Transition Form Factors at CLAS and CLAS12

M. Ungaro, M. Taiuti
for the CLAS collaboration

Overview
N* Form Factors are Back in Fashion
Single, Double Meson results
12 GeV Outlook
The discovery of resonances (‘50s)

Priceless
(at least for scientists)
Why N* ?

A major goal of hadron physics is to probe the internal structure of the nucleon.

*The N* spectrum is a direct reflection of the underlying degrees of freedom of the nucleon.*

Electromagnetic transition form factors probe the underlying *spatial and spin structure* vs distance scale.
Beyond CQM, pQCD

The structure of the nucleon and its excited states is a lot more complex than CQM.

Constituent Counting Rule tell us what will happen at high $Q^2$:

- $\gamma \lambda = 0, \pm 1$
- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$
- $G_M^* \propto 1/Q^4$

but pQCD cannot:

- produce mass in the chiral limit
- explain dynamics of quark-gluon interaction at low energy
- explain quark confinement
N* are back in fashion

Even as we speak, we need to fully understand:

- the essential nature of quark confinement.
- the dynamics of quark-gluon interaction at low energy

The role of quarks and gluon in nuclei
Step into the domain of relativistic quantum field theory where the key phenomena can only be understood with non-perturbative methods

Understanding nature using a non-perturbative approach is beginning to become a reality... and measurements of nucleon resonances play a crucial role in all this.

Lattice QCD
Dynamical Chiral Symmetry Breaking
Light Cone Sum Rule
Lattice QCD

JLAB
Carnegie Mellon
Univ. of Maryland
Trinity College (Dublin)

New Techniques:
Anisotropic Lattices
3 flavors of quarks

First time: baryon spectra for the excited states


Huey-Wen Lin: radial excitations to calculate form factors
We can use high precision measurements of nucleon-resonance transition form factors to chart the momentum evolution of the dressed-quark mass.
Light Cone Sum Rule

Transition Form Factor $\leftrightarrow$ Distribution Amplitudes

DA from Lattice QCD (Warkentin et al.):

Proton \[ \frac{1^+}{2} \]

\[ S_{11} \frac{1^-}{2} \]

29, 30: Dalton and Denizli
31: Brasse parameterization
32: Aznauryan analysis of e1-6 CLAS data
Most of the experimental data presented in the previous slides have been provided by the CLAS Collaboration
Transition Form Factors of the Nucleon

M. Taiuti

Outline

- Physics motivations
- Status of experiments
- CLAS - a detector for $Q^2 = \text{GeV}^2/c^2$
- Conclusions
N* Program in CLAS

Map the $\gamma NN^*$ electrocouplings as a function of photon virtuality with the combined analysis of the major electroproduction channels

<table>
<thead>
<tr>
<th>State</th>
<th>$\beta_{N\ell\ell}$</th>
<th>$\beta_{N\eta}$</th>
<th>$\beta_{N\ell\ell\ell\ell}$</th>
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<tr>
<td>$\Delta(1232)P_{33}$</td>
<td>0.995</td>
<td></td>
<td></td>
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<tr>
<td>$N(1440)P_{11}$</td>
<td>0.55-0.75</td>
<td></td>
<td>0.3-0.4</td>
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<tr>
<td>$N(1520)D_{13}$</td>
<td>0.55-0.65</td>
<td></td>
<td>0.4-0.5</td>
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<tr>
<td>$N(1535)S_{11}$</td>
<td>0.35-0.55</td>
<td>0.45-0.60</td>
<td>&lt;0.1</td>
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<tr>
<td>$N(1620)S_{31}$</td>
<td>0.20-0.30</td>
<td></td>
<td>0.7-0.8</td>
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<tr>
<td>$N(1650)S_{11}$</td>
<td>0.60-0.95</td>
<td>0.03-0.10</td>
<td>0.1-0.2</td>
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<tr>
<td>$N(1685)F_{15}$</td>
<td>0.65-0.70</td>
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<td>0.3-0.4</td>
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<tr>
<td>$\Delta(1700)D_{33}$</td>
<td>0.1-0.2</td>
<td></td>
<td>0.8-0.9</td>
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<tr>
<td>$N(1720)P_{13}$</td>
<td>0.1-0.2</td>
<td>0.01-0.15</td>
<td>&gt; 0.7</td>
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</table>

Several channels with entirely different non-resonant amplitudes allow the reliable determination of electrocouplings.
The CLAS Spectrometer

CEBAF Large Acceptance Spectrometer

PID

Elastic, B.H.

$\pi^0, \Delta$

$\eta, S_{11}$

$\rho, P_{13}$
Analysis Tools

Single pseudoscalar meson production, e.g. $N\pi$, $N\eta$

Unitary isobar model (UIM)
- non-resonant amplitudes incorporate nucleon and meson Born terms, vector meson exchanges, Regge terms at high energy
- resonant terms incorporate relativistic Breit-Wigner amplitude with energy-dependent widths
- full amplitude unitarized in K-matrix approximation

Fixed-t dispersion relations (DR)
- resonance amplitudes constructed in same way as in UIM
- non-resonant amplitudes from Born terms and dispersion relation.

Double pion channels, e.g. $p\pi^+\pi^-$

Isobar model (JM)
- Includes leading contributions as observed in the data.
- Fit to 9 single-dimensional projections diff. cross sections.
Selection of CLAS Results

A good summary can be found in
Single Meson Results

\[ \Delta_{33} \rightarrow (56, 0^+) \rightarrow (56, 0^+) \]

Roper \hspace{1cm} (56, 0^+) \rightarrow (56, 0^+) \hspace{1cm} \pi^0 + \pi^+ \hspace{1cm} Q^2 = 0.4 \text{ GeV}^2/c^2

\[ D_{13}(1520) \rightarrow (56, 0^+) \rightarrow (70, 1^-) \]
**N → Δ Transition Form Factor**

Meson-Baryon Dressing: Dynamical Reaction Models show huge contribution of pion cloud to Magnetic Form Factor

Pascalutsa: Large $N_C$ links $N \rightarrow \Delta$ Transition Form Factor to the e.m. properties of the nucleon!

$N \rightarrow \Delta$ GPD $H_M$ is related to isovector elastic GPD $E(x, \xi, t)$
The Roper Resonance


- Sign change of $A_{1/2}$ observed in both channels at same $Q^2$
- Magnitudes of $A_{1/2}$ and $S_{1/2}$ consistent in the two channels.
- High $Q^2$ behavior consistent with radial excitation of nucleon (-----)
- Rules out the Roper as a gluonic excitation (---)
- Meson, non resonant contributions necessary at low $Q^2$?
**$D_{13}(1520)$ Transition Amplitudes**

- First data set that allows determination of $S_{1/2}(Q^2)$
- Very Accurate result for the Transverse Amplitudes
- Clear evidence of helicity switch from helicity=3/2 dominance at $Q^2=0$ to helicity=1/2 dominance at high $Q^2$

$$A_{\text{hel}} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$
Double Meson Production

Single, double meson channels are the main players in the resonance region: sensitive to almost all excited proton states.

The combined analysis of $N\pi$, $N\pi\pi$ data is key in the entire $N^*$ program: allow us to determine with high precision both the resonant and non-resonant amplitudes.
JLAB-MSU meson baryon model for Nππ electroproduction

Channels included:

all N*s with πΔ decays
Reggeized Born Terms
additional πΔ Contact Term

all N*s with ρP decays and 3/2+(1720) candidate
Diffractive Ansatz for non-resonant part
ρ line shrinkage in N* region
JLAB-MSU meson baryon model for $N\pi\pi$ electroproduction

Channels included:

$D_{13}, F_{15}, P_{33}(1640)$

Direct 2 pion production
(required by Unitarity and confirmed by CLAS $P\pi\pi$ data)
P$\pi^+\pi^-$ Production

Fedotov, PRC 79 (2009)

W=1.5125 GeV, $Q^2=0.375$ GeV$^2$

Ripani, PRL 91 (2003)

W=1.71 GeV, $Q^2=0.65$ GeV$^2$

$\pi^-\Delta^{++}$

$\pi^+\Delta^0$

full JM calc.

$\pi^+F^0_{15}(1685)$

$\rho p$

$\pi^0D^0_{13}(1520)$

$2\pi$ direct
Resonant, non-resonant parts of $N\pi\pi$

$W=1.5125 \text{ GeV}$, $Q^2=0.375 \text{ GeV}^2$

$W=1.71 \text{ GeV}$, $Q^2=0.95 \text{ GeV}^2$

$\frac{d\sigma}{dM} \text{ mcbn/GeV}$

$\frac{d\sigma}{dM} \text{ mcbn/GeV}$

$\frac{d\sigma}{dM} \text{ mcbn/GeV}$

(full cross sections)  \hspace{1cm} (resonant part) \hspace{1cm} (non-resonant part)

International School of Nuclear Physics 16-24 Sept 2011 Erice, Italy
Towards 12 GeV

In just 14 months from today

✧ Remove much of CLAS May 14, 2012 (est. 5 ½ months )

✧ Begin CLAS12 installation Nov 1, 2012

✧ Complete CLAS12 installation 4th QT 2014
Full **CLAS12** Assembly in Hall B
not so distant future...

60 Days at $10^{35}$ cm$^{-2}$s$^{-1}$
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<th>Proposal</th>
<th>Contact Person</th>
<th>Physics</th>
<th>Energy (GeV)</th>
<th>Days requested</th>
<th>PAC days</th>
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<td>Gothe</td>
<td>$N^*$ at high $Q^2$</td>
<td>11</td>
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