A “Brief” Summary on the

Electromagnetic N-N* Transition Form Factors Workshop

which took place on October 13-15, 2008

at Jefferson Lab, Newport News, VA

For more information, see: http://conferences.jlab.org/EmNN/

International Organizing Committee:
V. Burkert
B. Juliá Díaz
R. Gothe
T.-S. H. Lee
V. Mokeev

Presented by Philip Cole
Idaho State University
November 1, 2008.
### Program

#### Monday, Oct 16th, 2006

**8:00**  Registration/Continental Breakfast
**8:45**  Introductory Remarks
**9:15**  Overview of the Reaction Models of Meson Production Reactions
**10:30** COFFEE BREAK
**11:00** Nu-N bar Form Factors from Lattice and Quark Models: Prediction
**11:50** Extraction of Formfactors from Meson-Nucleon Reactions
**12:30** LUNCH ON OWN
**14:00** Coffee Break
**14:30** Overview of models of the nucleon and Delta
**15:00** Longitudinal and transverse helicity amplitudes in NQQM
**15:30** COFFEE BREAK
**16:15** Short/Contribution:
  - Partial Wave Analysis of Single Pion Production
  - Current status of E906 project
  - Extraction of nucleon resonances by means of Genetic Algorithms
  - Dimensional coupled channel calculations of pion and omega meson production
  - How Uzunc is useful in radiative decay of strange baryons
**18:30 - 20:30** RECEPTION - CEBAP Center Lobby

#### Tuesday, Oct 17th, 2006

**8:30 - 9:00** Registration/Continental Breakfast
**9:00 - 9:45** Excitation of N*(1440) with light cone probes through non-diagonal DCS
**12:30 - 14:00** LUNCH ON OWN
**14:00 - 15:00** Coffee Break
**15:00 - 16:00** Overview of models of the nucleon and Delta
**16:30 - 18:00** Short/Contribution:
  - Extraction of asymmetries from the data of Complete experiments
  - Proposal on experiments on Nu-N form factor with 12 GeV upgrade
  - Discussion on white paper on 12 GeV upgrade
**18:30 - 20:30** RECEPTION - CEBAP Center Lobby

#### Wednesday, Oct 18th, 2006

**8:30 - 9:00** Continental Breakfast
**9:00 - 9:30** The potential for "complete" experiments in pion-nucleon scattering
**9:45 - 10:15** Extraction of asymmetries from the data of Complete experiments
**10:20 - 10:40** BREAK
**10:45 - 11:15** Proposal on experiments on Nu-N form factor with 12 GeV upgrade
**11:30 - 12:30** Discussion on white paper on 12 GeV upgrade
**14:00** END
Electromagnetic Excitation of N*’s

The experimental N* Program has two major components:

1) Transition form factors of known resonances to study their internal structure and confining potential

2) Spectroscopy of excited baryon states, search for new states.

Both parts of the program are being pursued in various decay channels, e.g. \( N\pi, p\eta, p\pi^+\pi^-, K\Lambda, K\Sigma, p\omega, p\rho^0 \) using cross sections and polarization observables.
Photoproduction amplitude

Theory:
states are defined up to a phase factor
\[ N \rightarrow N e^{i\phi} \quad N^* \rightarrow N^* e^{i\phi*} \]
the overall sign is left unchanged

Phenomenology:
Overall sign relative to Born amplitude

In order to extract the helicity amplitudes the sign of the strong vertex is used

Need for: a definite way of extracting the photon vertex
a general consensus

Mauro Giannini
Electromagnetic Excitation of N*’s

Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range \( Q^2 = 0.1 - 7 \text{ GeV}^2 \) and measure the electro- and photo-production of final states with one and two pseudo-scalar mesons.

DOE Milestone 2012

Volker Burkert
N* in meson electroproduction and Nucleon Resonances in $2\pi$ Electroproduction

- 2\pi channel is sensitive to N*’s heavier than 1.4 GeV
- Provides complementary information to the 1\pi channel
- Many higher lying N*’s decay preferably to $\pi\pi N$ final states
Electrocouplings of high lying N*'s.

First consistent mapping of $Q^2$-dependence for D33(1700), P13(1720) electrocouplings from CLAS data on $2\pi$ electroproduction.
hadron structure with electromagnetic probes

\(\pi, \rho, \omega \ldots\) resolution low

\(0 < Q^2 < 5 \text{ GeV}^2\)

\(3q\)-core + MB-cloud

\(5 < Q^2 < 9 \text{ GeV}^2\)

\(Q^2 > ? \text{ GeV}^2\)

\(pQCD\) high

Quark mass extrapolated to the chiral limit, where \(q\) is the momentum variable of the tree-level quark propagator using the Asquint action.

\(\text{LQCD, DSE and …}\)

\(\text{Independent QCD Analyses Line Fit: DSE Points: LQCD}\)

\(\text{Need to multiply by } 3q^2 \text{ to get the } Q^2 \text{ per quark}\)
Transition of the virtual photon interaction to the constituent quark. N.B. it is NOT the pQCD regime where photon interacts on the current quark.
Whitepaper on the Excited Baryon Program with the 12 GeV Upgrade

• **Contributors**: All who have contributed significantly

• **Table of Contents**
  
  - I. Introduction and Recent Progress
  - II. Experimental Developments for 12 GeV upgrade
  - III. Theoretical developments for 12 GeV upgrade
  - IV. Reaction Models for Data Analysis
  - V. Experiments to be proposed
  - VI. Acknowledgments

• **References**

Final Version by: Dec 8, 2008
Focus of
within the context of the Whitepaper

Theoretical Developments
- Lattice QCD (R. Edwards)
- Models based on Dyson-Schwinger Equations of QCD (C. Roberts)
- Relativistic constituent quark models (M. Giannini)
- GPD with $N^*$ (M. Polyakov)

Reaction Models
- Dynamical Analysis at EBAC (B. Julia-Diaz)
- Isobar model analysis at Mainz (L. Tiator)
- Isobar model analysis at JLab (I. Aznauryan, V. Mokeev)

Experiments to be Proposed.
- $N \rightarrow N^*$ Transition Form Factors with CLAS at 11 GeV
  (Gothe, Mokeev, Burkert, Joo, Stoler, Cole)
- Others?
List of the questions relating to the motivation of
N* studies using an 11-GeV electron beam for
probing photon virtualities from 5.0 to 10 GeV^2.

1. How will our proposed N* transition helicity amplitude
data in the Q^2 region of 5.0 to 10 GeV^2 impact your
theoretical approach and, in general, how will this data
extend our overall understanding of strong interactions
responsible in the formation of N*s?

A set 7 Questions was sent to all theorists who attended the Workshop
2. We anticipate that by studying $N^*$ behavior at photon virtualities ranging from 5.0 to 10 GeV$^2$, it will give us access to resonance structure at distances, where the expected contributions from meson-baryon dressing to the $N$-$N^*$ vertices are presumably small. Hence this probe will allow for effectively delineating the constituent quark-core configurations from other competing processes.

To justify this claim of being able to access quark-core degrees of freedom at high photon virtualities, we ask you to make estimates of the $Q^2$-behavior of the two components, i.e.

- a) constituent quark core
- b) meson-baryon dressing of $N$-$N^*$ photon vertices,

which contribute to the $A_{1/2}, A_{3/2}, S_{1/2}$ $N$-$N^*$ transition amplitudes:

For the $N^*$ states: $P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535), F_{15}(1685), P_{13}(1720), D_{33}(1700)$ in the region $5.0 \leq Q^2 \leq 10$ GeV$^2$. 

please note

- the **calculated** proton radius is about **0.5 fm**
  (value previously obtained by fitting the helicity amplitudes)
- the medium $Q^2$ behaviour is fairly well reproduced
- there is lack of strength at **low $Q^2$** (outer region) in the e.m. transitions
  specially for the $A_{3/2}$ amplitudes

- emerging picture: quark core (**0.5 fm**) plus (meson or sea-quark) **cloud**

"On the other hand, the confinement radius of ≈ 0.5 fm, which is currently used in order to give
reasonable results for the photocouplings, is substantially lower than the proton charge radius
and this seems to indicate that other mechanisms, such as **pair production and sea quark** contributions
may be relevant."

Transverse Charge Densities of the Nucleon and N-> Roper

(Lothar Tiator and Marc Vanderhaeghen)

unpolarized: $\rho_0(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2)$

proton

neutron

p -> Roper^+

n -> Roper^0

polarized along $\hat{x}$: $\rho_T(\vec{b}) = \rho_0(Q^2) + \frac{b_y}{b} \int_0^\infty \frac{dQ}{2\pi} \tau(Q^2) J_1(bQ) F_2(Q^2)$

proton

neutron

p -> Roper^+

n -> Roper^0
3. How will the data on N-N* transition helicity amplitudes, obtained at $5.0 < Q^2 < 10 \text{ GeV}^2$, extend our knowledge on the binding potential and effective interactions responsible for 3-quark configuration mixing (i.e. OGE, OPE, instanton,...) within constituent quark models?

- How will such data on N* electrocouplings at high $Q^2$ help us in getting access to light-cone wave functions of excited proton states and the associated currents?
- What can we learn about the evolution constituent quark form factors?
- What are the prospects of relating the constituent quark, covariant and Dyson-Schwinger models to the underlying QCD and, in turn, how will this data on N* electrocouplings at high $Q^2$ be useful in establishing these relations?

4. Is it possible or likely that data on N* electrocouplings at high $Q^2$ will afford us access to excited flux tubes as a possible active degree of freedom in the N* structure? And could this be used to study flux tube self-interactions?
5. How does the rapid rise of the dressed-quark running mass impact the N-N* transition helicity amplitudes, as revealed from both
   - the studies of the dressed-quark propagator within the framework of Dyson-Schwinger equations
   - and from lattice calculations?

   How then may this running mass phenomenon be established in the studies of N* electrocouplings at high $Q^2$?

6. What are the prospects of having lattice calculations
   - which relate the underlying QCD data in N-N* helicity transition amplitudes at $Q^2$ up to 10 GeV$^2$?
   - And would such N* electrocoupling data be of significant benefit in making lattice calculations within this high $Q^2$ regime, where the expected contributions from meson-baryon dressing of N-N* photon vertices become negligible?
Ralf Gothe

Hadron Structure with Electromagnetic Probes

Quark mass extrapolated to the chiral limit, where $q$ is the momentum variable of the tree-level quark propagator using the Asquaut action.

Need to multiply by $3q^2$ to get the $Q^2$ per quark.
What are the prospects of shedding light onto the unique relations among the various N-N* transition helicity amplitudes (or the N-N* transition form factors) in setting constraints on the moments of different combination of the N-N* GPDs?
We can extract reliable results on N* electro-couplings from meson electroproduction data as evidenced, for example, by the slides presented in Inna Aznauryan’s talk:

Helicity amplitudes from the \( g^* p \rightarrow P_{11} \ (1440) \)  
\( D_{13} \ (1520) \)  
\( S_{11} \ (1535) \)
Helicity amplitudes of the $\gamma^* p \rightarrow P_{11} (1440)$ transition

First measurements of $A_{1/2}$ at $Q^2 > 0$

First measurements of $S_{1/2}$

CLAS data:
- $N\pi$
- $N\pi, N\pi\pi, \text{combined}$
- $N\pi\pi$ (preliminary)
- $\gamma p \rightarrow p\pi^0$

M. Dugger et al., PR C76 025211, 2007

PDG

Victor Mokeev
Inna Aznauryan

**P_{11} (1440):** Additional components and contributions

---

Pion cloud contributions and additional $qqq\bar{q}q$ components in the Roper resonance can improve the description at small $Q^2$.

$\Gamma_{\text{theory}} = \Gamma_{\text{exp}}$

Li, Riska, PR C74(2006)015202
\[ \gamma^* p \rightarrow P_{11}(1440): \] 3q picture with \( P_{11}(1440) \) as \([56,0^+]_r\)

All LF RQM describe sign change of \( A_{1/2} \) the amplitude \( S_{1/2} \)

Strong evidence in favor of \( P_{11}(1440) \) as a first radial excitation of 3q ground state

All LF RQM fail to describe the amplitude \( A_{1/2} \) at \( Q^2 < 1 \text{ GeV}^2 \)

**LF RQM:**
- Weber, PR C41 (2783) 1990
- Capstick, Keister, PR D51 (1995) 3598
- Pace, Simula et.al., PR D51 (1995) 3598
- Aznauryan, PR C76 (2007) 025212
Helicity amplitudes of the $\gamma p \to D_{13}(1520)$ transition

**CLAS data:**
- $N\pi$
- $N\pi, N\pi\pi$, combined
- $N\pi\pi$ (preliminary)
- $\gamma p \to p\pi^0$, M. Dugger

**Old data:**
- Bonn, DESY, NINA

First definite results for $A_{1/2}$, $A_{3/2}$ in wide range of $Q^2$

First measurements of $S_{1/2}$
Helicity amplitudes of the $\gamma p \rightarrow S_{11} (1535)$ transition

First measurements of $S_{1/2}$:
- It is difficult to extract $S_{1/2}$ in $\eta$ electroproduction
- Results for $A_{1/2}$ obtained in $\pi$ and $\eta$ production agree with each other with $\beta_{\pi N} = 0.45$, $\beta_{\eta N} = 0.52$ →
  - PDG: $\beta_{\pi N} = 0.35\text{--}0.55$, $\beta_{\eta N} = 0.45\text{--}0.6$

Slow falloff of $A_{1/2}$ observed in $\eta$ production is confirmed by $\pi$ data
Resonance Analysis Tools

- Nucleon resonances are **broad and overlapping**, careful analyses of angular distributions for differential cross sections and polarization observables are needed.

- Amplitude & multipole analysis *(GWU-SAID, MAID)*

- Jlab/MSU Model *(JM06)* for $N^*$ analysis in charge double pi and electro- and photoproduction.

- Phenomenological analysis procedures have been developed, e.g. **unitary isobar models (UIM), dispersion relations (DR)**, that separate non-resonant and resonant amplitudes in single channels.

- Dynamical coupled channel approaches for single and double pion analysis are being developed within the Excited Baryon Analysis Center (EBAC) effort. They are most important in the extraction of transition form factors for higher mass baryon states.
**N(1440)\(P_{11}\)'s Puzzle**

- The analysis of the recent CLAS \(\pi^+\) electroproduction data
  \([W = 1.15 - 1.69 \text{ GeV} \& Q^2 = 1.7 - 4.5 \text{ GeV}^2]\)
  allows to extract helicities for \(\gamma p \to N(1440)P_{11}\) transition

- Model predictions allow to conclude that N(1440) is a first radial excitation of 3\(q\) ground state

- Most of analyses of N(1440) are based on its BW parameterization, which assumes that the Res is related to an isolated Pole
- However, the latest GW PWAs for the elastic \(\pi N\) scattering gives evidence that N(1440) corresponds to a more complicated case of several nearby singularities in the amplitude
- Then, the BW description is only an efficient one for N(1440), which could be different in different processes
- Some inelastic data indirectly support this point:
  they give the N(1440) BW mass and width essentially different from the PDG BW values

- Since \(Q^2\)-dependences for contributions of different singularities may be different, the set of several singularities might provide the N(1440) BW mass and width depending on the \(Q^2\)

- This problem can be studied in future measurements with CLAS12

-- \(GW: A_{1/2} = -50.6\pm1.9\)
N(1520)D_{13}'s Puzzle

•GW: $A_{3/2} = 143.1 \pm 2.0$

Resonance fit done over a narrow range in $W$ but for all $Q^2$
a and b are free params
(no $W$ dependence for the polynomial piece of the structure function)

• The good agreement for $A_{3/2}$ and $S_{1/2}$ determination between various
resonance extractions gives a more reliable estimate of systematics

• CLAS12 is favorable for $Q^2$ evaluation

Igor Strakovsky
in our MAID analysis the resonances are dressed

\[
\text{dressed resonance} = \text{bare resonance} + \text{pion loop contribution (pion cloud)}
\]

dressing and undressing can be studied in Dynamical Models:
e.g. Kamalov, Yang, Drechsel, L.T. and Sato, Lee, Julia-Diaz

in most cases quark models calculate the bare resonance couplings
a direct comparison with exp. analysis is not possible,
e.g. Giannini on the hypercentral quark model

Lothar Tiator
transition form factors of the Roper

comparison of MAID and JLab analysis

$A_{1/2}$

$S_{1/2}$

JLab analysis with $\pi^+$ data of Joo et al, 2004
Park et al, 2007

Lothar Tiator
transition form factors of the Roper

comparison of MAID and JLab analysis

\[ A_{1/2} \]

\[ S_{1/2} \]

results from:
Maid07
JLab
and
new Maid analysis
with Park data

Lothar Tiator
Theoretical Models

- Hypercentral Constituent Quark Model
- Covariant Models
- Light Cone Distr. Functions → Light Cone Sum Rules
- Lattice QCD
- Dyson Schwinger Equations
- Generalized Parton Distributions
Hypercentral Model (1)

\[ H_{3q} = 3m + \sum_{i=1}^{3} \frac{p_i^2}{2m} + V(x) + H_{\text{hyp}} \]


- \( V(x) = -\frac{T}{x} + \alpha x \);
- \( H_{\text{hyp}} = A \left[ \sum_{i<j} V^S(r_i, r_j) \sigma_i \cdot \sigma_j + \text{tensor} \right] \)

- 3 parameters \( \tau, \alpha, A \leftarrow \) fixed to the spectrum, \( m = \frac{M}{3} \)

\[ x = \sqrt{\rho^2 + \lambda^2} \]

hyperradius

\( \tau = 4.59 \)

\( \alpha = 1.61 \text{ fm}^{-1} \)

\( A \leftarrow (N - \Delta) \)

Mauro Giannini
D13  hCQM  predictions

Mauro Giannini
- Direct lattice calculations of form factors
  - restricted to $Q \ll 1/a$, currently $a = 0.06 - 0.08$ fm $\sim 1/(2 - 3 \text{ GeV})$; unlikely to go beyond $Q^2 \sim 3 \text{ GeV}^2$
  - black box

- Light-cone sum rules
  - need $N^*$ light-cone distribution amplitudes (DAs) or at least good interpolating current
  - in approaches based on duality, separation of states of different parity is very difficult:
    $$\langle 0|qqq|N(p)\rangle = f_N N(p) \quad \langle 0|qqq|N^*(p)\rangle = f_{N^*} \gamma_5 N(p)$$

- In this work
  - calculate moments of $N^*$ light-cone distribution amplitudes on the lattice
  - use them as input in LCSRs to calculate form factors
- why light-cone sum rules?

**Hard rescattering:**
- Small $b$
- Average $0 < x < 1$

**Soft (Feynman):**
- Average $b$
- Large $x \rightarrow 1$

- pQCD ‘hard’ contributions are included
- ‘soft’ contribution is built as a sum of contributions of DAs of increasing twist:
  - expansion parameter $(\Lambda^2_{QCD}/s_0)^{\text{Twist}}$ where $s_0$ is interval of duality
- there is no double counting but separation of ‘soft’ and ‘hard’ is scheme- and scale-dependent

This technique provides one with the most direct relation between form factors and parton structure that is available at present, with no other parameters.

Vladimir Braun
Results: $\gamma^* N \rightarrow N^*(1535)$

![Graph depicting the results of $\gamma^* N \rightarrow N^*(1535)$ with data points and error bars.]


Vladimir Braun
Spectator Quark Model: Nucleon and Delta

**S-state approach**

- Baryon = interacting quark \(\oplus\) spectator diquark
- **Nucleon** and \(\Delta\) represented with covariant S-state wave functions
- Describes Nucleon Elastic Form Factors: \(\frac{G_{EP}}{G_{M^*}}\) Jlab data
- Explains dominant contribution of the \(\gamma N \rightarrow \Delta\) transition
  *Quark core \(\approx 66\%\) of M1 (\(G_M^*\))
- \(G_M^* =\) Quark core \(\oplus\) Pion Cloud
  *Pion Cloud \(\approx\) remaining part
  *[Pion cloud can be estimated using Dynamical Models]
Spectator Quark Model: Nucleon and Delta


- Non-zero contributions for the quadrupole form factors $E2 \sim R_{EM}$ and $C2 \sim R_{SM}$
- Quark degrees of freedom insufficient to explain the data
- $G_X^+ = \text{Quark core} \oplus \text{Pion Cloud}$
- Pion Cloud contribution derived from large $N_c$ limit
- Pion Cloud dominate, but a small mixture of D-states improves the description of the data
- Pion cloud estimation must be improved (high $Q^2$)
- Differences between analyses (Jlab vs MAID) must be explained
Lattice QCD
Excited state nucleon spectrum

- Computation of excited hadron spectrum and meson photocouplings a major focus of the Hadron Spectrum Collaboration (JLab+CMU+UMD+Dublin)

- Key techniques:
  - Use of anisotropic lattices to resolve excited states. New gauge generation required.
  - Variational determination of energies using non-local operators.

- Initial results using quenched lattices

- New work involves dynamical $N_f=2$ lattices: $m_\pi = 400$ MeV.

- Current work: using $N_f=2+1$, lowering pion mass, disentangling decay states

David Richards/Robert Edwards
Nucleon-Roper form-factors

- Radiative transition form-factors: also major focus of collaboration.
- Exploratory study of excited nucleon form-factors. Quenched lattices: $m_\pi \sim 720\text{MeV}$. Reasonable signal. Pion cloud effects important.
- Computations in time-like region will shift with decreasing pion mass.
- Current work: using $N_f=2+1$, decrease pion mass, improved baryon operators, disentangle decay states.

**Proton-$P_{11}$**

**Neutron-$P_{11}$**

arXiv:0803.3020

David Richards/Robert Edwards
Nucleon-Roper Form Factors

Completed exploratory study on quenched lattices  
Proton-$P_{11}$  720 MeV Pion  Neutron-$P_{11}$

Possible decaying state (circled above)

200 configurations give us reasonable signal

Lower pion mass will shift the time-like region to space-like region

David Richards/Robert Edwards
Dyson-Schwinger Equations

Dyson-Schwinger Equations
CLAS at 11 GeV

Craig D. Roberts
cdroberts@anl.gov

Physics Division
Argonne National Laboratory
http://www.phy.anl.gov/theory/staff/cdr.html
Dynamical quark mass

- Spectrum of excited states and transition form factors provide unique information about long-range interaction between light-quarks and distribution of hadron's characterising properties amongst its QCD constituents.
- Dynamical chiral symmetry breaking (DCSB) is a FACT in QCD.
  - E.g., Exhibited in the momentum evolution of $M(p^2)$, which connects the nonperturbative and perturbative domains.
  - Predicted by DSE studies & confirmed by lattice-QCD simulations.
- DCSB is most important mass generating mechanism for visible matter in the Universe. Higgs boson is irrelevant to light-quarks.
Dyson-Schwinger Equations

- Poincaré covariant unification of meson and baryon observables – full machinery of quantum field theory
- All global and pointwise corollaries of DCSB are naturally manifested, without fine-tuning
- Foundation for proof of exact results in QCD
- Confinement is defined and expressed covariantly
- Excited states:
  - Mesons already being studied
  - Baryons are within practical reach
  - Ab-initio study of $N \rightarrow \Delta$ transition underway
- DSEs: Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks
  - Turn data on transition form factors into a map of $M(p^2)$
Programme Goals

- Peel away meson cloud & systematically define hadron’s quark core
  - To which $Q^2$ do meson cloud effects extend?
  - From which degrees of freedom is the quark core built?
- Strong indications from DSEs: Dressed-quarks & nonpointlike diquark correlations
- Map the long-range interaction between light-quarks; namely, determine the infrared behaviour of QCD’s $\beta$-function
- Strong interaction between experiment and theory is essential in order to achieve the goal
  - NB. Potential between static (infinitely heavy) quarks measured in simulations of lattice QCD is not related in any known way to the light-quark interaction

- Poincaré covariant DSEs provide a framework within which to rigorously pose and address the question. Progress being made.
GPDs
Maxim Polyakov

$N \rightarrow \text{meson} + N$ GPD-quintessence function

$N(x, t, W, t', x)$ is a complex function

- The whole machinery developed for can be applied to $N(x, t, W, t', x)$
- New is variable $x$, it is dual to the spin of the QCD string
  \[ \int dx \ x^{J-1} \] selects spin $J$
- $x$-dependence of quintessence function can be obtained from $x$-dependence of DVCS amplitude via tomography formula!

For tomography of DVCS amplitude and GPD quintessence function see Polyakov, PLB659 (2008) 542
There be Photons, too!
### CLAS Search for Excited Baryon States

<table>
<thead>
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<th>Experiment</th>
<th>reactions</th>
<th>beam pol.</th>
<th>target pol.</th>
<th>recoil</th>
<th>status</th>
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</thead>
<tbody>
<tr>
<td>G1/G10</td>
<td>γp→Nπ, ρη, ρππ, KΛ/Σ</td>
<td>-</td>
<td>-</td>
<td>Λ,Σ</td>
<td>complete</td>
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<tr>
<td>G8</td>
<td>γp→p(ρ,φ,ω)</td>
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<td>-</td>
<td>-</td>
<td>complete</td>
</tr>
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<td>G9-FROST</td>
<td>γp→Nπ, ρη, ρππ, KΛ</td>
<td>lin./circ.</td>
<td>long./trans.</td>
<td>Λ,Σ</td>
<td>2007</td>
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<td>G13</td>
<td>γD→KΛ, KΣ</td>
<td>circ./lin.</td>
<td>unpol.</td>
<td>Λ,Σ</td>
<td>2006/2008</td>
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<td>G14-HD</td>
<td>γ(HD)→KΛ, KΣ, Nπ</td>
<td>lin./circ.</td>
<td>long./trans.</td>
<td>Λ,Σ</td>
<td>2009/2010</td>
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This program will, for the first time, provide complete amplitude information on the KΛ final state (more than 7 independent polarization measurements at each kinematics), and nearly complete information on the Nπ final states.
Polarized Pseudoscalar meson photo-production:

\[ \vec{\gamma} + \vec{N} \rightarrow K + \bar{\Lambda} \]
**E asymmetry**

leading Pol dependence

\[ p_c^\gamma \cdot p_z^T \]

**T_2 asymmetry**

leading Pol dependence

\[ p_x^T \cdot p_z^\Lambda \]

measured via

\[ p_L^\gamma \cdot p_z^T \cdot p_x^\Lambda \]

Andy Sandorfi
Polarization observables in $J^p = 0^-$ meson photo-production:

- **single-pol observables measured from double-pol asym**
- **double-pol observables measured from triple-pol asym**

<table>
<thead>
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<th>Photon beam</th>
<th>Target</th>
<th>Recoil</th>
<th>Target - Recoil</th>
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<td>P, G</td>
</tr>
<tr>
<td>circular $P_\perp$</td>
<td>F</td>
<td>E</td>
<td>$C_{x'}$</td>
</tr>
</tbody>
</table>

- **not all are independent:**

\[
E^2 + F^2 + G^2 + H^2 = 1 + P^2 - \Sigma^2 - T^2
\]

\[
FG - EH = P - \Sigma T
\]

\[
C_{x'} x' + O_{x'}^2 + O_{z'}^2 = 1 - P^2 - \Sigma^2 + T^2
\]

\[
C_{z'} O_{x'} - C_{x'} O_{z'} = T - \Sigma P
\]

\[
T_{x'}^2 + T_{z'}^2 + I_{x'}^2 + I_{z'}^2 = 1 - P^2 + \Sigma^2 - T^2
\]

\[
L_{z'} T_{x'} - L_{x'} T_{z'} = -PT + \Sigma
\]

Andy Sandorfi
\[ \gamma n \rightarrow K^0 \Lambda \quad E_\gamma = 1.55 \, GeV \quad (W = 1.95 \, GeV) \]

- \text{Beam-Recoil}
- \text{Target-Recoil}

\[ C_x \quad L_x \]
\[ C_z \quad L_z \]
\[ O_x \quad T_x \]
\[ O_z \quad T_z \]

- \text{M2 solution}
- \text{no D}_{13}(1910)
- \text{no } \pi\text{-cloud}
- \text{no coupled-ch}

-B. Juliá-Díaz, T-S. H. Lee (preliminary)

Andy Sandorfi
• Spin observables in terms of density matrix elements

Vector meson decay distribution:

\[ W(\cos \theta, \phi, \Phi) = W^0(\cos \theta, \phi, \rho_{\alpha\beta}^0) - P_\gamma \cos 2\Phi W^1(\cos \theta, \phi, \rho_{\alpha\beta}^1) - P_\gamma \sin 2\Phi W^2(\cos \theta, \phi, \rho_{\alpha\beta}^2) + \lambda_\gamma P_\gamma W^3(\cos \theta, \phi, \rho_{\alpha\beta}^3), \]
Unpolarized decay distribution:

\[
W^0(\cos \theta, \phi, \rho_{\alpha \beta}^0) = \frac{3}{4 \pi} \left( \frac{1}{2} \sin^2 \theta + \frac{1}{2} (3 \cos^2 \theta - 1) \rho_{00}^0 \right) \\
- \sqrt{2} \text{Re} \rho_{10}^0 \sin 2 \theta \cos \phi \\
- \rho_{1-1}^0 \sin^2 \theta \cos 2 \phi,
\]

Linearily-polarized decay distribution:

\[
W^1(\cos \theta, \phi, \rho_{\alpha \beta}^1) = \frac{3}{4 \pi} (\rho_{11}^1 \sin^2 \theta + \rho_{00}^1 \cos^2 \theta) \\
- \sqrt{2} \text{Re} \rho_{10}^1 \sin 2 \theta \cos \phi \\
- \rho_{1-1}^1 \sin^2 \theta \cos 2 \phi,
\]

\[
\begin{align*}
\rho_{ik}^0 &= \frac{1}{A} \sum_{\lambda \lambda_2 \lambda_1} H_{\lambda \nu_i \lambda_2, \lambda \lambda_1} H_{\lambda \nu_k \lambda_2, \lambda \lambda_1}^*, \\
\rho_{ik}^1 &= \frac{1}{A} \sum_{\lambda \lambda_2 \lambda_1} H_{\lambda \nu_i \lambda_2, -\lambda \lambda_1} H_{\lambda \nu_k \lambda_2, \lambda \lambda_1}^*, \\
\rho_{ik}^2 &= \frac{i}{A} \sum_{\lambda \lambda_2 \lambda_1} \lambda H_{\lambda \nu_i \lambda_2, -\lambda \lambda_1} H_{\lambda \nu_k \lambda_2, \lambda \lambda_1}^*, \\
\rho_{ik}^3 &= \frac{i}{A} \sum_{\lambda \lambda_2 \lambda_1} \lambda H_{\lambda \nu_i \lambda_2, \lambda \lambda_1} H_{\lambda \nu_k \lambda_2, \lambda \lambda_1}^*,
\end{align*}
\]

e.g. The polarized beam asymmetry:

\[
\begin{align*}
\sigma_\perp - \sigma_\parallel &= \frac{2 \rho_{11}^1 + \rho_{00}^1}{2 \rho_{11}^0 + \rho_{00}^0}, \\
\sigma_\perp + \sigma_\parallel &= 2 \rho_{11}^1 + \rho_{00}^1 \\
\epsilon_\perp &= \hat{y} = i(\epsilon_{\gamma^+} + \epsilon_{\gamma^-})/\sqrt{2} \\
\epsilon_\parallel &= \hat{x} = -(\epsilon_{\gamma^+} - \epsilon_{\gamma^-})/\sqrt{2}
\end{align*}
\]

Zhao, Al-Khalili & Cole, PRC71, 054004 (2005); Pichowsky, Savkli & Tabakin, PRC53, 593 (1996)
Three ingredients in our quark model approach:

1. **s- and u-channel resonance excitations**
   Vector meson production via an effective Lagrangian for quark-vector-meson interactions in the s- and u-channel;

2. **t-channel natural parity exchange**
   Pomeron exchange for neutral vector meson ($\omega$, $\rho^0$, $\phi$) production in the t-channel, and t-channel scalar meson exchange;

3. **t-channel unnatural parity exchange**
   Light meson exchanges in the t-channel, e.g. $\pi^0$ exchange for $\omega$ production.

Refs.
Z., Li, & Bennhold, PLB436, 42(1998); PRC58, 2393(1998);
Z., Didelez, Guidal, & Saghai, NPA660, 323(1999);
Z., PRC63, 025203(2001);
Z., Saghai, Al-Khalili, PLB509, 231(2001);
Z., Al-Khalili, & Bennhold, PRC64, 052201(R)(2001); PRC65, 032201(R) (2002);
Z., Al-Khalili, & Cole, PRC71, 054004(2005);
Theoretical results for $\omega$ production -- data from GRAAL Collaboration + …

- Total cross sections

$\gamma + p \rightarrow \omega + p$

$N \leq 2$

Born terms +

- $P_{11}(1440)$, $S_{11}(1535)$,
- $D_{13}(1520)$, $P_{13}(1720)$,
- $F_{15}(1680)$, $P_{11}(1710)$,
- $P_{13}(1900)$, $F_{15}(2000)$

$N > 2$

degenerate in $N$

$a = 3.67$, $b = -3.85$

GRAAL Collaboration, PRL96, 132003(2006)
Outline

• Model

• Fitting
  → πN→πN, πN→ωN, YN→πN,YN→ωN

• Predictions
  → Σ_ω photon beam asymmetry
  → ρ^0_{λλ'} spin density matrix elements
  → ωN scattering length

• Conclusion

Dynamical coupled channel calculation of pion and omega meson production
Total cross section $\sigma_{\gamma p \rightarrow \omega p}$
Resonance Analysis Tools

- Nucleon resonances are broad and overlapping, careful analyses of angular distributions for differential cross sections and polarization observables are needed.

- Amplitude & multipole analysis (GWU-SAID, MAID)

- Phenomenological analysis procedures have been developed, e.g. unitary isobar models (UIM), dispersion relations (DR), that separate non-resonant and resonant amplitudes in single channels.

- Dynamical coupled channel approaches for single and double pion analysis are being developed within the Excited Baryon Analysis Center (EBAC) effort. They are most important in the extraction of transition form factors for higher mass baryon states.
EBAC strategy (summary)

Reaction Data
\[
\pi N \rightarrow \pi N, \eta N, \pi \pi N, \ldots \\
\gamma^{(*)} N \rightarrow \pi N, \eta N, \pi \pi N, \ldots
\]

Dynamical Coupled-Channels Analysis @ EBAC

Electromagnetic N-N* form factors

QCD

Hadron Models

Lattice QCD

Bruno Juliá Díaz
What is needed for extracting electromagnetic N-N* form factors?

Before analyzing $eN \rightarrow e'\pi N, e'\pi\pi N, \ldots$, we need

1. Fixing hadronic parameters

2. Good model to describe $\gamma N$ reactions at $Q^2 = 0$.
   - Critical for the model construction
   - Starting point to explore $Q^2 > 0$ region

Bruno Juliá Díaz
Current status of the analysis @ EBAC

Hadronic part

✓ $\pi N \rightarrow \pi N$ : fitted to the SAID PWA up to 2 GeV.
  Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)

✓ $\pi N \rightarrow \pi \pi N$ : cross sections calculated; not fitted yet.
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, submitted to PRC

✓ $\pi N \rightarrow \eta N$ : fitted to the data up to 2 GeV ( varied only bare $N^* \rightarrow \eta N$ )

Electromagnetic part

✓ $\gamma N \rightarrow \pi N$ : fitted to the data up to 1.6 GeV ( varied only $\Gamma^{bare}_{\gamma N \rightarrow N^*}$ )

✓ $\gamma^* N \rightarrow \pi N$ : in progress Julia-Diaz, Kamano, Lee, Matsuyama, Sato

✓ $\gamma N \rightarrow \pi \pi N$ : in progress Julia-Diaz, Kamano, Lee, Matsuyama, Sato

✓ $\gamma N \rightarrow \eta N$ : in progress Durand, Julia-Diaz, Lee, Saghai
Coupled Channel Analysis (EBAC)

\[ \gamma, M \quad M_I \quad \gamma, M \quad M_I \quad \gamma, M \quad M_{II} \quad M_{II} \]

\[ = \quad + \sum_{M_{II}, B_{II}} \quad + \quad + \]

- Pion-nucleon and 2-pion-nucleon contributions to the non-resonant T matrix.

T.-S. Harry Lee
Summary-I

• Transition form factors for $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, & $S_{11}(1535)$. measured over large $Q^2$ range.
  - no sign of approaching asymptotic QCD limit --> need for 12 GeV upgrade
  - pion dressing of vertex needed to describe form factors.

• Roper $P_{11}(1440)$ transition form factor determined for the first time.
  - zero-crossing of magnetic form factor
  - behaves like a $Q^3$ radial excitation at short distances
  - $Q^2 < 0.7$ $GeV^2$ determined from the 1π and 2π exclusive channels, as well as from a combined analysis of both these channels, are in a good agreement (also in agreement with MAID – Tiator)

• Able to extract reliable results on N* electrocouplings from meson electroproduction data.
  - the $P_{11}(1440)$ and $D_{13}(1520)$. 1π and 2π channels have completely different nonresonant mechanisms AND ARE IN AGREEMENT!
  - description of all observables in both these channels with common N* electrocouplings good testing ground for efficacy of 2π: JM06, 1π: JLab/GWU-SAID/MAID reaction models.
**Summary-II**

- Good prospects for relating QCD to the $Q^2$ evolution of $N^*$s within the framework of Dyson-Schwinger & Bethe-Salpeter approaches and Lattice QCD (with caveat of more powerful computers) as determined through Light Cone wavefunctions.

- Healthy advances in Constituent Quark Models

- Can extract reliable information on $N^*$ electrocouplings from combined fit of multiple polarization observables in $N\pi$, $N\pi\pi$, $p\eta$, and $KY$ in electro- and photoproduction needed to resolve ambiguities in baryon resonance analysis.

- EBAC essential to support the baryon resonance program with coupled channel calculations
• We have the roadmap (e.g. hCQM, LQCD, DSEs)

• We can extract reliable results on N* electrocoupling from meson electroproduction data as evidenced above.

• We need transition form factors at for N* the helicity amplitude data in the $Q^2$ region of 5.0 to 10 GeV$^2$.

• 12-GeV upgrade imperative to access higher $Q^2$. This will give access to the transition Form Factors to QCD by probing the regime, which free from meson-baryon dressing effects.

**Need Data** Experiments to be Proposed.

- N→N* Transition Form Factors with CLAS at 11 GeV (Gothe, Mokeev, Burkert, Joo, Stoler, Cole)
- Others?
Conclusion: Do Exclusive Electron Scattering

... to Learn QCD!

Ralf Gothe
Workshop on the Physics of Excited Nucleon – NSTAR2009, Beijing

Workshop on the Physics of Excited Nucleon – NSTAR2009 is to be hosted by the Institute of High Energy Physics (IHEP) of Chinese Academy of Sciences (CAS) in Beijing on April 19 – 22, 2009.


Scientific Aim:

The study of nucleons and their resonances has provided a rich source of information on strong interaction physics in the non-perturbative QCD regime, and also raised fundamental questions with profound significance for our understanding of Nature.