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Transition Form Factors: A Unique Window into the Baryon Structure

Ralf W. Gothe

Many Manifestations of Non-Perturbative QCD
April 30 to May 5, 2012
Caraguatatuba, São Paulo, Brazil

- $\gamma_{vNN^*}$ Experiments: The Best Access to the Baryon and Quark Structure?
  - Elastic Form Factors and Transition Form Factors
- Analysis: Phenomenological Extraction … can you do better?
  - Consistent extraction of $\gamma_{vNN^*}$ electrocouplings in various decay channel with various models
- QCD based Theory: Solve Non-Perturbative QCD and Confinement?
QCD for Bound and Confined Quarks?
Baryon Excitations and Quasi-Elastic Scattering

\[ E \text{ [GeV]} \quad Q^2 \text{ [(GeV/c)^2]} \]

\[ \theta = 4^\circ \]

\[ \begin{align*}
12 &\quad 1.05 - 1.48 \\
10 &\quad 0.27 - 0.47 \\
7 &\quad 0.09 - 0.23 \\
4.5 &\quad 0.06 - 0.09 \\
20 &\quad 1.45 - 1.84 \\
18 &\quad 1.15 - 1.50 \\
16 &\quad 0.87 - 1.19 \\
13 &\quad 0.53 - 0.79 \\
10 &\quad 0.27 - 0.47 \\
7 &\quad 0.09 - 0.23 \\
4.5 &\quad 0.06 - 0.09
\end{align*} \]

\[ W \text{ [GeV/c^2]} \]

\[ p_F = 0.67 \text{ GeV} \]

\[ m_Q = 0.36 \text{ GeV} \]

\[ m_Q = Q^2 / 2 \]

\[ r_F = 0.79 \text{ fm} \]

\[ \Delta r_F = \eta_c * \sqrt{9 / \pi} \]

Deep Inelastic Scattering
S. Stein et al., PR D22 (1975) 1884
Quark-Hadron Duality

E.D. Bloom and F.J. Gilman

W = 1.9 GeV
E' = 17.6 GeV
v = 2.37 GeV
Q^2 = 1.72 GeV
m_q = 0.36 GeV
m_q = Q^2/2v
p_F = 0.67 GeV
r_F = 0.79 fm

Deep Inelastic Scattering
S. Stein et al., PR D22 (1975) 1884
Baryon Excitations and Quasi-Elastic Scattering

\[ \gamma N \mapsto \frac{1}{2} \]
\[ \gamma N \mapsto \frac{3}{2} \]

Deep Inelastic Scattering
S. Stein et al., PR D22 (1975) 1884
Baryon Excitations and Quasi-Elastic Scattering

Deep Inelastic Scattering (DIS)

Parton Distributions

Deep Inelastic Scattering
S. Stein et al., PR D22 (1975) 1884
Baryon Excitations and Quasi-Elastic Scattering

Elastic Form Factors
Transition Form Factors

E, M, S Multipoles

hard and confined

Deep Inelastic Scattering
S. Stein et al., PR D22 (1975) 1884
Deep exclusive $\pi^+$ electroproduction off the proton

The red solid ($d\sigma/dt$), dotted ($d\sigma_L/dt$), and dashed ($d\sigma_T/dt$) curves are the calculations from the hadronic model (Regge phenomenology) with $(Q^2, t)$-dependent form factors at the photon-meson vertices. The blue solid and dotted curves are the calculations of $d\sigma/dt$ and $d\sigma_L/dt$, respectively, of the partonic model (handbag diagrams).

Kijun Park
Elastic Form Factors
Nucleon Form Factors: Last Ten Years

Proton

Neutron

J. Arrington
Extensions with JLab 12 GeV Upgrade

under development

under analysis

~8 GeV²

CDR or PAC30 approved
Recent Proton Form Factor Ratios

\[
\frac{\mu_p G_{Ep}}{G_{Mp}}
\]

\[Q^2 \text{ (GeV}^2)\]

- Zhan
- Ron
- Crawford
- other polarization
Small Sample of Recent Calculations

- VMD + pQCD (Lomon 2002)
- Soliton (Holzwarth b1)
- Soliton (Holzwarth b2)

- PFSA CQM GBE
- LF CQM qFF (Cardarelli)
- LF CQM π (Miller)
Transition Form Factors
Hadron Structure with Electromagnetic Probes

- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

\[ \pi, \rho, \omega \ldots \]

\[ Q^2 \]

\[ \text{low} \]

\[ q \]

\[ \text{high} \]

\[ 3q\text{-core} + \text{MB-cloud} \]

\[ 3q\text{-core} \]

\[ \text{pQCD} \]

\[ \text{meson dressed quark} \]

\[ \text{LQCD, DSE and …} \]

\[ \text{confinement} \]

\[ \text{current quark} \]

\[ \text{e.m. probe} \]

\[ \text{quark mass (GeV)} \]

\[ q \text{ (GeV)} \]
Evidence for the Onset of Scaling?

- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$
- $G_M^* \propto 1/Q^4$

New trend towards pQCD behavior does not show up.

- $R_{EM} \to +1$
- $G_M^* \to 1/Q^4$

CLAS12 can measure $G_M^*$, $R_{EM}$, and $R_{SM}$ up to $Q^2 \approx 12$ GeV$^2$. 
**N(1520)D_{13} Helicity Asymmetry**

\[ A_{\text{hel}} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2} \]

L. Tiator

- **N(1520)D_{13} Helicity Asymmetry**

- **PDG estimation**
- **N\pi** (UIM, DR)

\[ A_{1/2} \]

\[ S_{1/2} \]

\[ 10^{-3}\text{ GeV}^{-1/2} \]

\[ Q^2(\text{GeV/c})^2 \]

- **D_{13}(1520)**
- **F_{15}(1680)**
- **P_{33}(1232)**

**world data**
Phenomenological Analyses

- Unitary Isobar Model (UIM) approach in single pseudoscalar meson production
- Fixed-$t$ Dispersion Relations (DR)
- Isobar Model for $N\pi\pi$ final state (JM)

  see White Paper Sec. VII

- Coupled-Channel Approach (EBAC)

  see White Paper Sec. VIII
Unitary Isobar Model (UIM)
Nonresonant amplitudes: gauge invariant Born terms consisting of $t$-channel exchanges and $s$- / $u$-channel nucleon terms, reggeized at high $W$.
$\pi N$ rescattering processes in the final state are taken into account in a K-matrix approximation.

Fixed-\textit{t} Dispersion Relations (DR)
Relates the real and the imaginary parts of the six invariant amplitudes in a model-independent way. The imaginary parts are dominated by resonance contributions.

see White Paper Sec. VII
Legendre Moments of Unpolarized Structure Functions


\[ Q^2 = 2.05 \text{GeV}^2 \]

I. Aznauryan  \[ \text{DR fit} \]
I. Aznauryan  \[ \text{DR fit w/o } P_{11} \]
I. Aznauryan  \[ \text{UIM fit} \]

Two conceptually different approaches DR and UIM are consistent. CLAS data provide rigid constraints for checking validity of the approaches.

\[ \sigma_T + \epsilon \sigma_L = \sum_{l=0}^{n} D_{l}^{T+L} P_l(\cos \theta_{\pi}^*) \]
Energy-Dependence of $\pi^+$ Multipoles for $P_{11}$, $S_{11}$

The study of some baryon resonances becomes easier at higher $Q^2$.
Nucleon Resonances in $N\pi$ and $N\pi\pi$ Electroproduction

- $N\pi\pi$ channel is sensitive to $N^*$s heavier than 1.4 GeV
- Provides information that is complementary to the $N\pi$ channel
- Many higher-lying $N^*$s decay preferentially into $N\pi\pi$ final states

$Q^2 < 4.0\text{GeV}^2$

W in GeV

$p(e,e')X$

$p(e,e'p)\pi^0$

$p(e,e'\pi^+)n$

$p(e,e'p\pi^+)\pi^-$
JM Model Analysis of the $p\pi^+\pi^-$ Electroproduction

Baryon isobar channels

Meson isobar channels

see White Paper Sec. VII
Contributing Mechanisms to $\gamma^{(*)}p \rightarrow p\pi^+\pi^-$

Isobar Model JM05

- Full calculations
- $\gamma p \rightarrow \pi^-\Delta^{++}$
- $\gamma p \rightarrow \pi^+\Delta^0$
- $\gamma p \rightarrow \pi^+D_{13}(1520)$
- $\gamma p \rightarrow \rho p$
- $\gamma p \rightarrow \pi^-\Delta^{++}(1600)$
- $\gamma p \rightarrow \pi^+F_{015}(1685)$
- direct $2\pi$ production

➢ The combined fit of nine single differential cross sections allowed to establish all significant mechanisms.
JMs Mechanisms as Determined by the CLAS $2\pi$ Data

Each production mechanism contributes to all nine single differential cross sections in a unique way. Hence a successful description of all nine observables allows us to check and to establish the dynamics of all essential contributing mechanisms.
Electrocouplings of $N(1440)P_{11}$ from CLAS Data

The good agreement on extracting the $N^*$ electrocouplings between the two exclusive channels ($1\pi/2\pi$) – having fundamentally different mechanisms for the nonresonant background – provides evidence for the reliable extraction of $N^*$ electrocouplings.
Most recent Electrocouplings of N(1440)P_{11}

Gleb Fedotov

$A_{1/2}$

$S_{1/2}$

$10^{-3}$ GeV^{-1/2}

$Q^2$ (GeV$^2$)

$Q^2$ (GeV$^2$)

preliminary
Constituent Quark Models (CQM)

Relativistic CQM are currently the only available tool to study the electrocouplings for the majority of excited proton states. This activity represents part of the commitment of the Yerevan Physics Institute, the University of Genova, INFN-Genova, and the Beijing IHEP groups to refine the model further, e.g., by including $q\bar{q}$ components.

see White Paper Sec. VI
Progress in Experiment and Phenomenology

Meson-Baryon Dressing

- Resonance structures can be described in terms of an internal quark core and a surrounding meson-baryon cloud whose relative contribution decreases with increasing $Q^2$.

- Data on $\gamma \nu NN^*$ electrocouplings from this experiment ($Q^2 > 5 \text{ GeV}^2$) will afford for the first time direct access to the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and the subsequent $N^*$ formation.

\[ D_{13}(1520) \]

\[ P_{11}(1440) \]

CLAS: $N\pi$ and $N\pi/N\pi\pi$ combined (Phys. Rev. C80, 055203, 2009)
Dynamical Mass of Light Dressed Quarks

DSE and LQCD predict the dynamical generation of the momentum dependent dressed quark mass that comes from the gluon dressing of the current quark propagator.

These dynamical contributions account for more than 98% of the dressed light quark mass.

DSE: lines and LQCD: triangles

\[ Q^2 = 2.75 \text{ GeV}^2 \]

\[ Q^2 = 12 \text{ GeV}^2 = (p \times \text{number of quarks})^2 = 12 \text{ GeV}^2 \quad \rightarrow \quad p = 1.15 \text{ GeV} \]

The data on N* electrocouplings at 5 GeV^2 < Q^2 < 12 GeV^2 will allow us to chart the momentum evolution of dressed quark mass, and in particular, to explore the transition from dressed to almost bare current quarks as shown above.
DSE approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.

N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

The Faddeev-DSE calculation is very sensitive to the momentum dependence of the dressed-quark propagator.

By the time of the upgrade DSE electrocouplings of several excited nucleon states will be available as part of the commitment of the Argonne NL and the University of Adelaide.

see White Paper Sec. III
DSE and EBAC Approaches

Location of the first 3-dressed-quark core radial excitation predicted by DSE

Two poles associated with the Roper resonance and one with the next higher $P_{11}$ resonance are all seeded by the same bare 3-dressed-quark state.

Upcoming White Paper 2012
Latice QCD calculations of the $p(1440)_{P_{11}}$ transition form factors have been carried out with various pion masses, $m_\pi = 390, 450, \text{and } 875 \text{ MeV}$. Particularly remarkable is the zero crossing in $F_2$ that appears at the current statistics in the unquenched but not in the quenched calculations. This suggests that at low $Q^2$ the pion-cloud dynamics are significant in full QCD.

By the time of the upgrade LQCD calculations of $N^*$ electrocouplings will be extended to $Q^2 = 10 \text{ GeV}^2$ near the physical $\pi$-mass as part of the commitment of the JLab LQCD and EBAC groups in support of this proposal.

Upcoming White Paper 2012
LQCD & Light Cone Sum Rule (LCSR) Approach

LQCD is used to determine the moments of $N^*$ distribution amplitudes (DA) and the $N^*$ electrocouplings are determined from the respective DAs within the LCSR framework.

Calculations of $N(1535)S_{11}$ electrocouplings at $Q^2$ up to 12 GeV$^2$ are already available and shown by shadowed bands on the plot. By the time of the upgrade electrocouplings of others $N^*$s will be evaluated. These studies are part of the commitment of the Univ. of Regensburg group in support of this proposal.

Upcoming White Paper 2012
- Luminosity > $10^{35}$ cm$^{-2}$s$^{-1}$
- Hermeticity
- Polarization

- Baryon Spectroscopy
- Elastic Form Factors
- N to N$^*$ Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …
New Forward Time of Flight Detector for CLAS12

World-record time resolution of 44 ns averaged over the full length of 210 cm
Inclusive Structure Function in the Resonance Region

P. Stoler, PRPLCM 226, 3 (1993) 103-171
CLAS 12 Kinematic Coverage and Counting Rates

Genova-EG

(e',π⁺) detected

Genova-EG

(e',p) detected

<table>
<thead>
<tr>
<th>(E,Q²)</th>
<th>(5.75 GeV, 3 GeV²)</th>
<th>(11 GeV, 3 GeV²)</th>
<th>(11 GeV, 12 GeV²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N^{π⁺π⁺}</td>
<td>1.41*10⁵</td>
<td>6.26*10⁶</td>
<td>5.18*10⁴</td>
</tr>
<tr>
<td>N^{π₀π₀}</td>
<td>-</td>
<td>4.65*10⁵</td>
<td>1.45*10⁴</td>
</tr>
<tr>
<td>N^{ηη}</td>
<td>-</td>
<td>1.72*10⁴</td>
<td>1.77*10⁴</td>
</tr>
</tbody>
</table>

L=10³⁵ cm⁻² sec⁻¹, W=1535 GeV, ΔW= 0.100 GeV, ΔQ² = 0.5 GeV²

40 days PAC35
Kinematic Coverage of CLAS12

60 days

$L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}, \Delta W = 0.025 \text{ GeV}, \Delta Q^2 = 0.5 \text{ GeV}^2$

Genova-EG

$(e', p\pi^+\pi^-)$ detected

$2\pi \text{ limit} > 1\pi \text{ limit} > 1\eta \text{ limit} >$
Anticipated N* Electrocouplings from a Combined Analysis of Nπ & Nππ

Open circles represent projections and all other markers the available results with the 6-GeV electron beam.

- Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. S_{11}(1650), F_{15}(1685), D_{33}(1700), P_{13}(1720), ...

- This experiment will – for the foreseeable future – be the only experiment that can provide data on γ_vNN* electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2.
Summary

- We will measure and determine the electrocouplings $A_{1/2}$, $A_{3/2}$, $S_{1/2}$ as a function of $Q^2$ for prominent nucleon and $\Delta$ states,
  - see our Proposal http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf.
- Comparing our results with DSE, LQCD, LCSR, and rCQM will gain insight into
  - the strong interaction of dressed quarks and their confinement in baryons,
  - the dependence of the light quark mass on momentum transfer, thereby shedding light on
dynamical chiral-symmetry breaking, and
  - the emergence of bare quark dressing and dressed quark interactions from QCD.
- This unique opportunity to understand origin of 98% of nucleon mass is also an
  experimental and theoretical challenge. A wide international collaboration is needed
  for the:
    - theoretical interpretation on $N^*$ electrocouplings, see our previous White Paper
      arXiv:0907.1901v3 [nucl-th], and
    - development of reaction models that will account for hard quark/parton contributions at
      high $Q^2$.
- Any constructive criticism, help, or participation is very welcomed, please contact:
  - Viktor Mokeev mokeev@jlab.org or Ralf Gothe gothe@sc.edu.
Karen Yeats: “The Hopf Algebraic Approach to DSEs”. DSEs are very useful in how they mirror the recursive decomposition of Feynman diagrams into subdiagrams. This simple combinatorial observation is surprisingly powerful as it gives us hints as to how to unwind the combinatorial difficulties from the analytic ones. Furthermore, the Slavnov-Taylor identities for the coupling constants correspond to certain Hopf ideals. The lectures will explain these connections without expecting prior algebraic experience.

Piers Coleman: “DSE Applications in Condensed Matter Physics”. In his lectures, he explains the relevance of DSEs for condensed matter physics and will give a short introduction to interacting electron systems followed by five lectures on: “Feynman diagrams in many body physics”, “The interacting electron plasma”, “BCS theory I and II”, and “The Kondo effect and heavy Fermions”.

Craig Roberts: “The Emergence of DSEs in Real-World QCD”. The properties of QCD are dominated by two emergent phenomena: confinement and dynamical chiral symmetry breaking (DCSB). These phenomena are not apparent in the formulae that define QCD, and DSEs play a critical role in exploring them and in predicting Nature's observable phenomena in the world of strong interactions.

Ian Cloet: “Hadron Phenomenology and QCD’s DSEs”. An understanding of how the colored quarks and gluons bind together to form the observed color singlet hadrons remains one of the most important questions in all of nuclear physics. His lectures will explore the interplay between experiment and theory using the DSEs and provide a perspective on answering key questions concerning QCD’s nonperturbative structure.
The next workshop in our series “Nucleon Resonance Structure in Exclusive Electroproduction at High Photon Virtualities” will be held at the University of South Carolina on August 13-15, 2012. This three-day workshop will provide us extended opportunities to present and discuss in depth future developments and preliminary results on the continuous exploration of hadronic physics towards smaller distances. If you would like to participate please contact gothe@sc.edu or mokeev@jlab.org or visit www.jlab.org/conferences/EmNN2012/.

In the tradition of this workshop, we will focus on the extension of the $\gamma_v^{NN*}$ electrocoupling studies to high photon virtualities from 5.0 to 12.0 GeV$^2$. This is the kinematic area, where the N* structure is still almost unexplored, and which will be comprehensively covered by the approved experiment PR12-09-003 on N* studies in exclusive meson electroproduction off protons with the CLAS12 detector. The experiment will be carried out in the first five years after the completion of the Jefferson Lab 12-GeV Upgrade Project.

By that time ready-to-use methods for the extraction of the $\gamma_v^{NN*}$ electrocouplings at high photon virtualities are needed as well as general QCD-based frameworks for the theoretical interpretation of these fundamental N* parameters. Resonance electrocouplings will be measured for the first time at distance scales, where quark degrees of freedom are expected to dominate. These studies will focus on the exploration of quark interactions in the QCD running coupling regime, which are responsible for the baryon formation. They are vital in order to explore confinement in the baryon sector and to understand how the complexity of non-perturbative strong interactions emerges from QCD.

The scope of this three-day workshop focuses particularly on the development of future strategies, methods, and approaches to extract the $\gamma_v^{NN*}$ electrocouplings, where hard quark interactions become relevant, and on the interpretation of hadronic physics in this non-perturbative regime. The workshop aims to foster already initiated efforts and create opportunities to facilitate and stimulate further growth in this field.
Your Next Opportunities to Get Involved …

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