pi^- p$) was obtained at invariant masses of the final hadronic system W up to 2.5 GeV and photon virtualities Q^2 up to 5 GeV^2. The CLAS detector at JLab, with almost complete phase-space coverage [2], has provided the lion's share of the world's data on exclusive meson electroproduction in the resonance excitation region. Analyses of the CLAS data have enabled the extraction of the $\gamma_v NN^*$ electrocouplings for all resonances with masses less than 1.6 GeV for Q^2 up to 5 GeV^2 and have provided precise information on the $N \to \Delta$ transition form factors for $Q^2 < 7$ GeV^2 [1–4]. Moreover, the determination of mutually consistent results on the $N(1440)1/2^+$ and $N(1520)3/2^-$ electrocouplings from analyses of the major $N\pi$ and $\pi^+\pi^- p$ exclusive channels with distinctively different non-resonant contributions, strongly suggests that the extracted electrocouplings are reliable. These results, in turn, may then serve as an empirical benchmark.
- Theoretical analyses of the extracted $\gamma_v NN^*$ electrocouplings [5–14] reveal that the complexity of N^* structure derives from the interplay of the internal core of three dressed quarks with the meson-baryon cloud. Different N^* states, as expressed by their quantum numbers, will have distinctly different relative contributions for the quark core and meson-baryon cloud. The generation of each excited baryon is a manifestation of the interplay of these two mechanisms. Mapping out the electrocouplings over the entire spectrum of N^* states offers a unique means to explore the richness of the non-perturbative strong interaction in generating N^* states of different quantum

numbers as relativistic bound systems of quarks and gluons. As Q^2 increases, the relative quark core contribution increases for all excited nucleon states and gradually transitions to where the quark degrees of freedom dominate at $Q^2 > 5$ GeV^2; a mostly unexplored region of kinematics.

- Upon completion of the 12 GeV JLab upgrade, CLAS12 will provide the international nuclear physics community with a tool that is capable of determining resonance electrocouplings up to 12 GeV^2, the highest Q^2 ever achieved in exclusive measurements [13, 14]. A dedicated experiment that is tentatively scheduled to run directly after commissioning of CLAS12 in Hall B will determine the electrocouplings of all prominent resonances for Q^2 from 5 to 12 GeV^2 from data in the single meson-baryon ($N\pi$, KY, etc.) and $\pi^+\pi^- p$ channels [15,16]. Existing theoretical studies indicate that such data will, for the first time, penetrate the meson-baryon cloud and expose the dressed-quark core of nucleon resonances. It will thereby provide access to the inner workings of nucleon resonances and serve as a probe of length scales that are associated with the transition from the confinement regime to the perturbative domain. Furthermore, experiments at low Q^2 from 0.05 to 0.5 GeV^2 will become feasible, which are promising in the search for new states of hadronic matter, the so-called hybrid baryons, with glue as an explicit baryon constituent [17, 18]. Success in exploration of resonance structure strongly depends on development of the tools necessary for the reliable extraction of the resonance parameters from this wealth of data. A new effort, the JLab Physics Analysis Center (JPAC), has recently begun to support amplitude analysis for future experiments in hadron physics. Novel methods are needed in order to extend this activity toward high (5 GeV$^2 < Q^2 <$ 12 GeV^2) and low photon virtualities (0.05 GeV$^2 < Q^2 <$ 0.5 GeV^2). Plans for the development of these approaches are outlined in Ref. [14]. Reaction models capable of extracting the $\gamma_v NN^*$ electrocouplings in these Q^2 ranges from single meson-baryon and $\pi^+\pi^- p$ electroproduction represent the most pressing need in analyses of data from future experiments.
- Fostering the development of QCD-based theory, capable of computing the $\gamma_v NN^*$ electrocouplings, is crucial. Without such guidance, no amount of electroproduction data could uncover the novel features of the Standard Model. To be useful, theoretical approaches must relate the empirically determined $\gamma_v NN^*$ electrocouplings to the non-perturbative features emerging from the strong interaction so as to reveal the structure of N^* states (see Ref. [14]). There are two fundamental and conceptually different directions in analyses, the input of which are the extracted $\gamma_v NN^*$ electrocouplings, which will be based on the QCD Lagrangian, namely: the Dyson-Schwinger equation of QCD (DSEQCD) or Lattice QCD (LQCD). Notwithstanding advances in these QCD-related techniques, constituent-quark models remain important because they may readily be deployed for the description of the $\gamma_v NN^*$ electrocouplings over the entire spectrum of N^* states [14], especially after their improvements with input drawn from quantum field theory [10, 19]. High-level physics analyses of the $\gamma_v NN^*$ electrocouplings will address the most challenging and still open questions in the Standard Model on the nature of quark-gluon confinement and the mechanisms responsible for the generation of >98% of hadron masses. Eventually we will be able to see whether the Standard Model can successfully describe the complex structure of all N^* states and, if so, how the interactions between dressed-quarks and gluons create the spectrum of baryons.

2 Current Status and Prospects

A broad international effort aimed at determining the spectrum and structure of nucleon resonances provides a unique opportunity with which to forge an understanding of essentially non-perturbative features of the Standard Model. It offers the possibility of answering the three fundamental questions at the heart of hadronic physics:

- What is confinement?
- How is confinement connected with dynamical chiral symmetry breaking, which accounts for the origin of roughly 98% of the visible mass in the universe?
- Can the Standard Model successfully describe the complex structure of all N^* states and, if so, how do the interactions between dressed-quarks and gluons create the spectrum of baryons?

The emergence of effective degrees of freedom of the nucleon excited states in terms of the dressed quarks and gluons, which possess dynamical momentum-dependent mass and complex structure, makes them different with respect to the elementary quarks and gluons. Their strong interaction in the non-perturbative regime is much more complex than those of the elementary quarks and gluons encoded in the QCD Lagrangian. The measurement of the transition amplitudes or the $\gamma_v NN^*$ electrocouplings from the initial state virtual photon and ground-state nucleon to the excited nucleon states over a broad range of photon virtualities, Q^2, opens up a unique opportunity to explore many facets of the non-perturbative strong interaction in generating excited nucleon states of different quantum numbers. It is possible, and has been shown for the example of the Roper resonance [20], that unambiguous signals for new states of hadronic matter, such as the hybrid baryons predicted more than 30 years ago [21, 22] and reinforced by the recent lattice QCD studies [13, 18], could be realized by a clean theoretical explanation of the Q^2 evolution of the amplitudes.

The experimental study of N^* structure using meson electroproduction has a long and successful history of exposing the degrees of freedom and the interplay between them that determines the properties of nucleon resonances. Furthermore, the last decade has seen extraordinary progress in this regard owing to a capitalization of the new generation of electron scattering facilities such as CEBAF at JLab, the Mainz Microtron, and MIT/Bates [1]. Using a proton target, a large body of data in the nucleon resonance region relating to the crucial exclusive channels ($\pi^+ n$, $\pi^0 p$, ηp, KY, $\pi^+\pi^- p$) was obtained at invariant masses of the final hadronic system W up to 2.5 GeV and Q^2 up to 5 GeV^2. The largest part of the exclusive meson electroproduction data was obtained at JLab with the CLAS detector in Hall B and, for the first time, differential cross sections and a variety of polarization asymmetries were obtained for these reactions with almost complete phase-space coverage [2]. Analyses of a portion of this body of data were able to extract the $\gamma_v NN^*$ electrocouplings of all well-established resonances with masses less than 1.6 GeV and to provide precise information about the $N \to \Delta$ transition form factors for $Q^2 < 7$ GeV^2 [1–4]. Moreover, the determination of mutually consistent results from analyses of different exclusive channels, having distinctly different non-resonant contributions but with common resonance electrocouplings, strongly attests that the extracted electrocouplings are physically reliable and hence represent a valid empirical benchmark [4]. Exciting new data are also becoming available. For example, CLAS data on $\pi^+\pi^- p$ electroproduction have provided preliminary electrocouplings for several high-lying resonances (mass >1.6 GeV) [14,23]. Evidence for a new $3/2^+(1720)$ state from the CLAS $\pi^+\pi^-p$ data analysis reported in 2003 [24] was further enhanced in the recent studies with more measured observables. The CLAS KY data open up the prospects for the determination of the electrocouplings of high-lying resonances for $Q^2 < 5$ GeV^2 from independent analyses of this exclusive channel [25,26].

Theoretical analyses of the results for the $\gamma_v NN^*$ electrocouplings [5–14] have revealed N^* structure as a complex interplay between the internal core of three dressed quarks and an external meson-baryon cloud. The Excited Baryon Analysis Center (EBAC) at JLab has solved the fifty-year problem of the Roper resonance. This work demonstrated that the two-pole structure in the experimental data is generated by a single bare quark core pole that corresponds to the mass ∼300 MeV higher than the physical resonance mass after meson-baryon dressing [9,12]. Pronounced differences in the relative contributions from the quark core and the meson-baryon cloud to the structure of resonances with different quantum numbers were observed. For instance, the $A_{1/2}$ electrocoupling of the $N(1520)3/2^-$ state is dominated by the quark core at photon virtualities $Q^2 > 2.0$ GeV^2, while the meson-baryon cloud dominates electroexcitation of the $N(1675)5/2^-$ resonance off protons in the entire regime of photon virtualities $Q^2 < 5$ GeV^2 covered in current measurements. These results clearly demonstrate distinctly different manifestations of the non-perturbative strong interaction in generating excited nucleons of different quantum numbers. Studies of resonance electrocouplings over the full excited nucleon state spectrum are necessary to access particular components of the resonance structure. The behavior of all measured excited nucleon state electrocouplings has shown that the relative quark-core contributions grow with increasing photon virtualities in a gradual transition to where the quark degrees of freedom dominate for $Q^2 > 5$ GeV^2. This region of kinematics still remains to be explored in exclusive reactions. After completion of the 12 GeV JLab upgrade, CLAS12 will provide the international nuclear physics community with a tool that is capable of determining resonance electrocouplings up to 12 GeV^2, the highest Q^2 ever achieved in exclusive measurements. A dedicated experiment that is tentatively scheduled to run directly after the commissioning of CLAS12 in Hall B at JLab will determine the electrocouplings of all prominent resonances for Q^2 from 5 to 12 GeV^2 from data in the $N\pi$, $\pi^+\pi^-p$, and KY channels [15,16]. Existing theoretical studies indicate that such data will, for the first time, penetrate the meson-baryon cloud and expose the dressed-quark core of nucleon resonances. It will thereby provide access to the inner structure of nucleon resonances and serve as a probe of length scales that are associated with the transition from the quark-gluon confinement regime to the perturbative domain. Furthermore, experiments at low Q^2 from 0.05 to 0.5 GeV^2 are promising in the search for new states of hadronic matter, the so-called hybrid baryons with glue as an explicit baryon constituent [17]. These studies will also provide preferential conditions for accessing the meson-baryon cloud [9].

3 Understanding Non-Perturbative Strong Interactions: Synergy Between Experiment and Theory

Success in the exploration of resonance structure is strongly coupled to the development of the tools necessary for the reliable extraction of resonance parameters from the aforementioned wealth of data. For the first time, the electrocouplings of N^* states with masses less than 1.6 GeV are available from independent analyses of the $N\pi$ and ηp electroproduction channels, and for exclusive electroproduction of $\pi^+\pi^-p$ from protons. These studies have been carried out within the framework of different reaction models, which have independently employed each of these reaction channels [3,4,27,28]. Preliminary results on electrocouplings of many resonances with masses above 1.6 GeV that decay preferentially via two-pion emission are still only available from data on the $\pi^+\pi^-p$ channel [23, 29]. The development of approaches for the extraction of the resonance electrocouplings from the KY electroproduction data is of particular interest and importance. This channel is sensitive to electrocouplings of N^* states with masses above 1.6 GeV. The $\pi^+\pi^-p$ and KY exclusive channels will be capable of providing independent information on electrocouplings of high-lying nucleon resonances. The electrocouplings of the $\Delta(1232)3/2^+$, $N(1440)1/2^+$, and $N(1520)3/2^-$ resonances were also obtained from a global multi-channel analysis carried-out by the Argonne-Osaka Collaboration within the framework of an advanced coupled-channel approach, capable for the first time of accounting for the contributions from two-meson-baryon states [8, 9]. Consistent results on the $\gamma_v NN^*$ electrocouplings determined from independent analyses of different exclusive meson electroproduction channels with different non-resonant contributions and obtained in global multi-channel analyses of photo-, electro-, and hadroproduction data will provide sound evidence for the reliable extraction of these fundamental quantities for subsequent analyses within the framework based on QCD hadron structure theory. Sound results on the $\gamma_v NN^*$ electrocouplings from multiple final states offer a key matching point in the bridge between hadron structure theory and phenomenological studies of nucleon resonance structure from the exclusive meson electroproduction data.

Studies of the production of high-mass baryon resonances in the presence of multi-peripheral backgrounds and through multi-particle decay channels, necessitates new analysis methods to take advantage of the constraints imposed by the relativistic S-matrix theory. A new effort at JLab, the JLab Physics Analysis Center (JPAC), has recently been formed to support amplitude analysis for future experiments in hadron physics. Novel methods are needed in order to extend this activity toward high-photon virtualities (5 GeV^2 $< Q^2 <$ 12 GeV^2) and low-photon virtualities (0.05 GeV^2 $< Q^2 <$ 0.5 GeV^2), which will become accessible in future experiments using the CLAS12 detector. Plans on the development of these approaches are outlined in Ref. [14]. Reaction models capable of extracting the $\gamma_v NN^*$ electrocouplings at the aforementioned high- and low-photon virtualities from $N\pi$, $\pi^+\pi^-p$, and KY electroproduction represent the most pressing need in analyses of data from existing and near-term future experiments.

Studies of nucleon resonance electrocouplings over a broad range of photon virtualities up to 12 GeV^2 open up a promising avenue towards understanding the non-perturbative strong interaction mechanisms that are responsible for the generation of excited nucleons of different quantum numbers as relativistic bound systems with an infinite number of quarks and gluons. Fostering the development of a QCD-connected theory that is capable of computing the $\gamma_v NN^*$ electrocouplings is crucial in order to achieve these objectives. Without such guiding theory, no amount of electroproduction data will be useful in exposing the novel features of the Standard Model. Useful approaches will relate the empirically determined $\gamma_v NN^*$ electrocouplings to emergent non-perturbative features of the strong interaction and reveal the structure of N^* states. The efforts of the international community on the development of theoretical approaches for a QCD-based interpretation of the experimental results on the $\gamma_v NN^*$ electrocouplings are summarized in a recent white paper review [14] prepared by theorists and experimentalists at institutions in the US, Central and Latin America, Europe, Asia, and Australia.

At present, two methods for the interpretation of resonance electrocouplings starting from the QCD Lagrangian appear to be viable: a) the Dyson-Schwinger equation of QCD (DSEQCD) and b) Lattice QCD (LQCD). DSEQCD provides a symmetry-preserving non-perturbative approach that can simultaneously predict the hadron spectrum and the nucleon elastic and transition form factors. It relates electrocouplings to the behavior of the dressed-quark mass-function and hence the dynamical chiral symmetry breaking that is responsible for the origin of more than 98% of visible mass in the universe [30]. This tool can enable electroproduction data to be used to chart the infrared behavior of the running dressed quark and gluon couplings and masses in QCD. That behavior holds the key to understanding confinement.

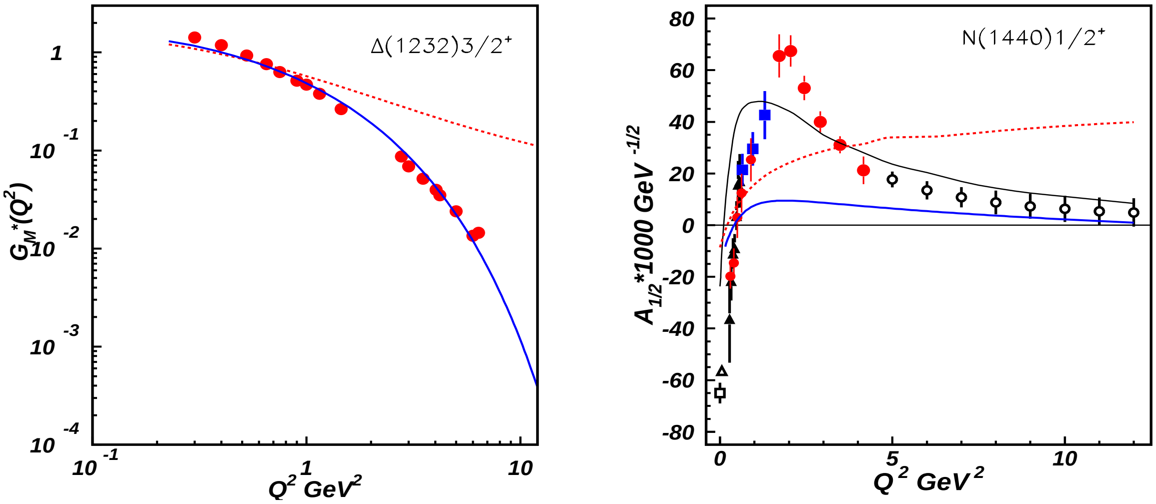

Figure 1: Resonance electroexcitation amplitudes and their physics analyses. (Left) JLab results on the $N \to \Delta$ magnetic form factor G_M^* in the Jones-Scadron convention [1,3] (red circles). (Right) $N(1440)1/2^+$ $A_{1/2}$ electrocoupling determined from the data on $N\pi$ [1,3] (red circles) and $\pi^+\pi^-p$ [4,28,29] (black triangles, blue squares) exclusive electroproduction. Photocouplings are taken from Refs. [31,32] and the projected results for experiments with CLAS12 [15] are shown by the open circles. The DSEQCD evaluations of the quark-core contributions [5,6] for momentum-independent and running dressed-quark masses are shown by the dashed red and solid blue lines, respectively. The results of an advanced light front quark model [10] employing running quark masses from DSEQCD [33] and taking into account the meson-baryon cloud are shown by the thin black line.

The results on the electroexcitation amplitudes of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ resonances available from JLab [1–4] are shown in Fig. 1 compared with evaluations of the quark-core contributions within the framework of the DSEQCD approach [5,6] starting from the QCD Lagrangian. The DSEQCD results were obtained employing: a) a simplified contact interaction between the dressed quarks that results in a momentum-independent quark mass function and b) a realistic full QCD parameterization of the quark-quark interaction that generates a momentum-dependent quark mass function as described in Ref. [33].

The experimental results on the $N \rightarrow \Delta(1232)3/2^+$ magnetic form factor are certainly in favor of a running-quark mass and provide for a promising opportunity to access the dressed-quark mass function. However, the DSEQCD approach [5, 6] takes into account the quark-core contribution only and can be compared to the data at photon virtualities where the major contribution to the resonance structure is from the quark core. This is the reason for the discrepancies between the DSEQCD results [5, 6] and the electrocouplings extracted from exclusive meson electroproduction data for the $N(1440)1/2^+$ for $Q^2 < 5$ GeV^2, where the meson-baryon dressing effects are substantial [8, 9]. A better description of the $A_{1/2}$ $N(1440)1/2^+$ electrocoupling in this area of photon virtualities was achieved in the advanced light front quark model [10] that takes into account meson-baryon dressing and employs running-quark masses from DSEQCD [33]. Therefore, future results on the $\gamma_v NN^*$ electrocouplings at photon virtualities above 5 GeV^2, where the quark-core contributions are expected to be dominant, are of particular importance for mapping the dressed-quark mass function. Both the $\Delta(1232)3/2^+$ and the $N(1440)1/2^+$ states have demonstrated sensitivity of their electroexcitation amplitudes to the momentum dependence of the quark running mass. This quantity is expected to be universal for all resonances. Therefore, consistent results on the dressed-quark mass function determined independently from $\gamma_v NN^*$ electrocouplings of different nucleon resonances will provide for reliable access to this fundamental ingredient of non-perturbative strong interaction physics.

LQCD has produced a baryon spectrum and preliminary results for some nucleon transition form factors [13, 14, 18]. Substantial focused efforts are required to produce electrocouplings in the domain 5 GeV$^2 < Q^2 <$ 12 GeV^2 in the foreseeable future. In this connection, the prospects for relating LQCD computations of partial waves for meson-baryon electroproduction amplitudes with the experimental results on the $\gamma_v NN^*$ electrocouplings are of particular importance. A successful description of the measured observables and the LQCD predictions on partial waves within the framework of the coupled-channel reaction models will provide resonance parameters that can be considered as consistent with LQCD expectations on excited nucleon structure. Currently LQCD offers the only approach for the description of *all* relevant degrees of freedom in the N^* structure based on the QCD Lagrangian over the entire range of photon virtualities.

A hybrid approach combines LQCD with light-cone sum rules (LCSRs), with LQCD providing moments of the quark distribution amplitudes for the ground- and excited-state nucleons and LCSRs being used to compute the electrocouplings [14, 34]. Furthermore, analyses of the $\gamma_v NN^*$ electrocouplings within the LCSR framework will offer access to the quark distribution amplitudes of the excited nucleon states. In this way, partonic degrees of freedom in the resonance structure will be revealed for the first time. These quantities will offer a valuable extension of the parton distribution functions currently available only for the ground state nucleons.

Notwithstanding advances in these QCD-related techniques, constituent-quark models remain important because they may readily be deployed widely for description of the $\gamma_v NN^*$ electrocouplings over the entire spectrum of excited nucleon states [14]. Improving such models with input drawn from quantum field theory [10], while maintaining their simplicity and widespread applicability, make them valuable tools for the QCD-motivated exploration of resonance structure. Such improvements include models based on concepts of AdS/CFT correspondence [19] and unquenched quark models, which offer promising opportunities for modeling of the meson-baryon cloud [11, 35]. The predictions of hadron structure theories for the existence and properties of hybrid baryons also represent a challenging problem for the models [36].

4 Interplay Between Resonance Structure and Deep Inelastic Physics

As mentioned in Section 3, studies of nucleon resonance structure from exclusive meson electroproduction data will extend our knowledge of the parton distribution functions currently available for ground state nucleons through the use of novel quark distribution amplitudes for excited nucleons of different quantum numbers inferred from the results on the $\gamma_v NN^*$ electrocouplings within the framework of LCSR [14,34]. The first results on the $N(1535)1/2^-$ quark distribution amplitude demonstrated distinctly different features in the quark distributions for the ground state nucleons and their chiral partner $N(1535)1/2^-$ that elucidated the impact of dynamical chiral symmetry breaking on resonance structure [34]. Moreover, the resonance $\gamma_v NN^*$ electrocouplings at high Q^2 available from resonance studies will allow us to extend exploration of inclusive and semi-inclusive structure functions toward values of Bjorken x_B close to unity. This will initiate development of approaches aimed at accessing transition GPDs between the ground and excited nucleon states from data on exclusive meson electroproduction in the DIS region offering possible additional direction for experiments at the Electron-Ion Collider. Data on $\gamma_v NN^*$ electrocouplings at high Q^2 can be used to constrain models of transition GPDs [14]. This will establish a collaborative bridge between experts in DIS and nucleon resonance physics.

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