Analysis of Baryon Transition Electromagnetic Form Factors

Teresa Peña
in collaboration with
Gilberto Ramalho
- Hadrons constitute the major part of the visible universe.

- Beyond spectroscopy, today’s experiments have a new level of scope, precision and accuracy on the still unexplored territory of Hadron structures (evidence for multiquark and exotic configurations.)

Special role of HADES@SIS at GSI and PANDA at FAIR:

- Exploring QCD phase diagram at high baryonic number and moderate temperatures

- Experiments with pion beam also allow for cold matter effects.
Two methods of obtaining information on structure of baryons

$q^2 \leq 0$: CLAS/Jefferson Lab, MAMI, ELSA, JLab-Hall A, MIT-BATES

$ep \rightarrow e'N(\cdots); \gamma^*N \rightarrow N^*$

$q^2 > 0$: HADES, ...., PANDA

$\pi^-p \rightarrow e^+e^-n; N^* \rightarrow \gamma^*N \rightarrow e^+e^-N$

Why use of pion beam:
Separation of in-medium propagation and mechanism, because pions are absorbed at the surface of the nucleus whereas in photon and proton absorption occurs throughout the whole nuclear volume.
Transition Electromagnetic form factors

**Spacelike form factors:**
- Structure information: shape, qqq excitation vs. hybrid, ...

**Timelike form factors:**
- Particle production channels

$q^2<0$

$q^2>0$

This talk:
Connect Timelike and Spacelike Transition Form Factors (TFF)
Obtain Baryon-photon coupling evolution with 4 momentum transfer
### Baryon resonances \( S=0 \) \( \text{PDG} \)

<table>
<thead>
<tr>
<th>( I )</th>
<th>( S )</th>
<th>( J^P = \frac{1}{2}^+ )</th>
<th>( \frac{3}{2}^+ )</th>
<th>( \frac{5}{2}^+ )</th>
<th>( \frac{1}{2}^- )</th>
<th>( \frac{3}{2}^- )</th>
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<tr>
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<td>0</td>
<td>\text{N}(940)</td>
<td>\text{N}(1720)</td>
<td>\text{N}(1680)</td>
<td>\text{N}(1535)</td>
<td>\text{N}(1520)</td>
<td>\text{N}(1675)</td>
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<td></td>
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<td>\text{N}(1440)</td>
<td>\text{N}(1900)</td>
<td>\text{N}(1860)</td>
<td>\text{N}(1650)</td>
<td>\text{N}(1700)</td>
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<td>( \frac{3}{2} )</td>
<td>0</td>
<td>\text{\Delta}(1910)</td>
<td>\text{\Delta}(1232)</td>
<td>\text{\Delta}(1905)</td>
<td>\text{\Delta}(1620)</td>
<td>\text{\Delta}(1700)</td>
<td>\text{\Delta}(1930)</td>
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<td>\text{\Delta}(1940)</td>
<td>\text{\Delta}(1920)</td>
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![Graph of \( \gamma p \rightarrow n \pi^+ \) with resonances and kinematics](image)
Our approach is phenomenological

“Murray looked at two pieces of paper, looked at me and said ‘In our field it is costumary to put theory and experiment on the same piece of paper’. I was mortified but the lesson was valuable”

Memories of Murray and the Quark Model

Zweig quark or the constituent quark
E.M. matrix element can be written in terms of an effective baryon composed by an off-mass-shell quark, and an on-mass-shell quark pair (diquark) with an average mass.

Baryon wavefunction reduced to an effective quark-diquark structure.
✓ The Diquark is not pointlike.

- Nucleon “wavefunction” (S wave) (symmetry based only; not dynamical based)
  - A quark + **scalar**-diquark component
  - A quark+ **axial vector**-diquark component

\[
\Psi_{N\lambda}^S(P, k) = \frac{1}{\sqrt{2}} \left[ \phi_1^0 u_N(P, \lambda_n) - \phi_i^1 \varepsilon_{\lambda P}^\alpha U_\alpha(P, \lambda_n) \right] \times \psi_{N\kappa}^S(P, k).
\]

\[
U_\alpha(P, \lambda_n) = \frac{1}{\sqrt{3}} \gamma_5 \left( \gamma_\alpha - \frac{P_\alpha}{m_H} \right) u_N(P, \lambda_n),
\]

- Delta (1232) “wavefunction” (S wave)
  - Only quark + **axial vector**-diquark term contributes

\[
\Psi_{\Delta}^S(P, k) = -\psi_{\Delta}^S(P, k) \phi_i^1 \varepsilon_{\lambda P}^\beta w_\beta(P, \lambda_\Delta).
\]
Quark E.M. Current

**Quark-photon vertex**

\[
\Gamma (p, Q) = \gamma_\mu + \int \frac{d^4 q}{(2\pi)^4} K(p, q, Q) S(q + \eta Q) \Gamma_\mu(q, Q) S(q - \eta Q)
\]

**Constituent quarks (quark form factors)**

\[
j_1^\mu = \left[ \frac{1}{6} f_{1+} + \frac{1}{2} f_{1-} \tau_3 \right] \gamma^\mu + \left[ \frac{1}{6} f_{2+} + \frac{1}{2} f_{2-} \tau_3 \right] \frac{i \sigma^\mu\nu q_\nu}{2 M_N}
\]

To parametrize the current we use Vector Meson Dominance at the quark level, a truncation to the rho and omega poles of the full meson spectrum contribution to the quark-photon coupling.

4 parameters
Transition E.M. Current

\[ \gamma N \rightarrow \Delta \]

\[ \Gamma^\beta\mu(P, q) = [G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^\beta\mu] \gamma_5 \]

- Only 3 \( G_i \) are independent: E.M. Current has to be conserved

\[ q^\mu \Gamma_{\beta\mu} = 0 \]

\( G_M, G_E, G_C \) Scadron-Jones popular choice.
Model independent feature

\[ \gamma N \rightarrow \Delta \]

\[ |G_M^*| = G_M^{B} + G_M^{\pi} \]

Separation seems to be supported by experiment. Missing strength of \( G_M \) at the origin.

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**Bare quark core:**
- dominates in the large \( Q^2 \) region.
- agrees with other calculations ("EBAC") with pion couplings switched off.
Model independent feature

\[ \gamma^N \rightarrow \Delta \]

**Missing strength of** $G_M$ **at the origin is an universal feature, even in dynamical quark calculations.**

Eichmann et al., Prog. Part. Nucl. Phys. 91 (2016)

Effect of vicinity of the mass of the Delta to the pion-nucleon threshold.

\[ |G_M^*| = G_B^M + G_{\pi}^M \]
Bare quark (partonic) and pion cloud (hadronic) components

For low $Q^2$ : add coupling with pion in flight.

- Bare quark component
- Pion cloud component

$q\bar{q}$ pairs from a single quark included in dressing

Pion created by the overall baryon not from a single quark

Pion cloud component suppressed for high $Q^2$ $\frac{1}{Q^8}$

Gilberto Ramalho (IIP/UFRN, Natal, Brazil)
SL and TL e.m. baryon FF
Estoril, October 9, 2015
VMD as link to LQCD

- In the current the vector meson mass is taken as a function of the running pion mass.
- Pion cloud contribution negligible for large pion masses.
- Experimental data well described in the large $Q^2$ region.
- Take the limit of the physical pion mass value.
- Quark model calibrated to the lattice data.
• Bare quark model gives good description in the high momentum transfer region.

• Use CST quark model to infer meson cloud from the data.

• Important role of meson cloud extracted dominated by the isovector part, due to the $\pi N$ and $\pi \Delta$ channels.

Consistent with Aznauryan and Burkert, PRC 85 055202 2012 and PDG

$$A^V_{3/2} \approx 0.13 \ ; \ A^S_{3/2} \approx 0.01 \ (GeV^{-1/2})$$

G. Ramalho, M. T. P , PHYSICAL REVIEW D 95 014003 (2017)
\( N \rightarrow N^* (1535) \textbf{TFFs} \)

\[ J^\mu = \bar{u}_R \left[ F_1^* \left( \gamma^\mu - \frac{q^\mu}{q^2} \right) + F_2^* \frac{i\sigma^{\mu\nu} q_\nu}{M_N + M_R} \right] \gamma_5 u_N \]

- Use CST quark model to infer meson cloud from the data.

Again good agreement of bare quark core with EBAC analysis

- Bare quark effects dominate \( F_1^* \) for large \( Q^2 \)

- Meson cloud effects dominate \( F_2^* \) with meson cloud extending to high \( Q^2 \) region. (effect from the \( \eta N \) channel?).

PDG

\[ A_{1/2}^V(0) = 0.090 \pm 0.013 \text{ GeV}^{-1/2} \]
\[ A_{1/2}^S(0) = 0.015 \pm 0.013 \text{ GeV}^{-1/2} \]
Extension to the Timelike region

The residue of the pion from factor $F_\pi(q^2)$ at the timelike $\rho$ pole is proportional to the decay $\rho \rightarrow \pi\pi$ decay

Diagram (a) related with pion electromagnetic form factor $F_\pi(q^2)$
Crossing the boundaries

$\gamma N \rightarrow \Delta$

$\Delta(1232)$ Dalitz decay


Parametrization of pion Form Factor

$$F_\pi(q^2) = \frac{\alpha}{\alpha - q^2 - \frac{1}{\pi} \beta q^2 \log \frac{q^2}{m_\pi^2} + i \beta q^2}$$

$\alpha = 0.696 \text{ GeV}^2$

$\beta = 0.178$
Timelike region

\[ \Delta(1232) \text{ Dalitz decay} \]

\[
\Gamma_{\gamma^*N}(q; W) = \frac{\alpha}{16} \frac{(W + M)^2}{M^2 W^3} \sqrt{y+y-y-} |G_T(q^2, W)|^2
\]

\[
|G_T(q^2; M_\Delta)|^2 = |G_M^*(q^2; W)|^2 + 3|G_E^*(q^2; W)|^2 + \frac{q^2}{2W^2} |G_C^*(q^2; W)|^2
\]

\[
y_\pm = (W \pm M)^2 - q^2
\]

\[
\Gamma_{\gamma N}(W) \equiv \Gamma_{\gamma^*N}(0; W)
\]

\[
\Gamma_{e^+e^-N}(W) = \frac{2\alpha}{3\pi} \int_{2m_e}^{W-M} \Gamma_{\gamma^*N}(q; W) \frac{dq}{q}
\]
Radiative decay widths

\( N^*(1520) \quad J^P=3/2^- \quad I=1/2 \)

60% decay \( \pi N \)

30% decay to \( \pi \Delta \)

Devenish (1976) normalization of transition form factors

Result Consistent with PDG value for \( \gamma N \) decay width.

\begin{align*}
G. \text{ Ramalho and M.T. P. Phys. Rev. D 95, 014003 (2017)}
\end{align*}
Dielectron Dalitz decay widths \( N^*(1520) \)

![Graph showing the neutron and proton light dilepton decay width](image)

\[ \Gamma_{e^+e^-N}(\text{GeV}) \]

Similar Proton and neutron results due to iso-vector dominance of meson cloud.

At higher energies evolution of \( G_T(q^2, W) \) with \( q^2 \) becomes important.

Different results for proton and neutron electromagnetic widths due to iso-scalar term in the eta meson cloud.

Timelike results give information on the neutron.
Comparison between different resonances

![Comparison between different resonances](image)


Dominance of the J=3/2 channel
Dilepton mass spectrum \( \Delta(1232) \) Dalitz decay

proton-proton collisions @1.25 GeV

![Graph showing dilepton mass spectrum](image)

**Signature of form factors q^2 dependence**

\( \Delta \) Dalitz decay branching ratio extracted \( 4.19 \times 10^{-5} \)

**Entry in PDG**

The obtained \( \Delta \) Dalitz branching ratio at the pole position is equal to \( 4.19 \times 10^{-5} \) when extrapolated with the help of the Ramalho-Peña model [27], which is taken as the reference, since it describes the data better. The branching ratio...
Dilepton mass spectrum

N*(1520) + N*(1535)

Dalitz decay

True CST prediction: Red line

Simulations based on the CST model (red line) for these resonances also give a satisfactory description of the data.

Below 200 MeV/c², data agrees with a pointlike baryon-photon vertex (QED orange line).

At larger invariant masses, data is more than 5 times larger than the pointlike result, showing a strong effect of the transition form factor.

HADES Collaboration

“First measurement of massive virtual photon emission from N* baryon resonances” e-Print: 2205.15914 [nucl-ex]
Extension to Strangeness in the timelike region

\[ e^+ e^- \rightarrow \gamma^* \rightarrow B \bar{B} \]

\[
|G(q^2)|^2 = \left(1 + \frac{1}{2\tau}\right)^{-1} \left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right] \\
= \frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau + 1}.
\]

Effective Form factor that gives the integrated cross section

Unitarity and Analyticity demand that for \( q^2 \rightarrow \infty \)

- \( G_M(q^2) \approx G_M^{\text{SL}}(-q^2) \),
- \( G_E(q^2) \approx G_E^{\text{SL}}(-q^2) \).


CST seems to work well at large \( Q^2 \).
Extension to Strangeness in the timelike region

\[ e^+ e^- \rightarrow \gamma^* \rightarrow B \bar{B} \]

Data from
Babar, CLEO, BESIII

\[ G_M(q^2) \approx G_M^{\text{SL}}(-q^2), \]
\[ G_E(q^2) \approx G_E^{\text{SL}}(-q^2). \]

Summary

With a CST phenomenological ansatz for the baryon wave functions we described different excited stated of the nucleon, with a variety of spin and orbital motion.

1 Evidence of separation of partonic and hadronic (pion cloud) effects from the $\Delta (1232)$

2 Made consistent with LQCD in the large pion mass regime, enabling extraction of “pion cloud” effects indirectly from data.

3 Spacelike e.m. transition FFs for: $N^*(1440), N^*(1520), N^*(1535), \ldots$, baryon octet, etc.

4 Extension to timelike e.m. transition FFs and predictions for dilepton mass spectrum and decay widths.

5 Descriptions consistent with experimental data at high $Q^2$. 