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TRANSITION FORM FACTORS: A UNIQUE OPPORTUNITY TO CONNECT NON-PERTURBATIVE STRONG INTERACTIONS TO QCD*

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Meson-photoproduction measurements and their reaction-amplitude analyses can establish more sensitively, and in some cases in an almost model-independent way, nucleon excitations and non-resonant reaction amplitudes. However, to investigate the strong interaction from 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 range. Elastic *and* transition form factors are uniquely suited to trace this evolution by measuring elastic electron scattering *and* exclusive single-meson and double-pion electroproduction cross sections off the nucleon. These exclusive measurements will be extended to higher momentum transfers with the energy-upgraded CEBAF beam at JLab to study the quark degrees of freedom, where their strong interaction is responsible for the ground and excited nucleon state formations. After establishing unprecedented high-precision data, the imminent next challenge is a high-quality analysis to extract these relevant electrocoupling parameters for various resonances that then can be compared to state-of-the-art models and QCD-based calculations. Recent results will demonstrate the status of the analysis and of their theoretical descriptions, and an experimental and theoretical outlook will highlight what shall and may be achieved in the new era of the 12-GeV upgraded transition form factor program.

Keywords: Meson electroproduction; transition form factors; CLAS detector.

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1. Introduction

Already in the early inclusive high-energy deep inelastic scattering (DIS) experiments at SLAC [1], scaling and quasi-free scattering off still dressed quarks was observed at the then highest beam energies of up to $E = 20\,GeV$ but yet moderate four-momentum transfers of $Q^2 < 2\,(GeV/c)^2$. In these early inclusive measurements, as shown and discussed previously [2], the quasi-free peak becomes visible at

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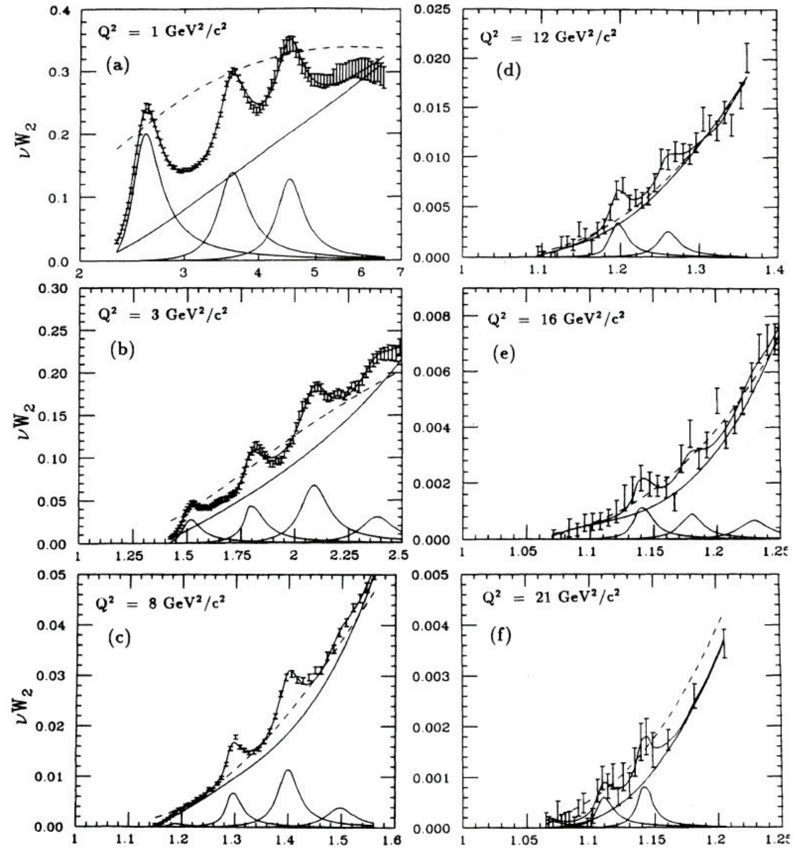

Fig. 1. The inclusive inelastic-scattering structure function νW_2 versus ω' in the resonance region for various values of nominal Q^2, where $\omega' \equiv 1 + W^2/Q^2$. The solid curves are fits to the data that include the $\Delta(1232)$ and the second and third resonance region contributions. The dashed curves are fits to the data in the scaling region extrapolated down to the resonance region. [3]

high beam energies and high center-of-mass energies W, where the electrons seem to scatter off constituent quarks. Although the absolute strength of quasi-free scattering starts to dominate the elastic and resonance contributions with increasing W and Q^2, Figure 1 shows clearly that it is pushed out so far in W [3] that its relative contribution in the resonance regions becomes even smaller with increasing Q^2. This is not so for the $\Delta(1232)$ yields, since they drop faster than the resonance contributions in the second and third resonance region [3], where the individual resonances can only be separated in exclusive electroproduction measurements as in those carried out with the large-acceptance spectrometer CLAS at Jefferson Lab.

Mapping out the transition from exclusive resonance production to quasi-free scattering over W and Q^2 in detail generates the experimental foundation to investigate quark-hadron duality [4], scaling, the bound-quark structure, confinement, dynamical mass generation, and the structure of baryons. The accepted research proposal PR-09-003 at Jefferson Lab, Nucleon Resonance Studies with CLAS12 [5], will lay this experimental foundation to address in a unique way these most pressing questions in QCD. Properly extracting and interpreting the results from the measured electron scattering data, particularly for transition form factors to specific excited nucleon states, might even pose a greater challenge than the measurement itself. A steadily growing collaboration of experimentalists and theorists is working together to enable the measurements, the analysis of the data, and the QCD-based interpretation of the results. The progress in this field is summarized in the most recent review article, Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction [6].

2. Hadronic Structure Analysis

The general analogy to the hydrogen atom – which is the simplest atom bound by electromagnetic fields of well-known dynamics – that the ground state can be unambiguously described by the spectrum of its excited states, does not hold for the nucleon – which is the lightest three-quark system bound by strong fields – since the evolution of the strong interaction from small to large distance scales is not known. Hence even the spectrum of *all* excited states is by itself not sufficient to pin down the baryonic structure, but it is the best possible approach to disentangle the individual interfering resonance and background amplitudes in an almost model-independent way by so-called complete experiments. Here in the simplest case of pseudo-scalar meson photoproduction, the cross section can be decomposed into four gauge- and Lorentz-invariant complex amplitudes. In a combination of unpolarized, beam-, target-, and recoil-polarization experiments, a total of up to 16 observables can be measured with a large solid angle detector, where only eight (or seven, taking into account an overall undetermined phase) are linearly independent. With the caveat that most baryon resonances, except the lowest lying ones, decay dominantly into vector-meson or multi-meson channels, complete experiments in single pseudo-scalar meson photoproduction and corresponding partial wave analyses will allow for the highest quality extraction of resonance parameters under minimal model assumptions. New complete sets of observables [7,8] that exploit the high analyzing power of some hyperon decays led to several new or PDG-upgraded [9] excited states seen in the recently updated Bonn-Gatchina coupled-channel analysis [10].

Beyond baryon spectroscopy at the real photon point $Q^2 = 0\,(GeV/c)^2$, electron scattering experiments are essential to investigate the strong interaction and hence the internal hadronic structure at various distance scales by tuning the four-momentum transfer from $Q^2 \approx 0\,(GeV/c)^2$, where the meson cloud contributes significantly to the baryon structure, over intermediate Q^2, where the three constituent-quark core starts to dominate, to Q^2 up to $12\,(GeV/c)^2$, attainable after the $12\,GeV$ upgrade at JLab (see Fig. 3) [5], where the constituent quark gets more and more undressed towards the bare current quark (see Fig. 4) [11,12].

Although originally derived in the high Q^2 limit, constituent counting rules describe in more general terms how the transition form factors and the corresponding helicity amplitudes scale with Q^2 dependent on the number of effective constituents. Available CLAS results for $Q^2 < 5\,(GeV/c)^2$ [6,13] may already indicate for some helicity amplitudes, like $A_{1/2}$ for the electroexcitation of the $N(1440)P_{11}$, $N(1520)D_{13}$, and $N(1535)S_{11}$, the onset of proper scaling assuming three constituent quarks. If verified at higher Q^2 [5], this furthermore indicates that in these cases the meson-baryon contributions become negligible in comparison to those of the three constituent-quark core, which coincides with the Argonne-Osaka dynamical coupled channel calculation [14] shown in Fig. 2 (right). Along the same line of reasoning perturbative QCD (pQCD) predicts in the high Q^2-limit, by neglecting higher twist contributions, that helicity is conserved. The fact that this predicted behavior seems to set in already at much lower Q^2 values than expected [13] challenges our current understanding of baryons even further. For $N(1520)D_{13}$ the helicity conserving amplitude $A_{1/2}$ starts to dominate the helicity non-conserving amplitude $A_{3/2}$ at $Q^2 \approx 0.7\,(GeV/c)^2$, as typically documented by the zero crossing of the corresponding helicity asymmetry $A_{hel} = (A^2_{1/2} - A^2_{3/2})/(A^2_{1/2} + A^2_{3/2})$. The $N(1685)F_{15}$ resonance shows a similar behavior with a zero crossing at $Q^2 \approx 1.1\,(GeV/c)^2$, whereas the $\Delta(1232)P_{33}$ helicity asymmetry stays negative with no indication of an upcoming zero crossing; and even more surprising are the preliminary results

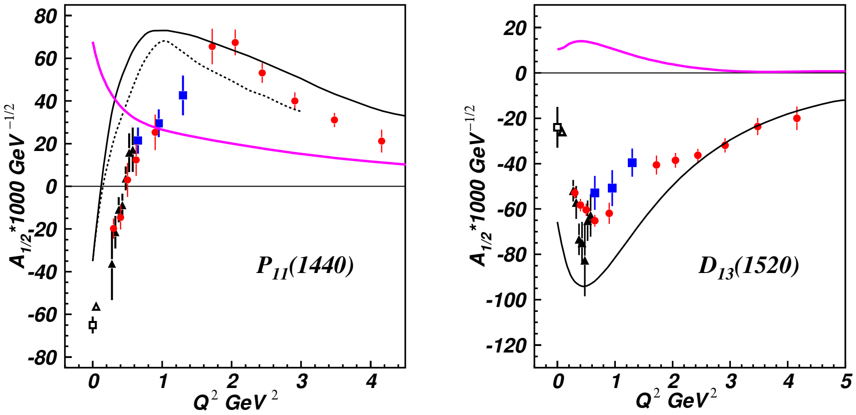

Fig. 2. (Color online) Left: The $A_{1/2}$ electrocoupling of the $P_{11}(1440)$ excited state from the analyses of the $N\pi$ electroproduction data (circles), $\pi^+\pi^-p$ electroproduction data (triangles), and preliminary results from the $\pi^+\pi^-p$ electroproduction data at Q^2 from 0.5 to 1.5 GeV^2 (squares). The photocouplings are taken from PDG [9] (open square) and the CLAS data analysis (open triangle). Predictions from relativistic light-front quark models [19,20] are shown by black solid and dashed lines, respectively. The absolute value of the meson-baryon cloud contribution as determined by the Argonne-Osaka-DCC coupled-channel analysis [14] is shown by the magenta thick solid line. Right: The $A_{1/2}$ electrocoupling of the $D_{13}(1520)$ state. The data symbols are the same as in the left panel. The results of the hypercentral constituent quark model [21] and the absolute value of meson-baryon dressing amplitude [14] are presented by the black thin and magenta thick solid lines, respectively. [6]

for the $N(1720)P_{13}$ $A_{1/2}$ amplitude, which decreases so rapidly with Q^2 that the helicity asymmetry shows an inverted behavior with a zero crossing from positive to negative around $Q^2 \approx 0.7\,(GeV/c)^2$ [15].

This essentially different behavior of transition form factors to various excited states with different quantum numbers underlines that it is necessary but not sufficient to extend the measurements of the elastic form factors to higher momentum transfers. To comprehend the strong interaction at intermediate distance scales where dressed quarks degrees of freedom are responsible for the formation of the diverse spectrum of baryons in distinctively different quantum states, the Q^2 evolution of transition form factors to multiple resonances up to $12\,(GeV/c)^2$ is absolutely crucial [5,6]. Attempts to extract N to N^* transition form factors in vector-meson electroproduction and off the neutron in deuterium are currently pursued to further complement the data base. Figure 3 shows two examples of projected results for the $A_{1/2}$ helicity amplitudes of the the p to $N(1440)P_{11}$ and $N(1520)D_{13}$ transitions.

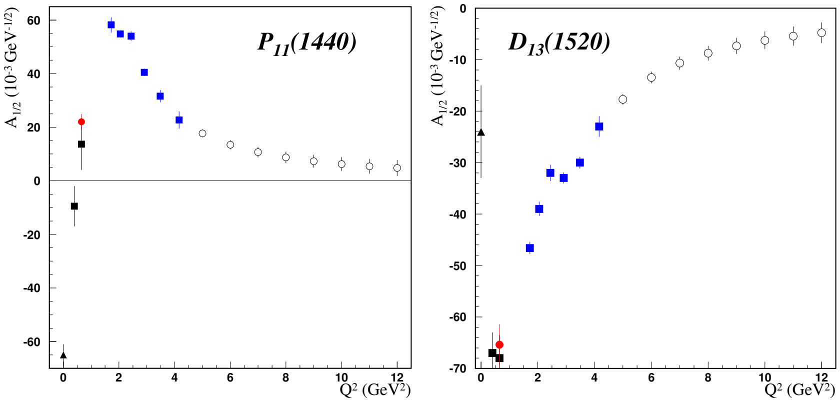

Fig. 3. (Color online) Available (filled symbols) and projected CLAS12 [5] (open symbols) $A_{1/2}$ elecrocouplings of the $P_{11}(1440)$ (left) and the $D_{13}(1520)$ (right) excited states.

Figure 2 exemplifies the three cornerstones of the status quo in this baryonic structure analysis endeavor. First, the analysis of the $N\pi$ channel data is carried out in two phenomenologically different approaches based on fixed-t dispersion relations and a unitary isobar model [13,16]. The main difference between the two approaches is the way the non-resonant contributions are derived. The $p\pi^+\pi^-$ CLAS data is analyzed within a phenomenological meson-baryon model [17,18] that fits nine independent differential cross sections of invariant masses and angular distributions. The good agreement of the resonant helicity amplitude results in the single- and double-pion channels, that have fundamentally different non-resonant contributions, provides evidence for the reliable extraction of the $\gamma_v NN^*$ electrocoupling amplitudes. Second, the high Q^2 behavior is most consistently described by relativistic light-front or recently optimized quark models, as for example in Refs. 19, 20, and

21, but their description of the low Q^2 behavior is less satisfactory. Third, the Argonne-Osaka collaboration (formerly EBAC) predicts, based on a full dynamical coupled-channel analysis [14], meson-baryon dressing (meson-cloud) contributions that seem to bridge the gap between the quark model predictions and the measured results at low Q^2.

Digging deeper into the baryonic structure by increasing the momentum transfer beyond $5\,(GeV/c)^2$ [5] opens a unique window to investigate the dynamic momentum-dependent structure of the constituent quarks. This becomes apparent in Fig. 4, where the quark mass function for momenta larger than $2\,GeV/c$ describes a current-quark that propagates almost like a free single parton. However, for momenta less than that, the quark mass function rises sharply, entering the confinement regime and reaching the constituent-quark mass scale in the infrared. In this domain, the quark is dressed by a cloud of low-momentum gluons and sea-quarks attaching themselves to the current-quark and thus increasing the dressed-quark mass, which is a direct manifestation of dynamical chiral-symmetry breaking.

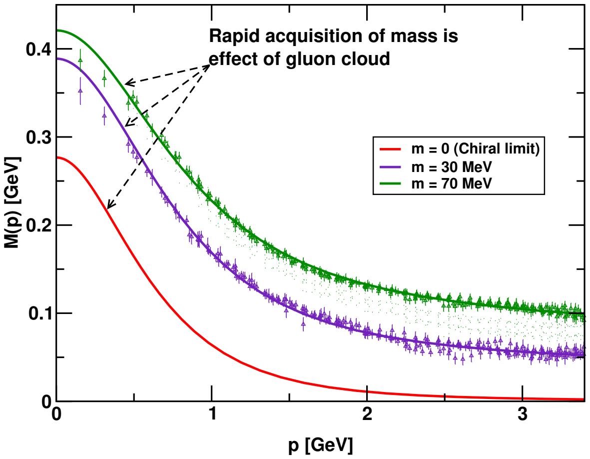

Fig. 4. (Color online) Dressed quark mass function, $M(p)$, for light-quarks, obtained in Landau gauge: solid curves are the DSE results, including the chiral-limit [11]; points with error bars are the results from unquenched LQCD [12]. The elastic and transition form factor data, that will become available after the $12\,GeV$ upgrade, probe $M(p)$ up to a quark propagator momentum of $1.15\,GeV/c$, which spans the transition from dressed constituent quarks to the almost completely undressed current quarks.

3. Summary

All visible matter that surrounds us is made of atoms, which are made of electrons and nuclei; the latter are made of nucleons, which are finally made of quarks and gluons. Contrary to the more publicized discussions, the Higgs, or more frequently called the God Particle, is not responsible for the generation of all mass. It is already known that 98% of all visible mass is generated by strong fields non-perturbatively. Establishing an experimental and theoretical program that provides access to

- the dynamics of non-perturbative strong interactions among dressed quark, their emergence from QCD, and their confinement in baryons,
- the dependence of the light quark mass on the momentum transfer and thereby how the constituent quark mass arises from dynamical chiral-symmetry breaking, and
- the behavior of the universal QCD β-function in the infrared regime,

is indeed most challenging on all levels, but recent progress and future commitments [6] bring a solution of these most fundamental remaining QCD problems into reach. Single- and double-polarization experiments are essential to establish the baryon spectrum, branching ratios, and a detailed separation of individual resonance and background contributions. Elastic and particularly transition form factors are on the other hand needed to uniquely access non-perturbative QCD from long to short distance scales.

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