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Nuclear Physics B Proceedings Supplement 00 (2012) 1–6
Nuclear Physics B Proceedings Supplement

Nucleon Resonance Structure from Exclusive Meson Electroproduction with CLAS and CLAS12

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Abstract

The CLAS detector at Jefferson Lab is a unique instrument, which has provided the lion's share of the world's data on meson photo- and electroproduction in the resonance excitation region. The electroexcitation amplitudes for the low-lying resonances $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$ were determined over a wide range of $Q^2 < 5.0\,\mathrm{GeV}^2$ in a comprehensive analysis of exclusive single-meson (π^+n, π^0p) reactions in the electroproduction off protons. Further, we were able to precisely measure $\pi^+\pi^-p$ electroproduction differential cross sections provided by the nearly full kinematic coverage of the CLAS detector. And, for the first time, the electrocouplings of the $P_{11}(1440)$ and $D_{13}(1520)$ excited states are determined from the exclusive-$\pi^+\pi^-p$ reaction. Consistent results on the electrocouplings from two-independent analyses (single- and double-pion electroproduction) have provided compelling evidence for the reliable extraction of the N^* electrocouplings. And preliminary results on the electrocouplings of the $S_{31}(1620)$, $S_{11}(1650)$, $D_{33}(1700)$, and $P_{13}(1720)$ states have recently become available. Theoretical analyses of these results have revealed that there are two major contributions to the resonance structure: a) an internal quark core and b) an external meson-baryon cloud. These CLAS results have had considerable impact on QCD-based studies on N^* structure and in the search for manifestations of the dynamical masses of the dressed quarks. Future CLAS12 N^* structure studies at high photon virtualities will considerably extend our capabilities in exploring the nature of confinement in baryons.

Keywords:
electromagnetic form factors, meson production, baryon resonances, JLab, CLAS, LQCD, DSEQCD, quark models

1. Introduction

In May of 2012 we completed the successful 6-GeV program with the CLAS detector in Hall B of Jefferson Lab. Among the many data runs with photons and electrons were several dedicated experiments focusing on hadron spectroscopy and hadron structure. The CEBAF Large Acceptance Spectrometer (CLAS) is a unique instrument formed of a set of detectors and designed for the comprehensive exploration of exclusive meson electroproduction off nucleons. CLAS afforded excellent opportunities to study the electroexcitation of nucleon resonances in detail and with great precision. The CLAS detector has contributed the lion's share of the world's data on meson photo- and electroproduction in the resonance excitation region [1, 2, 3, 4, 7, 6, 8, 9, 10]. In this paper, we shall focus on N* structure studies from exclusive meson electroproduction.

Studies of nucleon resonance electrocouplings $\gamma_v NN^*$ from the data on exclusive meson electroproduction off nucleons represent a key component of the N* Program with the CLAS detector. . Extracting the electromagnetic amplitudes for the transitions between ground and excited nucleon states ($\gamma_v NN^*$), and their ensuing evolution with photon virtualities Q^2, is fundamental for understanding the nature of the strong interaction in the non-perturbative regime [11, 12, 13, 14, 15, 16, 17]. Our studies of the $\gamma_v NN^*$ electrocouplings with the CLAS detector have already allowed us to map out the relevant degrees of freedom for the N* structure at the distances which correspond to the transition from combined contributions of meson-baryon and quark degrees of freedom to the onset of the dressed quark component [3, 4, 18]. Our approved CLAS12 experiment [17] will enable us to explore the nature of the non-perturbative strong interaction through studying the $\gamma_v NN^*$ electrocouplings in transitioning from confinement to pQCD [5, 16].

The non-perturbative strong interaction is enormously challenging. The degrees of freedom are not asymptotically-free current quarks and gauge gluons. The non-perturbative interaction of quarks and gluons is entirely different from that which exists within the pQCD realm and it gets quite complicated with all current quarks and gauge gluons becoming "dressed" by a cloud of virtual gluons and $q\bar{q}$ pairs. In the regime of large quark-gluon coupling, dressing of current bare quarks by dressed gluons gives rise to a momentum-dependent dynamical mass and structure of dressed quarks; and these are the effective degrees of freedom employed in constituent quark models. More than 98% of the hadron mass is generated non-perturbatively through Dynamical Chiral Symmetry Breaking (DCSB) processes, while the Higgs mechanism accounts for less than 2% of the light-quark baryon masses. The studies of the Dyson-Schwinger Equation of QCD (DSEQCD) have shown that dressing processes in the large quark-gluon running coupling regime are responsible for quark-gluon confinement [19]. Extracting the $\gamma_v NN^*$ electrocouplings gives information on the dressed quark mass structure and non-perturbative interaction, which is critical in exploring the nature of quark/gluon confinement and DCSB in baryons. In conjunction with these efforts, extracting the $\gamma_v NN^*$ electrocouplings from data on meson electroproduction off nucleons [3, 4, 5] will amply serve in accessing the non-perturbative character of the strong interaction.

2. Objectives, approaches and status for extraction of resonance electrocouplings

The CLAS research program on the electroproduction of nucleon resonances that decay through various meson channels is focused on the extraction of $\gamma_v NN^*$ electrocouplings for all prominent resonances for photon virtualities of $Q^2 < 5.0$ GeV^2. The studies are from both independent and combined analyses of the major meson electroproduction channels [3, 4]. A torrent of experimental data on the $\pi^0 p$ and $\pi^+ n$, $\pi^+\pi^- p$, ηp, and KY exclusive channels in the resonance excitation region has become realized from measurements with the CLAS detector. Independent extractions of the $\gamma_v NN^*$ electrocouplings from different exclusive meson electroproduction channel analyses were carried out employing phenomenological reaction models from fits to the data. The model separates contributions from resonant and non-resonant parts for the observables. The N^* parameters are determined at the resonant point on the real-energy axis employing a Breit-Wigner parametrization to the resonant amplitudes [18, 20, 21]. Analyses of independent exclusive channels are essential for the reliable extraction of the resonance parameters. At present, the separation of resonant and non-resonant parts of the electroproduction amplitudes can only be done within phenomenological reaction models. And hence, the resonance parameters extracted from the meson electroproduction data fit may be adversely affected by model assumptions. Non-resonant mechanisms in various meson-electroproduction channels are completely different, while the $\gamma_v NN^*$ electrocouplings are the same. Independent analyses of different exclusive channels make it possible to test whether they give consistent results for the resonance electrocouplings. Most nucleon resonances decay into both $N\pi$ and $N\pi\pi$ final states. Studies of resonance electroexcitations in these channels with completely different non-resonant contributions offer independent information on N^* electrocouplings. Therefore, a successful description of the data from $\pi^+ n$, $\pi^0 p$, and $\pi^+\pi^- p$ electroproduction off protons with consistent N^* electrocoupling values provides clear evidence for the reliable extraction of these quantities from meson-electroproduction data. Two conceptually different approaches have been developed for extracting the $\gamma_v NN^*$ electrocouplings from analyses of the CLAS single pion electroproduction data [21], allowing us to establish systematic uncertainties for $\gamma_v NN^*$ electrocouplings related to their model dependence. Extraction of $\gamma_v NN^*$ electrocouplings from the CLAS $\pi^+\pi^- p$ electroproduction data [6, 7] was carried out within the framework of the data-driven phenomenological reaction model JM developed in the Jefferson Lab – Moscow State University collaboration. At present, it is the only available worldwide approach for evaluation of $\gamma_v NN^*$ electrocouplings from the data of the exclusive $\pi^+\pi^- p$ electroproduction off protons.

Most of the N^* states having masses above 1.6 GeV decay preferentially to the $N\pi\pi$ final states. Thus

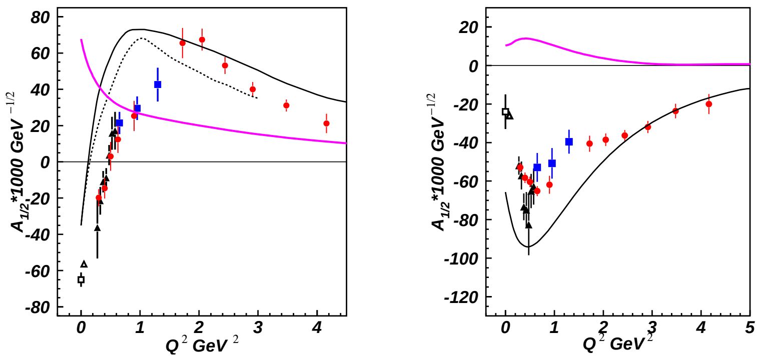

Figure 1: (color online) (Left) The $A_{\frac{1}{2}}$ electrocoupling of the $P_{11}(1440)$ state from the analyses of the $N\pi$ electroproduction data [21] (circles), $\pi^+\pi^-p$ electroproduction data [6] (triangles), and preliminary results from the $\pi^+\pi^-p$ electroproduction data at Q^2 from 0.5 to 1.5 GeV^2 [7] (squares). The photocouplings are taken from RPP [34] (open square) and the CLAS data analysis [35] (open triangle). Predictions from relativistic light front quark models [38, 39] are shown by black solid and dashed lines, respectively. Absolute values of meson-baryon cloud amplitudes from the EBAC-DCC coupled channel analysis [26] are shown by magenta thick solid line. (Right) The $A_{\frac{1}{2}}$ electrocoupling of the $D_{13}(1520)$ state. The data symbols are the same as in the left panel. The results of hypercentral constituent quark model [40] and absolute values of meson-baryon dressing amplitudes [26] are shown by black thin and magenta thick solid lines, respectively.

making it difficult to explore these states in the single-pion electroproduction channel. Analyses of the CLAS data on KY electroproduction [10] would therefore offer independent information on electrocouplings of high-lying resonances. Consistent results on electrocouplings from both exclusive $N\pi\pi$ and KY electroproduction would certainly offer compelling evidence for the reliable extraction the of $\gamma_v NN^*$ electrocouplings for high-mass resonances. Furthermore, the KY electroproduction data are critical in order to further explore signals from new N^* states, which were recently observed from analyses [24] of the CLAS/world data on cross section and polarization asymmetries in KY photoproduction. The next step is developing reaction models for the extraction of $\gamma_v NN^*$ electrocouplings from the KY electroproduction data, which is strongly needed for the N^* Program with the CLAS detector.

A global analysis of six major meson electroproduction channels was carried out within the framework of an advanced coupled-channel approach (EBAC-DCC) developed by the Excited Baryon Analysis Center at Jefferson Lab [26, 27, 28, 29, 30, 31, 32]. This approach incorporates hadronic final interactions between the final states of different exclusive photo- and electroproduction channels and accounts for restrictions imposed by a general unitarity condition. It further allows us to find the contribution from the N^* meson-baryon dressing amplitudes to the $\gamma_v NN^*$ electrocouplings, thereby giving insight into the N^* structure provided strictly by experimental data analysis, which is free from any *ad hoc* assumptions on resonance structure. First results of the EBAC-DCC approach to extracting the $\gamma_v NN^*$ electrocouplings can be found in Ref. [25].

3. Resonance Structure from the results on $\gamma_v NN^*$ Electrocoupling

We ultimately seek to establish an unambiguous relation between the information extracted phenomenologically and the non-perturbative strong interaction mechanisms that are responsible for baryon formation. From our analysis of the CLAS data on the Q^2-evolution of the $\gamma_v NN^*$ electrocouplings, we are able to describe the resonance structures in terms of an internal quark core and the surrounding meson baryon cloud, which can be viewed as originating from the reaction mechanisms as indicated in Fig. 1. Most of the single-pion (double-pion) data, upon which these analyses were based, were in the range $Q^2 < 5.0$ GeV^2 ($Q^2 < 1.3$ GeV^2) [6, 7, 16, 36, 37]. We encourage the reader to review our latest N* papers (Ref. [4, 18] and the references therein) for further clarification on extracting the transition helicity amplitudes and attendant resonance decay parameters.

Figure 1 shows the CLAS electrocoupling data from independent analyses of single- and double-pion electroproduction for the two excited-baryon states.

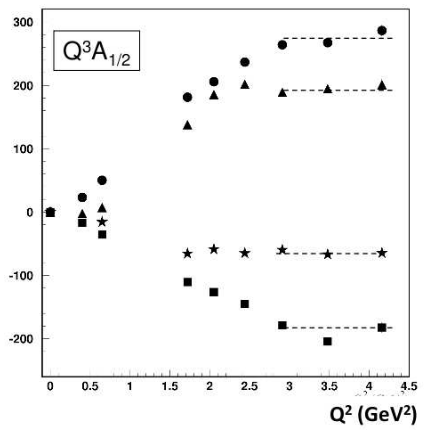

Figure 2: The $A_{\frac{1}{2}}$ electrocouplings as a function of Q^2 for four baryon resonances. The transition helicity amplitudes $A_{\frac{1}{2}}$ are scaled by Q^3 from the CLAS data analysis [21]. (triangles) $P_{11}(1440)$, (squares) $D_{13}(1520)$, (circles) $S_{11}(1535)$, and (stars) $F_{15}(1685)$.

Consistent values of the $\gamma_v NN^*$ electrocouplings are found. The two separate analyses of these two major electroproduction channels have completely different non-resonant mechanisms. That these two independent analyses agree so well strongly argues that we have reliably extracted the electrocoupling parameters. Superimposed are the contributions from the quark degrees of freedom, estimated within the framework of several quark models [38, 39, 40] and from the meson baryon dressing on the electrocouplings of the $P_{11}(1440)$ and $D_{13}(1520)$ states, calculated within the framework of the dynamical coupled channel EBAC-DCC approach [26]. These models find that the meson-baryon dressing contributions are substantial, particularly at $Q^2 < 1.0\,\text{GeV}^2$, and are quite complex, thus making it difficult to access unambiguously the quark degrees of freedom at low Q^2.

In a recent paper [33], the electrocouplings of the $P_{11}(1440)$ resonance, for the very first time, were evaluated within the framework of the Dyson-Schwinger Equation (QCD gap equation) starting from the QCD Lagrangian. These results have further revealed substantial contributions from the external meson-baryon cloud at $Q^2 < 5.0\,\text{GeV}^2$. Furthermore, and most importantly, they provide guidelines in searching for manifestations of dynamical masses of dressed quarks in the Q^2-evolution of $\gamma_v NN^*$ electrocouplings. For these studies to be complete, however, we will need to measure the resonance electrocouplings at distances where the contributions from the quark degrees of freedom will become dominant.

At photon virtualities of $Q^2 > 5.0\,\text{GeV}^2$, the quark degrees of freedom are expected to dominate the N^* structure [16]. CLAS analyses [18, 21] have strongly indicated that photons at higher virtualities penetrate the external meson-baryon cloud and hence will interact primarily with the internal quark core. This expectation is supported by the high Q^2-behavior of the $\gamma_v pN^*$ electrocouplings as is shown in Fig. 2. In this figure are plotted the nucleon resonance electrocouplings scaled by the third power of Q. This scaling factor of Q^3 is the expectation from constituent counting rules. The possible onset of scaling, as indicated by the dashed lines in Fig. 2 for $Q^2 > 3.0\,\text{GeV}^2$, is most likely due to preferential interaction of the photon with dressed quarks, while deviations of this scaling behavior at lower Q^2 are indicative of probing of the meson-baryon cloud. At these higher virtualities (for $Q^2 > 5.0\,\text{GeV}^2$), the quark degrees of freedom in the N^* structure are directly accessible to experiment and the contributions from the external meson-baryon cloud should be small or even negligible . This is a new and unexplored regime in the electroexcitation of nucleon resonances. It is therefore timely to measure the $\gamma_v pN^*$ nucleon resonance electrocouplings for $Q^2 > 5.0\,\text{GeV}^2$, a measurement which heretofore has not yet been done.

A dedicated experiment E12-09-003 [17] on the N* studies in exclusive meson electroproduction off protons with the CLAS12 detector is scheduled to run within the first five years of the commissioning of JLab 12-GeV Upgrade Project. This CLAS12 experiment seeks to extract the electrocouplings of all prominent N^*-states in the still unexplored domain of photon virtualties $5 < Q^2 < 12\,\text{GeV}^2$ through measuring the differential cross sections in the electroproduction off protons in exclusive single-meson and double-pion channels. We boil our research inquiries on the N^* structure at high Q^2 down to two fundamental questions on the non-perturbative strong interaction: a) What is the mechanism for confinement and b) how is confinement tied to dynamical chiral symmetry breaking? This bears upon the most basic of questions of where mass does come from. How exactly does dynamical chiral symmetry breaking in the nucleon become responsible for more than 98% of all visible mass in the universe?

4. Comments on the Dressed Quark Function

There are two conceptually very different approaches presently employed to interpret the experimentally-extracted resonance electrocouplings starting from QCD Lagrangian, which are: a) Lattice QCD (LQCD)

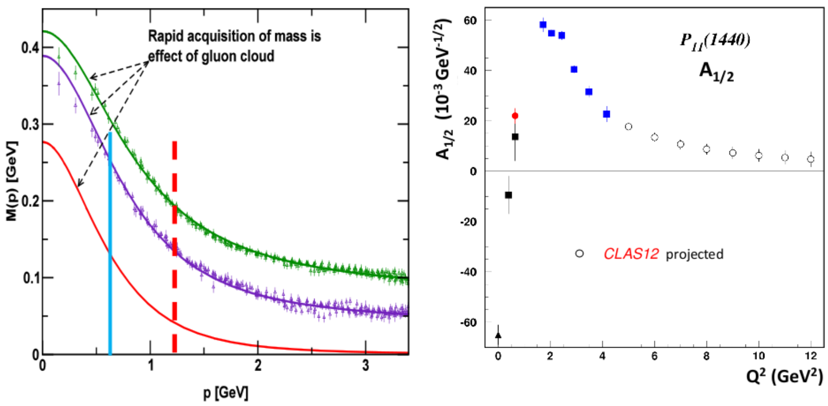

Figure 3: (color on line) (Left) The mass function for the s-quark evaluated within the framework of LQCD [42] (points with error bars) and DSEQCD [41] (solid lines) for two values of bare masses: 70 MeV and 30 MeV, and shown in green and magenta, respectively. The chiral limit of zero bare quark mass, which is close to the bare masses of u and d quarks, is shown in red. Momenta $p < 0.4$ GeV correspond to the confinement, while those at $p > 2$ GeV corresponds to the regime which is close to pQCD. The areas accessible for mapping of the dressed quark mass function by the $\gamma_v NN^*$ electrocoupling studies with 6 GeV and 11 GeV electron beam are shown on the left of blue solid and red dashed lines, respectively. (Right) Data from CLAS6 (filled symbols) and projected CLAS12 data [17] (open symbols) for the $A_{\frac{1}{2}}$ electrocouplings of the $P_{11}(1440)$ state.

and b) Dyson-Schwinger Equation (DSE) of QCD. Plotted on the left-hand side of Fig. 3 is the dressed-quark mass as a function of momentum, $M(p)$, is for light-quarks, obtained in the Landau gauge; the solid curves are from Dyson Schwinger Equation results, including the chiral-limit [41] and the points with error bars are the results from unquenched LQCD [42]. These two conceptually-different approaches agree quite well; for high momenta ($p > 2$ GeV), the behavior of the mass function is close to that expected in the pQCD regime. However, for momenta less than this transition boundary, the mass function rises sharply, reaching the constituent-quark mass-scale at low momentum as is depicted on the left plot in Fig. 3. In this domain, the dressed-quark is far from being a QCD current quark, where the effect is manifested as quarks acquire mass as in the low-momentum regime. Both LQCD and DSE-QCD argue that the dominant part of dressed quark and consequently hadron masses is generated through non-perturbative strong interactions.

The rapid acquisition of mass of the quark arises from a cloud of low-momentum gluons attaching themselves to the current-quark in the regime where the running quark-gluon coupling is large and is completely outside of the scope of pQCD [12, 19]. This is exactly the phenomenon of dynamical chiral symmetry breaking. The region where the dressed quark mass increases the most, also represents the transition domain from pQCD ($p > 2$ GeV) to confinement (p < 0.4 GeV). A solution of the DSE gap-equation [19] shows that the propagator pole in the confinement regime goes off the real momentum axis, and the momentum squared p^2 of the dressed quark becomes substantially different than the dynamical mass squared $[M(p)]^2$. This means, that the dressed quark in the confinement regime will never be on-shell as it is required for a free particle when it propagates in space-time. Dressed quarks have to be strongly bound and locked inside the nucleon. And these dressing mechanisms are responsible for DCSB as well.

The data expected from our CLAS12 N* experiment [17] at 5.0 GeV^2 < Q^2 < 12 GeV^2 will, for the first time, allow one to study the kinematic regime for momenta running over the quark propagator for momenta $p < 1.1$ GeV, where the momentum running over the quark propagator is $p = \sqrt{Q^2/3}$. This kinematic regime spans the transition from the almost-completely dressed constituent quarks to the almost-completely undressed current quarks. On the right-hand side of Fig. 3 we show the $A_{\frac{1}{2}}$ electrocouplings of the $P_{11}(1440)$ state extrapolated to a Q^2 of up to 12 GeV^2. And we expect comparable high-quality data for the other prominent N^*s. It is important to bear in mind that the dressed-quark propagator is gauge-covariant and hence the features evident in this figure have a genuinely measurable impact on observables. Probing the $\gamma_v pN^*$ electrocouplings will be sensitive to the transition from confinement to pQCD, since high-Q^2 photons interact, for the most part, with the electromagnetic current of the dressed quark, which encodes the dressed quark's structure. Momentum dependence of the dressed quark mass should affect all dressed quark propagators and therefore should be seen in the Q^2-evolution of $\gamma_v NN^*$ electrocouplings.

5. Summary

Studying N*s gives insight into the active degrees of freedom in baryon structure at various distance scales. The 6-GeV Program already offers information on the transition in N^* structure from a superposition of meson-baryon and quark degrees of freedom to quark-core dominance. The 12-GeV program, with the higher Q^2 reach, will allow for directly accessing quarks decoupled from meson-baryon cloud contributions and will further allow for probing the change of the dynamical quark mass, structure, and quark interactions with distance. Our set of experiments aims to map out the momentum-dependent dressed-quark function and thereby seek evidence for how dynamical chiral symmetry breaking generates baryonic mass.

6. Acknowledgments

PLC would like to thank the organizers for inviting the speaker to present a talk on medium-energy nuclear physics at this wonderful high-energy physics conference. This work was supported, in part, through NSF grant PHY-0855661 and from the Jefferson Lab JSA/DOE contract No. DE-AC05-06OR23177.

References

[1] V.D. Burkert, "Evidence of new nucleon resonances from electromagnetic meson production," arXiv:1209.2402[nucl-ex].
[2] V.D. Burkert, Fizika B **20**, 237 (2011).
[3] I.G. Aznauryan, V.D. Burkert, T-S.H Lee and V.I. Mokeev, J. Phys: Conf. Ser. **299**, 012008 (2011).
[4] I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. **67** , 1 (2012).
[5] V.D. Burkert," The JLAB 12 GeV Upgrade and the Initial Science Program", arXiv:1203.2373[nucl-ex].
[6] G.V. Fedotov *et al.*, (CLAS Collaboration), Phys. Rev. C **79**, 015204 (2009).
[7] M. Ripani *et al.*, (CLAS Collaboration,) Phys. Rev. Lett. **91**, 022002 (2003).
[8] H. Denizli *et al.*, (CLAS Collaboration), Phys. Rev. C **76**, 015204 (2007).
[9] D.S Carman *et al.*, (CLAS Collaboration), Phys. Rev. C **79**, 065205 (2009).
[10] P. Ambrozewicz, D.S Carman *et al.*, (CLAS Collaboration), Phys. Rev. C **75**, 045203 (2007).
[11] M.R. Pennington, The 8th International Workshop on the Physics of Excited Nucleons, NSTAR2011, May 17-20, 2011, Newport News, VA, USA, ed. by V. Burkert, M. Jones, M. Pennington, and D. Richards, AIP Conf. Proc, **1432**, 176.
[12] C.D. Roberts, The 8th International Workshop on the Physics of Excited Nucleons, NSTAR2011, May 17-20, 2011, Newport News, VA, USA, ed. by V. Burkert, M. Jones, M. Pennington, D. Richards, AIP Conf. Proc, **1432**, 19.
[13] J.J. Dudek and R.G. Edwards, Phys. Rev. D **85**, 054016 (2012).
[14] H-W. Lin and S.D. Cohen, arXiv:1108.2528 [hep-lat].
[15] R.W. Gothe, The 8th International Workshop on the Physics of Excited Nucleons, NSTAR2011, May 17-20, 2011, Newport News, VA, USA, ed. by V. Burkert, M. Jones, M. Pennington, D. Richards, AIP Conf. Proc, **1432**, 26.
[16] I. Aznauryan *et al.*, "Theory Support for the Excited Baryon Program at the JLAB 12 GeV Upgrade," arXiv:0907.1901[nucl-th]. *www.jlab.org/exp_prog/12GEV_EXP*.
[17] R.W. Gothe, V.I.. Mokeev, V.D. Burkert, P.L. Cole, K. Joo, P. Stoler *et al.*, JLab experiment E12-09-003, "Nucleon Resonance Studies with CLAS12," (see: www.jlab.org/exp_prog/12GEV_EXP).
[18] V.I. Mokeev *et al.* (CLAS Collaboration), Phys. Rev. C **86**, 035203 (2012).
[19] C.D. Roberts, "Strong QCD and Dyson-Schwinger Equations," arXiv:1203.5341[nucl-th]
[20] V.I. Mokeev *et al.*, Phys. Rev. C **80**, 045212 (2009).
[21] I.G. Aznauryan *et al.* (CLAS Collaboration), Phys. Rev. C **80**, 055203 (2009).
[22] I.G. Aznauryan *et al.*, The 8th International Workshop on the Physics of Excited Nucleons, NSTAR2011, May 17-20, 2011, Newport News, VA, USA, ed. by V. Burkert, M. Jones, M. Pennington, D. Richards, AIP Conf. Proc, **1432**, 68.
[23] P. Ambrozewicz *et al.* (CLAS Collaboration), Phys. Rev. C **75**, 035205 (2007).
[24] A.V. Anisovich *et al.*, Eur. Phys. J. A **48**, 15 (2012).
[25] H. Kamano *et al.*, AIP Conf.Proc. **1432**, 74 (2012).
[26] B. Julia-Diaz *et al.*, Phys. Rev. C **77**, 045205 (2008).
[27] T.-S.H. Lee, Int. J. Mod. Phys. E **18**, 1215 (2009).
[28] B. Julia-Diaz *et al.*, Phys. Rev. C **80**, 025207 (2009).
[29] H. Kamano *et al.*, Phys. Rev. C **80**, 065203 (2009).
[30] H. Kamano *et al.*, Phys. Rev. C **81**, 065207 (2010).
[31] N. Suzuki *et al.*, Phys. Rev. Lett. **104**, 042302 (2010).
[32] N. Suzuki, T. Sato, and T.-S.H. Lee, Phys. Rev. C **82**, 045206 (2010).
[33] D.J. Wilson, I.C. Cloet, L. Chang and C. Roberts, Phys. Rev. C **85**, 025205 (2012).
[34] K. Nakamura *et al.*, J. Phys. G, **37**, 075021 (2010).
[35] M. Dugger *et al.* (CLAS Collaboration), Phys. Rev. C **79**, 065206 (2009).
[36] K. Park *et al.* (CLAS Collaboration), Phys. Rev. C **77**, 015208 (2008).
[37] I.G. Aznauryan *et al.*, Phys. Rev. C **71**, 015201 (2005).
[38] I.G. Aznauryan, Phys. Rev. C **76**, 025212 (2007).
[39] S. Capstick and B.D. Keister, Phys. Rev. D **51**, 3598 (1995).
[40] M. Aiello, M M. Giannini, and E. Santopinto, J. Phys. G **24**, 753 (1998).
[41] C.D. Roberts, Prog. Part. Nucl. Phys. C **61**, 50 (2008); M. Bhagwat and P.C. Tandy, AIP Conf. Proc. **842**, 225 (2006).
[42] P.O. Bowman *et al.*, Phys. Rev. D **71**, 054507 (2005).