WORKSHOP SCIENTIFIC REPORT

TITLE

Nucleon Resonance Spectrum and Structure from Exclusive Meson Production up to High Photon Virtualities

DATE

12-16 October 2015

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NUMBER OF PARTICIPANTS

39

MAIN TOPICS

The workshop focused on the study of the nucleon resonance (N*) spectrum and structure as it becomes accessible through the electromagnetic excitation of the nucleon (EmNN*) in exclusive meson production. The main topics were:

(a) baryon spectrum in exclusive meson photoproduction,

(b) search for new baryon states in combined studies of exclusive photo- and electro-production,

(c) electroexcitation of N* states and their structure at photon virtualities up to 5 GeV^2,

(d) extension of these studies with CLAS12 to low (>0.01 GeV^2) and highest (up to 12 GeV^2) photon virtualities ever achieved in exclusive electroproduction,

(e) advances in the reaction models and amplitude analyses for the extraction of resonance parameters, and

(f) progress of QCD-based approaches relating measured resonance electrocouplings to the non-perturbative strong interaction mechanisms that are behind the formation of nucleon resonances and elucidate their emergence from QCD.

Rapid growth of high-quality experimental results on exclusive meson photoproduction off nucleons from CLAS, ELSA, GRAAL, and MAMI gives us the unique opportunity to establish the baryon spectrum from experimental data with minimal model dependence. Resonance electrocouplings obtained in a wide area of photon virtualities, mostly from CLAS exclusive meson electroproduction off nucleons data, offer valuable information allowing us to explore the complex interplay between meson-baryon and quark degrees of freedom in the N* structure and provide unique access to many facets of the non-perturbative strong interaction as it generates excited nucleons with various quantum numbers. Future extension of these studies toward high photon virtualities will allow us to explore the transition from quark-gluon confinement to perturbative QCD as it is revealed in the structure of excited nucleons. The workshop focused particularly on new results and the development of future strategies, methods, and approaches to extract, predict, and understand the baryon spectrum and its photo- and electrocouplings γNN* based on

Standard Model QCD. The workshop thus addressed the most challenging problems of contemporary hadron physics, namely the generation of hadron mass by strong interaction in the non-perturbative regime through dynamical chiral symmetry breaking and the nature of quark-gluon confinement as they emerge from the studies of the light baryon structure. The workshop aimed to foster already initiated efforts and to create new opportunities to facilitate and stimulate further discussions and growth in this field.

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SCIENTIFIC REPORT

Substantial progress has been demonstrated during the workshop on the measurements of meson-photoproduction off nucleons and their amplitude analyses as well as on the extension of our knowledge of the excited nucleon state spectrum, photocouplings, and their partial hadronic decay widths by employing elaborated and in some cases even almost model-independent reaction model approaches. They are carried out by either analyzing the reaction amplitudes as constrained by the data or by employing reaction models to differential cross sections and polarization asymmetries. In the future, similar analyses of exclusive electroproduction at low Q^2 will be important to cross-check the observation of the new N*-states that have been seen in photoproduction data, to enhance the capabilities for new state discovery in exclusive channels due to the improved resonance-to-background ratio at higher Q^2, and to potentially provide compelling evidence for hybrid baryons through the specific Q^2-evolution of their transition form factors. These studies will be further extended by new results on exclusive meson electroproduction off bound neutrons, offering new prospects to access the electrocouplings of resonances excited off neutrons.

The presented studies and results of exclusive meson electroproduction off protons provide for the first time a set of information on electrocouplings of low-lying N* states with masses less than 1.6 GeV at photon virtualities up to 5.0 GeV^2 and preliminarily on electrocouplings of most N* states in mass range up to 1.8 GeV. The reliability of the $\gamma_v NN^*$ electrocoupling results of low-lying N*-states, that have been published in the 2014 edition of the PDG report, has been established through consistent results from independent analyses of the major exclusive meson electroproduction channels off the proton, namely $N\pi$ and $\pi^+\pi^-p$. Physics analyses of these results revealed the N* structure as a complex interplay between the inner core of three dressed quarks and external meson-baryon cloud.

Furthermore, to investigate the nucleon resonance structure from partially explored – where meson-cloud degrees of freedom contribute substantially to the baryon structure – to still unexplored distance scales – where quark degrees of freedom dominate and the transition from dressed to current quarks occurs – we depend on experiments that allow us to measure observables that are probing this evolving non-perturbative QCD regime over its full distance range. Resonance transition form factors are uniquely suited to trace this evolution by measuring of their Q^2 dependence in a broad area of photon virtualities from 0.01 GeV^2 up to 12 GeV^2. Extending the information on the nucleon ground-state structure in terms of elastic form factors and various partonic structure functions by data on the excited nucleon structure based on the $\gamma_v NN^*$ electrocouplings is essential in order to explore the non-perturbative strong interaction mechanisms, which are responsible for generation of both the ground and excited nucleon states.

The extension of exclusive electroproduction measurements with the CLAS12 detector at Jefferson Lab by the approved experiments E-09-003 and E12-06-108A into the range of photon virtualities from 5 to 12 GeV^2, where quark degrees of freedom are expected to dominate, was discussed. They will then cover continuously the interaction distance range that corresponds to the transition from the quark-gluon confinement towards the pQCD regimes of strong interaction. The current and upcoming experimental data in conjunction with advanced QCD-based approaches that relate the N*-resonance properties to QCD will allow us to systematically study:

- the N*-spectrum and its emergence from the underlying complex dynamics of the non-perturbative strong interaction in QCD,
- the manifestation of "missing" baryon and potentially other new states of hadron matter, the so-called hybrid-baryon states, in exclusive photo- and electroproduction,

- the complex interplay of quark-gluon and meson-baryon degrees of freedom in the N*-structure,
- the transition from fully dressed constituent to bare current quarks, elucidating the nature of quark-gluon confinement in baryons and the behavior of the universal QCD beta-function in the infrared regime, and
- the emergence of more than 98% of the baryon mass and of the dressed quark structure, both generated non-perturbatively through dynamical chiral symmetry breaking.

The close collaboration and open discussions of experimentalists and theorists, as we could experience at this ECT* workshop, is essential to provide the best high-precision data, high-quality analyses, and state-of-the-art QCD-based calculations on γNN* photo- and electrocouplings of the resonance spectrum.

RESULT AND HIGHLIGHTS

The Workshop gave us a unique opportunity to merge expertise and knowledge of experimentalists with that of theorists from European, US, and other international institutions on the nucleon resonance spectrum and structure as well as to develop and refine the best suited approaches for the reliable extraction of resonance parameters and their sound theoretical interpretation in a comprehensive QCD-based hadron structure theory.

We have developed the strategies for the extraction of the N*-spectrum from combined analyses of exclusive meson photo- and electroproduction data. In addition various approaches were discussed and refined to extract resonance photo- and electrocouplings, such as: dynamical coupled-channel models for global multi-channel analyses incorporating multi-meson-baryon states, reaction models for independent analyses of Nπ, N$\pi\pi$, ηp, ωp, and KY exclusive channels, state-of-the-art methods for reaction amplitude extractions, and reaction models applicable at high photon virtualities. Analyses of CLAS data on exclusive Nπ and N$\pi\pi$ electroproduction provided consistent information on electrocouplings for most of the excited nucleon states in the mass range up to 1.8 GeV and at photon virtualities up to 5 GeV^2. Furthermore, preliminary results on exclusive Nπ electroproduction off bound neutrons have become available. In combination with the advances in the reaction models by Agronne-Osaka and GWU groups for exclusive reactions inside the deuteron, these data open up prospects to extract electrocouplings of resonance states excited off neutrons. Finally, experimental efforts and signatures of hybrid-baryons in electroproduction were discussed.

QCD-based efforts were presented and fostered to describe and interpret resonance parameters within the framework of Lattice QCD and continuum strong QCD as well as by employing advanced quark models (like for example the Unquenched Quark Model that is a systematic coupled channel model, or the Interacting Quark Diquark Model that implements systematic use of the diquark effective degrees of freedom). Continuum strong QCD (DSEQCD) describes successfully the nucleon elastic form factors as well as the N$\rightarrow\Delta$(1232)3/2+ and N$\rightarrow$N(1440)1/2+ transition form factors with the same dressed quark mass function, demonstrating for the first time the ability to access this fundamental ingredient of the non-perturbative strong interaction with the help of data on elastic and transition form factors. This new results by ANL theory group represents one of the most important continuum QCD results of the last decade that has been achieved in synergy of experimental and theoretical efforts with leading contribution from the CLAS experimental results on the N$\rightarrow\Delta$(1232) and N$\rightarrow$N(1440)1/2+ transition form factors. Advances in the

Light Cone Sum Rule approach reported at this workshop by the Regenburg-Dubna collaboration allow us now to probe quark distribution amplitudes (DA) of the N(1535)1/2- resonance based on the CLAS electrocouplings for this state. These quark DA's can thus be derived starting from the QCD Lagrangian within LQCD. This approach offers an alternative way of relating resonance electrocouplings to first principles of QCD. The JLab LQCD group keeps developing the only available LQCD approach capable to derive resonance electrocouplings from the QCD Lagrangian accounting for all relevant contributions to the resonance structure including their decays.

On another side, the recent development of the Unquenched Quark Model (UCQM) formalism, that makes up for various deficiencies of other three quark models, offers an alternative tool that can be used when LQCD or Chiral Effective Theory still cannot be applied to describe the N* spectrum and structure. UCQM takes into account in a systematic way the sea components and is a coupled channel quark model with continuum components. Recent systematic results regarding the calculation of the longitudinal and transverse electromagnetic NN* transition form factors, as well as their strong decays, have also been described within a collective hypercentral model. This is a simple model based on the three quark symmetry that describes the basic baryon features, so that it can be used as a first step or as guidance for observable without continuum components. Finally, it has been discussed, that the recent development of the Interacting Quark Diquark Model (IQDM), which is based on direct and exchange interactions using the effective quark-diquark degrees of freedom, is able to assess in a systematic way the baryon spectrum and structure. IQDM also predicts many missing resonances, although many less than the three quark model, and is able to describe the P13(1900).

All the presented and discussed advances will allow us to further explore the emergence of nucleon resonances from quarks and gluons and to address the most challenging open problems of the Standard Model on the origin of hadron masses and quark-gluon confinement in baryons within a QCD-based framework.

We fostered and broadened already initiated experimental and theoretical efforts, and created opportunities to facilitate and stimulated the needed growth in this field that tries to uncover the emergence of the non-perturbative regime from QCD.

This five-day workshop focused on current and future experimental data, phenomenological data analyses, and QCD-based interpretations of the baryon spectrum and the resonance electrocouplings, and in particular provided the opportunity to initiate international efforts to develop new approaches for the extraction of resonance photo- and electrocouplings from exclusive meson production induced by real to highly virtual photons. The workshop was an important step in the development of methods towards a QCD-based theoretical interpretation of the EmNN* couplings that will allow us to probe the strong interaction at continuously varying length scales, covering the transition from sizeable meson-baryon to the dominance of quark degrees of freedom in the N* structure at $Q^2 < 5$ GeV^2 with the currently available data and the gradual transition from dressed to pQCD quarks with the prospective data at $Q^2 > 5$ GeV^2.